An Evaluation of Modern Pressure Recording Systems

By DONALD L. FRY, M.D., FRANK W. NOBLE, M.E.E. AND ALEXANDER J. MALLOS, B.S.

An evaluation of the stability and accuracy of modern physiologic pressure measuring systems is reported with a brief review of some of the problems of catheter pressure recording. Evaluation of stability consisted of measuring the drift of the baseline and of the calibration factors of the gage and amplifier combination with time and temperature change. Evaluation of the accuracy of these pressure measuring systems consisted of determining their static accuracy, their dynamic accuracy, and the pressure errors introduced by catheter accelerations and bending.

The recording of pressure is of interest and importance in physiologic studies. Physiologic pressure measuring systems should be evaluated from three viewpoints: operational simplicity, stability, and accuracy. A comprehensive evaluation of the various commercially available systems along these general lines does not appear in the literature. It is the purpose of this report to present data on stability and accuracy for those interested in design of physiologic studies, especially of the cardiovascular system.

METHOD AND RESULTS

Stability. The stability of the baseline and calibration factors was determined in a temperature controlled room. Voltage regulation in addition to that already present in the respective amplifiers was not attempted. The amplifiers and gages were allowed to warm up for the period recommended by the manufacturers at 22 C. ambient. At this point the stability study began. The stability of the baseline and calibration factors of the amplifier and gage combination was determined at 22 C. for a period of 2 hours. At this point the temperature of the room was raised to 30 C. as rapidly as possible. Measurements at 30 C. were continued for 2 more hours. The temperature was then brought back to 22 C. as rapidly as possible. Measurements then continued for another 2 hours. The baseline drift as mm. Hg/degree C. and the calibration factor drift as per cent change/degree C. appear in table 1 with their respective maximum measurement errors.

Accuracy. The accuracy of the gages to static pressure was uniformly good. Each gage was subjected to 20 mm. Hg pressure increments from 0 to +360; then 20 mm. Hg decrements to -60; then 20 mm. Hg increments back up to 0. This sequence was repeated 5 times on each gage. The reproducibility of pressure vs. pen deflection of the recorder was excellent for each gage and recorder combination. The pressure range of linearity for each gage appears in table 1. The linear range is defined as the maximum range over which the calibration curve does not deviate from a straight line by more than ±1 per cent of 420 mm. Hg full scale. The maximum width of the hysteresis loop for each gage and recorder system also appears in table 1. The loop width of the recorder alone over the same excursions was 0.2 to 1.0 per cent of full scale deflection. The reproducibility of reading of the paper was ± 0.3 per cent of full scale.

Adequate sensitivity for both systemic and pulmonary vascular pressures was obtained in all of the systems tested without the appearance of significant electric noise. The Gauer microgage and Sanborn gages have extremely high sensitivity.

The accuracy of the gages to dynamic pressure was measured by subjecting the gages to sinusoidal pressure waves having various frequencies. The pressure monitor device consisted of a Lilly model 115H1 gage modified so that its diaphragm formed part of one wall of the pressure chamber. The response of this monitor was uniform to over 1000 c.p.s. The electric output of the test gage and of the monitoring pressure gage inside the pressure chamber were placed on a dual beam DaMont 322 oscilloscope. The amplitude and phase vs. frequency response could then be measured directly from the oscilloscope face. The amplitude response was expressed as percentage of the amplitude response at 1 c.p.s.

When the gages were initially filled with tap water, it was found impossible to obtain reproducible frequency response curves. Boiled water with a few drops of aerosol per liter or about 50 per cent alcohol in water made reproducible curves possible. Since no leaks could be demonstrated and since the lack of reproducibility could be corrected ultimately by repeated flushing with wetting agents, it was as-
assumed that the lack of reproducibility was caused by small amounts of gas trapped in the system. This problem is of practical importance to the physiologist who cannot always use freshly boiled solutions or wetting agents, nor take the time required to get reproducible frequency response curves.

Data from the frequency response curves of each gage when used with an 18 gage needle and when used with a no. 6-155 cm. cardiac catheter are compared in table 1.

The first double column of data in this part of table 1 represents the frequency to which the system may be considered to have an essentially uniform dynamic response (+5 per cent), the second double column the resonant frequency, the third double column the per cent overshoot at resonance, and the fourth double column the frequency at which the amplitude response curve recrosses the 100 per cent line. The response data for the needle and for the catheter appear in the left and right halves of each double column respectively.

