CHAPTER 20

System Concepts for Invasive Pressure Monitoring

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IMMEDIATE CONCERNS

The invasive pressure monitoring that is routinely performed at the patient's bedside incorporates technology more advanced than was formerly used in heart cardiac catheterization laboratories, enabling the clinician to comprehend the relationship between the pressure and blood flow in the patient's cardiovascular system. Because every measuring system can produce false information, constant vigilance and a thorough understanding of the system are necessary to ensure high-quality pressure monitoring information.

INVASIVE BLOOD PRESSURE MEASUREMENT

Arterial blood pressure can be measured by invasive and non-invasive means, but central venous pressure, pulmonary artery pressure, and pulmonary artery occlusion pressure can only be measured by invasive means.

Although continuous and accurate assessment of blood pressures can only be made invasively, the continuous pressure data enables detection of dangerous hemodynamic events and provides the information necessary to initiate and titrate therapy. Nevertheless, invasive pressure monitoring provides valuable information only when it is obtained accurately with correct technique.

This chapter covers the technical aspects of invasive monitoring. Information about catheter insertion techniques are presented in Chapters 15 and 21. Associated complications, physiologic measurements, and managing patient-related problems are discussed in other chapters.

EQUIPMENT

The components used for invasive pressure monitoring are shown in Figure 20-1.[1,2] This diagram illustrates an arterial site, but a similar setup is appropriate for pulmonary artery pressure measurement. The components known as the "plumbing system" (1–6 in the figure) must remain sterile because they directly contact the patient's blood. These components are usually disposable items and are often discarded after 48 hours of use to minimize the risks of infection. The other components (7–10) in the system are used for processing and displaying pressure waveforms and obtaining hemodynamic parameters.

PLUMBING SYSTEM COMPONENTS

Catheter

Arterial and pulmonary artery catheters provide access to the patient's blood vessels for pressure monitoring and for blood sample withdrawal for blood gas analysis and other tests.

Stopcock Number 1

The stopcock number 1 is used as a site for withdraw of blood for analysis. In filling the plumbing system with fluid, be sure all central switching cavities of the stopcock are fluid filled.

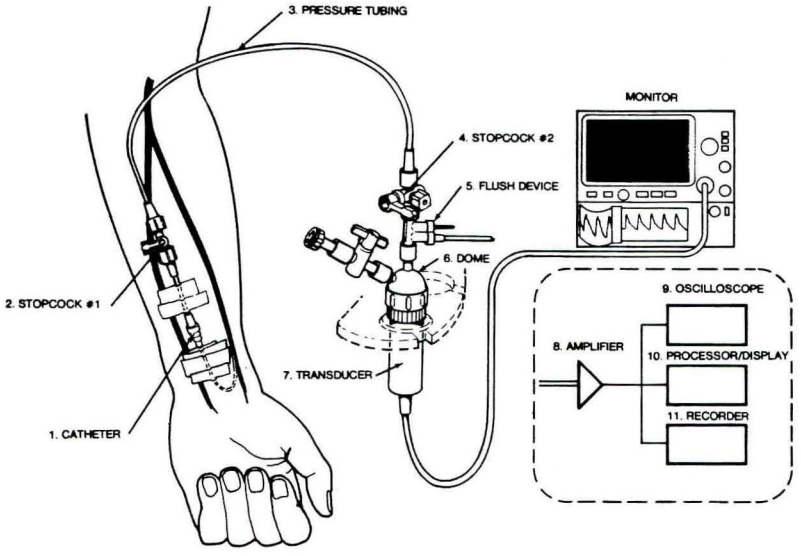

FIG. 20-1. Components used to monitor blood pressure directly are almost the same in a radial, brachial, or femoral artery and in the pulmonary artery. The size of the transducer and plumbing components were enlarged for illustration purposes. (Adapted from Gardner RM, Hollingsworth KW: Optimizing ECG and pressure monitoring. *Crit Care Med* 1986; 14:651)

All entrapped air bubbles must be removed. Stopcocks are particularly vulnerable sources of patient contamination. Therefore, stopcocks should be handled with extreme care; ports not in active use should be covered with sterile caps, and the open ports should never be touched.

