Anesthesiology
73:1058–1059, 1990

Dynamic Testing of Catheter Manometer Systems

To the Editor:—The complex and elegant article by Hipkins *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 (f_0) decreases dramatically (25.9 *vs.* 8.5 Hz). *In vivo*, there is no change in f_0 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 f_0 will remain the same (or actually increase!).* 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 f_0 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."*[,3] In addition, all of the air 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 the f_0.

Secondly, one of the pillars on which their conclusions of their paper stands is their definition of working heart rate. Working heart rate (f_{wh}) is, as they define it, the predicted heart rate up to which a system of given f_0 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 Hipkins *et al.*,[1] as:

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

Hipkins *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 f_{wh} is calculated as:

$$f_{wh} = [(\tau_{1.05} \cdot f_0)\text{Hz} \cdot 60] \div 10 \text{ beats per min}$$

where $\tau_{1.05} \cdot f_0$ 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 $[(\tau_{1.05} \cdot f_0) \cdot 60]$ by 10 will give the fundamental frequency, or in this case, the f_{wh}. The results in Hipkins *et al.*'s paper show a large disparity between the predicted behavior of a monitoring system, quantified by f_{wh}, 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 f_{wh} involves the measurement of α and f_0, this disparity leads the authors to conclude that, in fact, the whole process of dynamic testing (*i.e.*, the measurement of f_0 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 f_{wh}—their measure of the predicted behavior of a monitoring system. The assumption that ten harmonics are necessary for the accurate reproduction of a wave form is debatable. Certainly peak amplitudes of waves, or systolic peaks, can be reproduced reliably with less than ten harmonics. Hansen[5] 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 f_{wh} is seriously flawed. The number ten, in fact, cannot be assumed. Probably much smaller numbers are indicated. If this is so, then the f_{wh}—the measure of predicted behavior—may not deviate that much from measured behavior *in vivo*. Hence, Hipkins *et al.*'s conclusion that dynamic testing of monitoring systems is not valid may be incorrect.

BRUCE KLEINMAN, M.D.
Associate Professor of Anesthesiology and Medicine
Department of Anesthesiology
Loyola University of Chicago
2160 South First Avenue
Maywood, Illinois 60153

REED M. GARDNER, PH.D.
Professor and Co-Director
Medical Computing
LDS Hospital
325 8th Avenue
Salt Lake City, Utah 84143

STEVEN POWELL
Chief Technician
Department of Anesthesiology
Loyola University of Chicago
2160 South First Avenue
Maywood, Illinois 60153

* Vierhout RR: The response of catheter manometer systems used for direct blood pressure measurements (thesis). University of Nijmegen, The Netherlands: Thoben Offset, 1966, pp 79–90

REFERENCES

1. Hipkins SF, Rutten AJ, Runciman WB: Experimental analysis of catheter-manometer systems *in vitro* and *in vivo*. ANESTHESIOLOGY 71:893–906, 1989
2. Kleinman B, Powell S: Dynamic response of the Rose® damping device. J Clin Monit 5:111–115, 1989
3. Van der Tweel LH: Some physical aspects of blood pressure, pulse wave, and blood pressure measurements. Am Heart J 53:4–17, 1957
4. Geddes LA: The direct and indirect measurement of blood pressure. Chicago: Year Book Medical, 1970, p 46
5. Hansen AT: Pressure measurement in the human organism. Acta Physiol Scan [Suppl] 19(68):1–227, 1949
6. Patel DJ, Mason DT, Ross J, Braunwald E: Harmonic analysis of pressure pulses obtained from the heart and great vessels of man. Am Heart J 69:785–794, 1965

(Accepted for publication September 13, 1990.)

Anesthesiology
73:1059–1060, 1990

In Reply:—In response to the letter of Kleinman *et al.*, we would like to reemphasise 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 those 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 those systems would behave satisfactorily. The calculation of working heart rate (f_{wh}) was undertaken to solve a particular problem in analyzing the dynamics of resonating single-degree-of-freedom catheter–manometer systems: since the resonant frequency (f_0) and damping coefficient (α) of a given system can change independently, we sought to define a single term that relates f_0 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 clear that if the definition of f_{wh} is to be made less conservative, five harmonics would be the minimum allowable value. Gardner[4] suggests that systems with a "natural" frequency (presumably damped resonant frequency) of less than 10 Hz ($\approx$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 f_{wh} values we have reported; for example, the f_{wh} of system 1 with HP would rise from 35 to only 70 beats per min, and the f_{wh} 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 f_{wh} 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 f_{wh} 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 f_{wh} 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 f_{wh} 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. Rothe and Kim[5] report similar disagreement between the fast-flush test and other methods of dynamic testing. Billiet and Colardyn* 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 f_0 and α.

SCOTT HIPKINS
ALBERT RUTTEN
Department of Anaesthesia and Intensive Care
Flinders University of South Australia School of Medicine
Bedford Park
South Australia, 5042
Australia

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

REFERENCES

1. Patel DJ, Mason DT, Ross J, Braunwald E: Harmonic analysis of pressure pulses obtained from the heart and great vessels of man. Am Heart J 69:785–794, 1965
2. Attinger EO, Anné A, McDonald DA: Use of Fourier series for the analysis of biological systems. Biophysical J 6:291–304, 1966