Each gage had a three-way stopcock and a 1½ inch thin walled number 18 gage needle transmitting the pressure to it from the sinusoidal pressure generator. In each case the electric signal from the test gage was taken from its amplifier at a point where the signal represented the response of the gage itself unmodified by any electrical network. All of the systems are underdamped. The Hathaway system as normally used has been optimally damped by electric means so that the frequency response curve from the over-all system is essentially uniform to about 120 c.p.s. when an 18 gage 1½ inch thin wall needle and three way stopcock are used. Only data from the curve showing the unmodified Hathaway response appears in table 1.

Data from the frequency response curves of the same water filled gages attached to 155 cm. number 6 cardiac catheter through a three way stopcock appear in the right half of the double column in table 1. Each gage and catheter system was thoroughly flushed with boiled water initially and then allowed to "soak" for at least 2 hours with periodic flushings until the frequency response curve achieved a reproducible form. Reproducible curves were not obtainable without both repeated flushing and soaking. Frequency response curves of the catheter systems in general had multiple resonances. The data in table 1 refer only to the first resonance. Multiple resonances are especially well shown on the curve for the Lilly gage in figure 1. This is a property of wave transmitting systems such as transmission lines and organ pipes.¹

The effect on the frequency response of warming the catheters to 37 C. was determined. A thermostatically controlled water bath was used. The first frequency response curve was performed at 20 C. The body of the catheter to be tested was then placed in the bath until it was considered to have reached thermal equilibrium with the bath at 37 C. Then another frequency response curve was determined. Although the catheter became quite soft and pliable at 37 C., the response characteristics were not seriously affected. The differences shown in figure 1 were typical of all the other systems. In general, the resonant peak is slightly lowered and occurs at a slightly lower frequency.

To determine the behavior of an assortment of catheters, the Statham P23D was then tested with all of the commonly used arterial and venous catheters. These frequency response curves appear in tabular form in table 2. The first five catheters are the Cournand type cardiac catheters.* The nylon filament catheter was an experimental intravascular catheter from the same company. The polyethylene filament catheters are commonly used, chemically inert, opalescent, plastic tubing. The heat treated polyvinyl filament catheters are the stiff opaque catheters commonly used for central aortic pressures.† The adaptors for forming the union of plastic tube to gage are sold by Clay-Adams Co.† This important link in the pressure transmission system works well with polyethylene plastic, poorly with the polyvinyl plastic and not at all with the nylon plastic. It is interesting to note that the frequency response of the relatively soft poly-

---

¹ U. S. Catheter and Instrument Company, Glens Falls, N. Y.
† Clay-Adams Company, Inc., New York, N. Y.
‡ Mr. Albert Afford, Williams Avenue, Barrington, N. J.
<table>
<thead>
<tr>
<th>Gage</th>
<th>Amplifier</th>
<th>Recorder</th>
<th>Stability</th>
<th>Accuracy</th>
<th>Dynamic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Baseline drift mm. Hg/degree C.</td>
<td>Calibration factor drift, per cent/degree C.</td>
<td>Hysteresis as maximum width of loop in per cent of 420 mm. Hg full scale</td>
</tr>
<tr>
<td>Sanborn 121B capacitance</td>
<td>Sanborn 121B thru a D.C.</td>
<td>Sanborn 67-1200</td>
<td>+3.25±0.02</td>
<td>-0.52±0.25</td>
<td>-20 to 300</td>
</tr>
<tr>
<td>Sanborn 467B differential transformer</td>
<td>Sanborn 67-500</td>
<td>Sanborn 67-1200</td>
<td>+0.53±0.02</td>
<td>-0.38±0.25</td>
<td>-40 and &gt;360</td>
</tr>
<tr>
<td>Technitrol 115 H-1 capacitance</td>
<td>Technitrol 115-A2</td>
<td>Brush BL-222</td>
<td>-12.25±0.04</td>
<td>-1.54±0.38</td>
<td>0 to 300</td>
</tr>
<tr>
<td>Hathaway PSSAI I</td>
<td>Hathaway MBP-1 thru a MBC-2 control unit</td>
<td>Hathaway SI4C with OA-2</td>
<td>+0.12±0.13</td>
<td>-0.63±0.32</td>
<td>&lt;40 and &gt;360</td>
</tr>
<tr>
<td>A35981G1 inductance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Statham P23A resistance</td>
<td>Sanborn 67-500</td>
<td>Sanborn 67-1200</td>
<td>&lt;0.06</td>
<td>&lt;0.25</td>
<td>&lt;40 and &gt;360</td>
</tr>
<tr>
<td>Statham P23D resistance</td>
<td>Sanborn 67-500</td>
<td>Sanborn 67-1200</td>
<td>&lt;0.06</td>
<td>&lt;0.25</td>
<td>&lt;40 and &gt;360</td>
</tr>
<tr>
<td>Consolidated 4-312 resistance</td>
<td>Sanborn 67-500</td>
<td>Sanborn 67-1200</td>
<td>&lt;0.06</td>
<td>-0.60±0.25</td>
<td>&lt;40 and &gt;360</td>
</tr>
<tr>
<td>Gauer inductance</td>
<td>Gauer thru a Sanborn D. C. 67-300</td>
<td>Sanborn 67-1200</td>
<td>+0.25±0.02</td>
<td>-0.63±0.25</td>
<td>&lt;40 to 180</td>
</tr>
</tbody>
</table>