Pressure Tubing

The catheter and stopcock are normally attached to the flush device and transducer by non-elastic pressure tubing. To optimize the dynamic response of the plumbing system, long lengths of tubing should be avoided.

Stopcock Number 2

If the transducer is patient mounted when measuring arterial pressures, stopcock number 2 may not be necessary.

Continuous Flush Device

The continuous flush device is used to fill the pressure monitoring system and helps prevent blood from clotting in the catheter by continuously flushing fluid through the system at a rate of 1 to 3 ml each hour.

Pressure Transducer

Most pressure transducers used today are miniature, rugged, disposable devices.[5-7] Because of their miniature size, they can be patient mounted. All available disposable pressure transducers are resistive devices that convert the movement of their sensing diaphragm into an electrical signal. Standards for blood pressure transducers have been developed by the Association for the Advancement of Medical Instrumentation (AAMI) and adopted by the American National Standards Institute (ANSI).[3,4] The AAMI/ANSI standards have greatly simplified transducer selection and allow transducers from different vendors to be used interchangeably with any monitor.

WAVEFORM MONITORING SYSTEM COMPONENTS

Amplifier

The output voltage required to drive an oscilloscope or strip recorder is provided by an amplifier system inserted between the transducer and display. Transducer excitation is provided from a direct current (DC) or alternating current (AC) source at a voltage of 4 to 8 volts root mean squared (RMS). Most amplifier systems include low-pass filters that diminish unwanted high-frequency signals. Pressure amplifier frequency response should be "flat" from 0 to 50 Hz to avoid pressure waveform distortion.[1,2]

Display

Pressure waveforms are best visualized on a calibrated oscilloscope.

Digital displays provide a simple method for presenting quantitative data from the pressure waveform. They are found on most modern pressure monitoring equipment. Systolic, diastolic, and mean pressures are derived from the pressure waveforms.

Recorder

Strip chart recorders are frequently used to document dynamic response characteristics, respiratory variations in pulmonary artery pressures, and aberrant rhythms and pressure waveforms.

EQUIPMENT SETUP

ZEROING THE TRANSDUCER

The accuracy of blood pressure measurement requires an accurate reference point from which all measurements are made. The patient's mid-axillary line (right heart level) is the

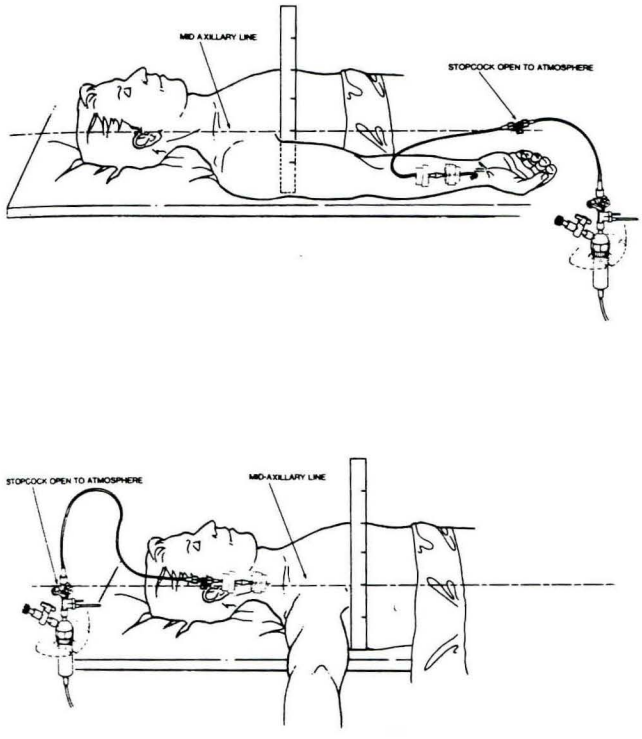

FIG. 20-2. Two methods of zeroing a pressure transducer. The place at which the water-air interface occurs should always be at the mid-axillary line when zeroing. *Top.* The stopcock is placed near the transducer at the mid-axillary line. *Bottom.* The stopcock near the catheter is placed at the mid-axillary line. (Adapted from Gardner RM, Hollingsworth KW: Optimizing ECG and pressure monitoring. *Crit Care Med* 1986; 14:651)