Fig. 1. Frequency response curves of the Technitrol (Lilly type) manometer attached to a number 6-155 cm. cardiac catheter filled with boiled water. Ordinate, per cent of response at 1 c.p.s.; abscissa, c.p.s.

Table 2.—Frequency Response Curves of Various Catheters Attached through a Three-way Stopcock to a Statham P 23 D Strain Gage at Room Temperature (20 C.)

<table>
<thead>
<tr>
<th>Catheter</th>
<th>Frequency to which system response was flat to within ±5 per cent</th>
<th>Resonant frequency</th>
<th>Per cent response at resonance, referred to response at 1 c.p.s.</th>
<th>Frequency at which response curve recrossed 100 per cent line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number 6 Cardiac catheter 150 cm..............</td>
<td>14</td>
<td>64</td>
<td>495</td>
<td>100</td>
</tr>
<tr>
<td>Number 6 Cardiac catheter 160 cm..............</td>
<td>12</td>
<td>44</td>
<td>400</td>
<td>90</td>
</tr>
<tr>
<td>Number 6 Cardiac catheter 155 cm..............</td>
<td>8</td>
<td>37</td>
<td>340</td>
<td>65</td>
</tr>
<tr>
<td>Number 6 Cardiac catheter 120 cm..............</td>
<td>15</td>
<td>45</td>
<td>355</td>
<td>80</td>
</tr>
<tr>
<td>Number 4 Cardiac catheter 105 cm..............</td>
<td>18</td>
<td>74</td>
<td>280</td>
<td>115</td>
</tr>
<tr>
<td>Nylon filament catheter to go thru 18 gage thin wall needle 75 cm.............................</td>
<td>11</td>
<td>37</td>
<td>230</td>
<td>55</td>
</tr>
<tr>
<td>Polyethylene filament catheter to go thru 18 gage thin wall needle 80 cm, P.E. 50...........</td>
<td>12</td>
<td>37</td>
<td>230</td>
<td>55</td>
</tr>
<tr>
<td>Polyethylene filament catheter to go thru 18 gage thin wall needle 22 cm, P.E. 50...........</td>
<td>30</td>
<td>92</td>
<td>335</td>
<td>125</td>
</tr>
<tr>
<td>Polyethylene filament catheter to go thru 15 gage needle 80 cm, P.E. 60 ......................</td>
<td>14</td>
<td>47</td>
<td>330</td>
<td>70</td>
</tr>
<tr>
<td>Heat treated Polyvinyl filament catheter to go thru 18 gage thin wall needle 50 cm.........</td>
<td>15</td>
<td>56</td>
<td>320</td>
<td>80</td>
</tr>
<tr>
<td>Heat treated Polyvinyl filament catheter to go thru 18 gage thin wall needle 82 cm.........</td>
<td>14</td>
<td>41</td>
<td>270</td>
<td>60</td>
</tr>
<tr>
<td>Heat treated Polyvinyl filament catheter to go thru 19 gage thin wall needle 82 cm.........</td>
<td>12</td>
<td>29</td>
<td>180</td>
<td>40</td>
</tr>
</tbody>
</table>

Ethylene catheters compares favorably with the more stiff heat treated polyvinyl filament catheters of the same outside diameter. The polyethylene catheters also show less propensity toward fibrin deposition and toward kinking. On the other hand, they are more difficult to pass since their flexibility leads to easy coiling.