reference point most commonly used. The zeroing process compensates for offset caused by hydrostatic pressure differences or offset in the pressure transducer, amplifier, oscilloscope, recorder, and digital displays. Zeroing is accomplished by opening an appropriate stopcock to the atmosphere and aligning the resulting fluid-air interface with the mid-axillary reference point.[1,2,8] Figure 20-2 shows two methods for zeroing the transducer.[1,2]

After the system is zeroed, the appropriate stopcock can be switched to allow the patient's waveform to be displayed. Because pulmonary artery pressure and pulmonary artery occlusion pressure are especially susceptible to improper zeroing, the zero should be verified with each measurement.

VERIFYING SENSITIVITY OF THE TRANSDUCER

The sensitivity of the AAMI/ANSI interchangeable blood pressure transducer is fixed at 5.0 μV/V/mm Hg and calibrated by the manufacturers to within $\pm$1%.[4] This degree of accuracy is appropriate for clinical purposes. Using transducers that meet the AAMI/ANSI interchangeability standard and monitors that interconnect with standardized transducers virtually eliminates the need to calibrate the transducer or verify its sensitivity.

OPTIMIZING DYNAMIC RESPONSE CHARACTERISTICS

Catheter-tubing-transducer setups used in the intensive care unit are underdamped second-order dynamic systems.[1,2,9–11] Characteristics of second-order systems are described mathematically by a second-order differential equation with characteristics determined by three mechanical parameters: elasticity, mass, and friction. These same parameters apply to a catheter-tubing-transducer system in which the natural frequency (Fn, in hertz) and damping coefficient zeta (ζ) determine the dynamic characteristics of the plumbing system.

Dynamic response characteristics of catheter-tubing-transducer systems are expressed by two interrelated techniques. One specifies a bandwidth (frequency) and requires that the system's frequency response be flat up to a given frequency, so that a specified number of harmonics (usually 10) of the original pulse wave can be reproduced without distortion (Fig. 20-3). The second specifies Fn and ζ (Fig. 20-4).[9] If the characteristics of the plumbing system fall in the adequate or optimal areas of the graph, the pressure waveforms are adequately reproduced. If this point falls in any of the remaining three areas, there are waveform distortions. Catheter-tubing-transducer plumbing systems assembled under optimal conditions are usually underdamped, although a few fall into the unacceptable areas.

Methods for optimizing the plumbing system components have been outlined.[1,9,10,12] In the clinical setting, in which there are dramatic differences between patient setups, it is mandatory to test the adequacy of each pressure monitoring system. This can be done using the fast-flush technique. A fast flush is produced by opening the valve of the continuous-flush