The damping effect of blood as it works back into a cardiac catheter during physiologic pressure recording was evaluated by filling the pressure chamber with heparinized whole blood. Theoretically this effect could be quite large especially in small catheters with compliant* gages. The Statham P23A and P23D gages with number 6 long cardiac catheters were chosen as test systems since they represented two rather opposite degrees of stiffness. In general, the less stiff gage should show the damping effects of blood sooner. The gage catheter system was initially filled with normal saline. A frequency response curve was obtained. The catheter was flushed with saline. Then the pressure generator was filled with blood and set to run at 1 c.p.s. with a peak to peak amplitude of about 50 mm. Hg pressure to approximate the conditions met by the

* Compliance is the opposite of stiffness.
EVALUATION OF MODERN PRESSURE RECORDERS

Fig. 2. Simultaneously recorded pressures from the same point in the pulmonary artery and from the right ventricle as measured by three different pressure measuring systems. The gage and catheter system, C, consists of a Statham P23D gage with a number 6, 155 cm. long, cardiac catheter. The monitor system, M, consists of a Statham P23D gage attached directly to a 18 gage thin walled needle thru a three-way stopcock. P.A.P. = pulmonary artery pressure; R.V.P. = right ventricular pressure; G = Gauer microgage.

catheter in the vascular system. Frequency response curves after as much as 20 min. of pressure pulsing in blood were indistinguishable from the initial curve. Thus 20 min. of pulsing in blood has no significant damping effect even on the less stiff or compliant gage.

The physical theories of the simple gage as well as the more complicated gage and catheter system are based on the assumption that the systems are linear. If a system is linear, the frequency response curve is independent of the amplitude of the input sinusoidal pressure wave. This provides a test for the linearity of the system. Frequency response curves for all the systems both with needles and catheters were done with a peak to peak amplitude of 50 mm. Hg pressure and again with 25 mm. Hg pressure. Within the limits of measurement error the frequency response curves were all found to be independent of the amplitude of the input sinusoidal pressure wave. Thus the evidence indicates that all of the gage systems tested are essentially linear. This is in agreement with other studies. The displacement linearity was already apparent from table 1.

The pressure errors due to accelerations and volume changes of the catheter produced by the motions of the heart and blood mass were evaluated in dogs. The catheter system to be evaluated was introduced in the usual manner via the jugular vein to the point from which pressure measurement was desired. The tip of the catheter was then located at thoracotomy. A pressure monitoring system consisting of the Statham P23D directly attached to a number 18 gage thin wall needle was then introduced so that the needle opening would coincide as closely as possible with the catheter tip. The Statham P23D under these conditions has a frequency response curve essentially uniform through 70 c.p.s. It may thus be considered to be recording the true pressure quite accurately. Simultaneous pressure recordings were then made from the monitoring system and the test catheter system. The test catheter system consisted of a P23D gage and a number 6-155 cm. long cardiac catheter. In one experiment the Gauer microgage was passed parallel to the cardiac catheter so that their tips coincided. Tracings from this experiment at various points in the right heart and pulmonary artery with these three different systems appear in figure 2. The Gauer microgage curve closely followed the monitor system curve. The conventional cardiac catheter demonstrates very large superimposed transient pressure errors frequently amounting to 20 per cent of the true
value. In spite of these large errors in the instantaneous values of the pressure, there was no detectable error in the mean pressure.

It should be mentioned that the greater the heart rate and the stiffer the gage the greater will be the acceleration errors. Since all of the heart rates were high and a rather stiff gage was used in these studies, the acceleration errors shown in figure 2 probably are greater than those usually encountered during human cardiac catheterization with the commonly used P23A Statham gage.

**Discussion**

The foregoing data describe the major features of the physical behavior of the various commercially available pressure measuring systems as the physiologist and clinician would normally use them. The significance of the data concerning the stability and accuracy to static pressures is intuitively clear. The significance of the data concerning the dynamic accuracy of these systems is not generally appreciated.

Any physiologic pressure wave may be described quantitatively by one of several mathematical devices called "infinite series." One in particular, the Fourier series, has the simplest physical interpretation. When a pressure pulse is represented by a Fourier series, every point of the pressure curve may be considered as the sum of all the corresponding points at that moment of a series of superimposed sinusoidal waves. The amplitudes, frequencies and phases of these sinusoidal waves are uniquely determined by the shape of the pressure pulse. This sum of an infinite series of sinusoidal waves is the Fourier series for this particular pressure pulse.