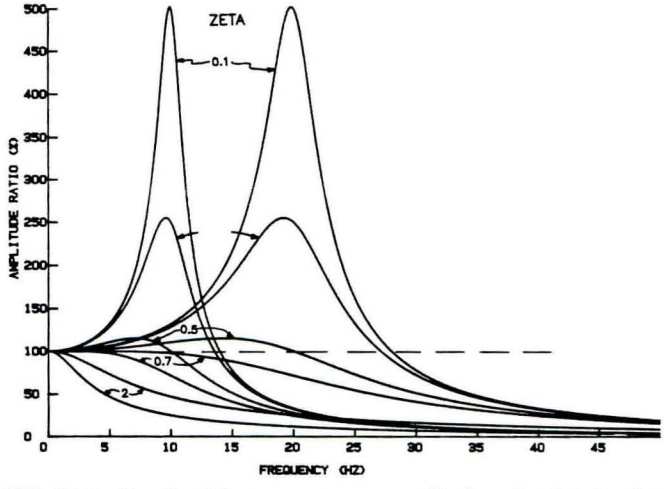

FIG. 20-3. Family of frequency *versus* amplitude ratio plots for five damping coefficients (ζ) and two natural frequencies at 10 and 20 Hz. A damping coefficient of 0.1 occurs if the system is very underdamped, and a damping coefficient of 2.0 occurs if a system is overdamped. The *dashed line* shows the ideal or "flat" frequency plotted against amplitude response. The response of the system with a 10-Hz natural frequency can be brought closer to the flat response if the damping coefficient is between 0.5 and 0.7. However, by increasing the natural frequency to 20 Hz, the range of damping coefficients can be widened and give almost the same flat frequency response.

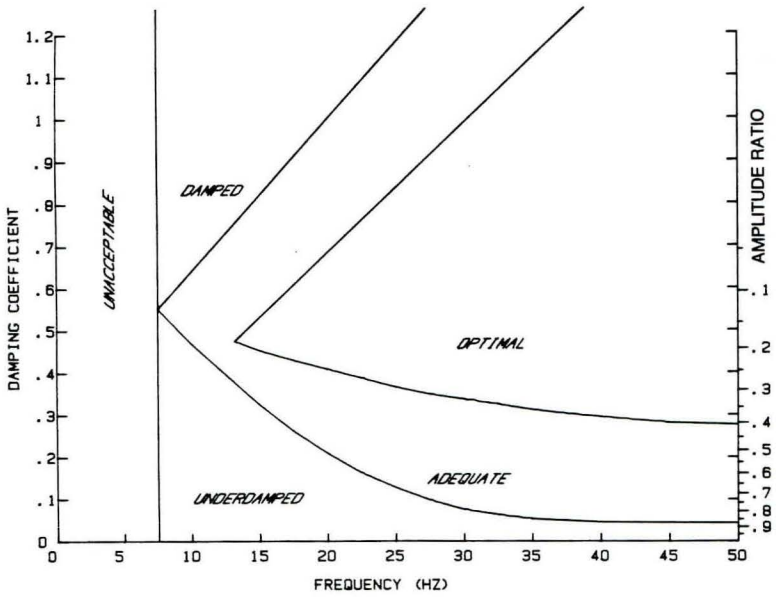

FIG. 20-4. The plot shows the range of damping coefficients and natural frequencies, outlining regions that indicate the type of distortion of the pressure wave. See Figure 20-5 for examples.

device (*e.g.*, quickly releasing the fast-flush valve on the continuous-flush system). The rapid closure generates a square wave from which Fn and ζ of the plumbing system can be measured.

After the fast-flush test has been executed two or three times, the dynamic response characteristics (Fn and ζ) can be quickly determined.[1,9] Natural frequency can be estimated by measuring the period of each full oscillation on a strip chart recorder (Fig. 20-5A) after a fast flush and calculating the frequency from the period. Damping coefficients are determined from any two successive peak amplitudes. An amplitude ratio, obtained by dividing the measured height of the lower peak by that of the larger peak (Fig. 20-5B), is converted to ζ.

After Fn and ζ have been determined, the data can be plotted on the graph in Figure 20-4 to ascertain the adequacy of dynamic response. Some bedside monitors and recorders may compromise the fast-flush technique with their built-in low-pass filters. These filters should be expanded to at least 50 Hz or eliminated.

Several factors yield poor dynamic responses: air bubbles in the system, usually caused by a poor initial plumbing system setup; pressure tubing that is too long, too elastic, or with a diameter that is too small; and pressure transducers that are too elastic. The best way to enhance the system's dynamics is to maximize its Fn.

CLINICAL AND LABORATORY MEASUREMENTS OF DYNAMIC RESPONSE

Several investigators have studied the dynamic response characteristics of catheter-transducer systems in the laboratory.[1,2,9–25] A recent study determined the dynamic response fidelity of catheter-transducer systems in the laboratory and in the clinical setting.[26,27] Some investigators have evaluated the dynamics of pressure monitoring systems by evaluating only one element in the system, but recent studies have examined the complete pressure monitoring plumbing system.[26,27]

Simpler mechanical plumbing setups for pressure monitoring systems correlate with higher fidelity.[26] The greater the number of components within the system, the greater is the susceptibility to degraded dynamic performance. Lack of tubing or shorter lengths of tubing minimize the chances of air bubble entrapment. Chances for setup error were also minimized with simpler plumbing systems.

Pressure monitoring systems that use elastic catheters or elastic tubing or that contain air bubbles have large volume displacements and, therefore, poor dynamic response characteristics. Systems that use long narrow catheters (*e.g.*, pulmonary artery catheter) or have long lengths of small-diameter pressure tubing are not desirable because Fn decreases and ζ increases. Conversely, if the catheters and tubing are not elastic and short, with large diameters and no air bubbles, the Fn increases and ζ decreases.

Figure 20-6 illustrates the effects of tubing length and air bubbles entrapped in the system. As the volume displacement (V_d) increases, there is a decrease in Fn and an increase in the damping coefficient. The magnitude of the change is multiplied for systems with long catheters or tubing (*e.g.*, pulmonary artery catheter and radial catheter with 183-cm tubing). For the short radial arterial catheter, the effect of tubing length is also apparent. Increasing the tubing from 30 to 183 cm with no air bubbles in the system reduces the Fn from 39 to 23 Hz. For a pulmonary artery catheter system without pressure tubing, the effect of increasing air bubble size (V_d) on the system is shown. Notice that the operating point moves upward and to the left. Despite what is taught in some medical centers, adding air to the transducer to damp the pressure waveform is *not* a good idea.

The use of extension tubing for pulmonary artery lines was especially detrimental to the system's response. The adverse effects of long tubing are compounded by the long length of the pulmonary artery catheter. The use of extension tubing,