Furthermore, it can be proved that the response of a linear measuring system to any pressure wave will be the same as the sum of its individual responses to each of the sinusoidal components making up the Fourier series of the pressure wave. This is why the frequency response of a system to simple sinusoidal pressure waves at all frequencies defines its response to any arbitrary complex pressure pulse. If the Fourier series of an arbitrary pressure pulse is known, the frequency response curve of a pressure measuring system defines the adequacy with which the measuring system will indicate that pressure pulse. It is for this reason that the frequency response curves were determined in the present study.

The behavior of pressure measuring systems consisting only of a gage attached directly to either a needle or a short noncompliant catheter has been shown experimentally to correspond to that predicted from relatively simple mathematical theory. This is not the case when relatively compliant or long catheters are used. The many resonances of the long catheter systems as illustrated in figure 1 as well as data from other studies indicate that the more complicated mathematical theory of electric transmission lines describes the physical behavior of catheter systems better. The implications of transmission line theory are that pulse waves are distorted during transmission through the catheter by (1) multiple reflections of frequency components, (2) unequal attenuation of the different frequency components during transmission, and (3) different transmission times for each frequency component. The magnitude of the distortion due to wave transmission can only be determined by further study. It is unlikely that transmission distortion will be as serious as the distortion secondary to catheter acceleration and bending such as illustrated in figure 2.

From these considerations and the data presented in this study it is curious that the micromanometer of Gauer and Wetterer has not enjoyed wider use in this country.

**Summary**

An evaluation of the stability and accuracy of modern physiologic pressure measuring systems is reported with a brief review of some of the problems of catheter pressure recording.

Evaluation of stability consisted of measuring the drift of the baseline and of the calibration factors of the gage and amplifier combination with time and temperature change.

Evaluation of the accuracy of these pressure measuring systems consisted of determining their static accuracy, their dynamic accuracy and the pressure errors introduced by catheter accelerations and bending. The static accuracy
of the systems was found to be uniformly good. The calibration curves were reproducible and none showed more than 2.8 per cent of full scale hysteresis. All systems were reasonably linear in the physiologic range of pressures.

The dynamic response of the systems could be obtained in a reproducible fashion only after great care had been taken to eliminate gas bubbles from the system. The Technitrol and Gauer gages had the highest resonant frequencies. The frequency response of catheter systems was affected only moderately by warming to 37 C. and not all by substituting blood for water in the pressure generator. Large pressure errors often amounting to 20 per cent of the true instantaneous value were found to occur in catheter systems when recording from the pulmonary artery. The mean pressures recorded from the same point with the catheter system were accurate.

SUMMARY IN INTERLINGUA
Es reportate un evaluacion del stabilitate e del exactitude de moderne systemas de mesuration del pression physiologic, insimul con un breve revista de certes del problemes in le registration de pression per medio de catheteres.

Le evaluacion del stabilitate consisteva in le mesuration del effecto de tempore e de alterationes de temperatura super le stato del linea de base e de factores de calibration in le combination de manometro e amplificator.

Le evaluacion del exactitude de ille systemas de mesuration consisteva in determinar lor exactitude static, lor exactitude dynamic, e le errores de pression introduciti per le acceleratio e le curvation del catheter. Esseva constatatate que le exactitude static del systemas esseva uniformemente bon. Le curvas de calibration esseva reproducibile, e nulle de illos monstrava un hysterese de plus que 2,8 pro cento. Omne le systemas esseva adeguatemente linear intra le limites de pressiones physiologic.

Le reproductibilitate del responsas dynamic del systemas esseva assecurable solmente per le plus caute elimination de omne bullas gasose. Le instrumentos de Gauer e Technitrol habeva le plus alte frequenties resonante. Le responsas de frequenties in systemas a catheter esseva afficite solmente a grados moderate per calefacion a 37 C e non del toto per le substitution de sanguine pro aqua in le generator del pression. Grande errores de pression, amontante frequentemente a 20 pro cento del ver valor instantaneous, esseva constatatate in systemas a catheter quando le registration esseva facite ab le arteria pulmonar. Le pressiones medie registrate ab le mesme puncto per medio del systema a catheter esseva accurate.

REFERENCES
An Evaluation of Modern Pressure Recording Systems
DONALD L. FRY, FRANK W. NOBLE and ALEXANDER J. MALLOS

Circ Res. 1957;5:40-46
doi: 10.1161/01.RES.5.1.40

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1957 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circres.ahajournals.org/content/5/1/40

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation Research 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 Research is online at:
http://circres.ahajournals.org/subscriptions/