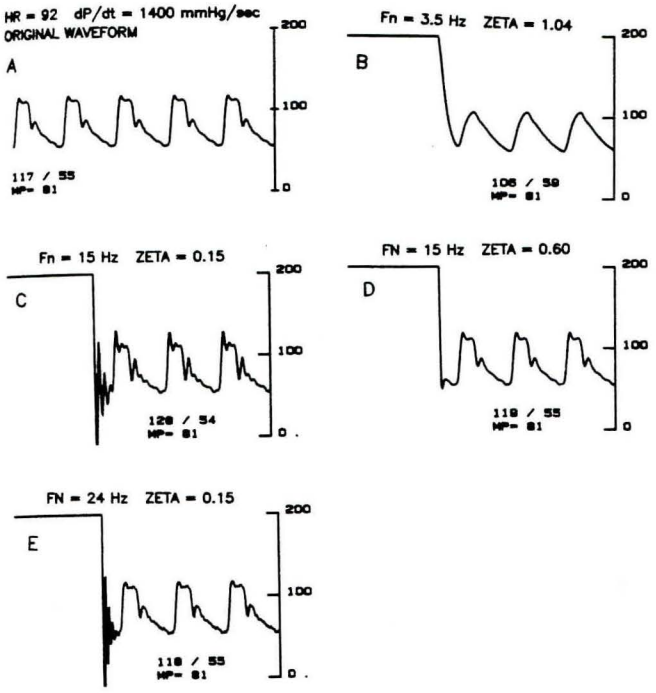

FIG. 20-5. Arterial pressure waveforms recorded with different pressure monitoring systems. The patient's heart rate is 92, with a maximum dP/dt of 1400 mm Hg/sec. *A.* The original patient waveform as it might be recorded with a catheter-tipped pressure transducer. The systolic pressure is 118 mm Hg, diastolic is 55 mm Hg, and mean pressure is 81 mm Hg. *B.* The same patient's arterial pressure waveform recorded with an overdamped plumbing system. Zeta is 1.04 and Fn is 3.5 Hz. The fast-flush signal (*upper left*) returns slowly to the patient's waveform. Systolic pressure is underestimated at 106 mm Hg, diastolic pressure is overestimated at 59 mm Hg, but mean pressure is unchanged at 81 mm Hg. *C.* Shows an underdamped condition with a low damping coefficient of 0.15 and a natural frequency of 15 Hz. After the fast-flush, the pressure waveform oscillates rapidly and returns to the original waveform shape quickly. Systolic pressure is overestimated at 128 mm Hg, diastolic is almost the same as the original at 54 mm Hg, and the mean pressure is unchanged at 81 mm Hg. *D.* Same as in *C*, but now a damping device has been inserted and adjusted. The waveform is optimally damped with a damping coefficient of 0.60 and a natural frequency of 15 Hz. *E.* Shows an underdamped condition, but with high natural frequency of 24 Hz. The pressure waveform is only slightly distorted, and the pressures are close to the true pressures.

which affords greater freedom of mobility from the transducer to the catheter, appears to be contraindicated.

Each clinical catheter-tubing-transducer system must have its dynamic response verified at frequent intervals.[26] There can be vast differences in fidelity between the ideal laboratory setting and the clinical setting, in which the system is subject to changes over time, human assembly error, repeated blood sample withdrawal, and air entrapment. The fast-flush method of determining the dynamic response characteristics is a simple, rapid, and safe testing modality that can be easily incorporated clinically.[1,2,9] Performing the fast-flush testing on each clinical system can verify or optimize the adequacy of dynamic response. If the fast-flush testing produces dynamic response characteristics that are inadequate, the operator can take the opportunity to correct the system (*e.g.*, remove excessive tubing length, purge air bubbles, reattach membrane dome according to protocol) until acceptable characteristics are obtained.

SELECTING BLOOD PRESSURE TRANSDUCERS

The objective of the AAMI/ANSI blood pressure transducer standards was to provide labeling and performance requirements, testing methods, and consistent terminology to ensure that health care professionals are supplied with safe, accurate blood pressure transducers that can be used interchangeably with any monitor.[4] Virtually all of the current disposable transducer manufacturers meet these new standards. The AAMI/ANSI connector has not been accepted and applied, but the deleterious effects of this noncompliance has been minimal. Today, most transducer vendors provide interconnect cables for their transducers that interface with any bedside monitor. Most modern bedside monitors are able to meet the other AAMI/ANSI requirements by providing excitation voltages between 4 and 8 volts RMS in the DC frequency range of 0 to 5000 Hz; are able to accept a transducer unbalance between ±75 mm Hg; supply an excitation voltage and accept transducers with an excitation impedance of greater than 200 ohms; are based on a transducer sensitivity of 5.0 μV/V/mm Hg; and maintain an accuracy when used with transducers that have a signal impedance of less than 3000 ohms.

INTERCHANGEABILITY STANDARD FOR AAMI/ANSI PRESSURE TRANSDUCERS

There are several factors governing the interchangeability standard for AAMI/ANSI pressure transducers.

The transducer should be able to operate at temperatures between 15°C and 40°C.

The transducer must operate over a pressure range of −30 to +300 mm Hg and not be damaged by pressures of −400 to +4000 mm Hg. Luer-Lok or Linden fittings should meet the ANSI performance standard for medical Luer taper fittings.

Transducer excitation should be within 4 to 8 volts RMS in the DC frequency range of 0 to 5000 Hz. The transducer excitation impedance should be greater than 200 ohms over this same frequency range. The transducer signal impedance should be less than 3000 ohms over the same frequency range. The transducer sensitivity should be 5.0 μV/V/mm Hg ±1% under specified conditions. The linearity and hysteresis must be within ±2% of the pressure reading or ±1 mm Hg, whichever is greater.

The transducer must maintain electrical isolation between the fluid column and the case to prevent unsafe electrical current leakage into the patient. The transducer must withstand five repeated discharges of a defibrillator.

Besides these performance criteria, the instruction manual for the transducers should contain the following information:

Information, cautions, and warnings about storage, use handling, and sterilization of the transducer, in addition to the names and addresses of acceptable customer service facilities

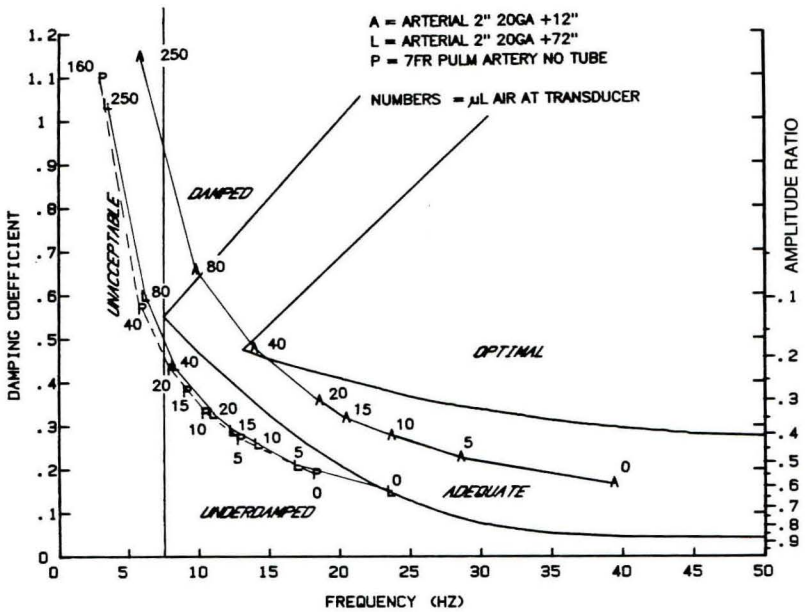

FIG. 20-6. Plot of natural frequencies *versus* damping coefficients for two arterial and one pulmonary artery pressure monitoring systems, showing the effect of inserting small bubbles into the transducer dome. The inserted volumes (V_d) of air in microliters are shown near the marks on the curves. The curves were generated using the modeling techniques of Taylor and colleagues.[23] Results are presented for short radial catheters (Deseret 2″) with 12″ (Index A) and 72″ (Index L) of pressure tubing. The results from a pulmonary artery catheter system without extension tubing are shown as Index P. For all situations, the operating point moves upward and to the left with the addition of air into the system. The best condition is NO air in the system.

The "shock" that the transducer can withstand and still meet the standard's requirements

The "volume displacement" of the transducer and attached accessories, because volume displacement is one of the most important determinants of dynamic response

The expected warm-up drift

The changes in zero and sensitivity with temperature change over the range of 15°C to 40°C

The light sensitivity of the transducer, because some of the disposable transducers are also light sensitive

COMPLICATIONS OF INVASIVE PRESSURE MONITORING

The three most important risks associated with vascular cannulation and direct blood pressure monitoring are air embolism, thrombosis, and infection.

AIR EMBOLISM

Air embolism is the introduction of air into the circulatory system. Air insufflation can occur in a variety of ways into the venous or arterial portions of the circulation. Venous air embolism may reduce or stop the flow of blood through the heart or may cause neurologic complications. The exact amount of venous air that is fatal to adults is unknown, but is estimated to be between 300 and 1600 ml.[24] The rate of air injection into the venous circulation is of primary importance. Death appears to be caused by the right ventricle compressing air rather than pumping blood.

The complication from arterial air embolism is different. Air entering the left side of the heart passes quickly into the aorta. Depending on the position of the patient, the air may flow into the coronary or cerebral arteries.[24] Air entering these vessels obstructs the blood flow. In dogs, 0.05 to 1.0 ml of air injected into the coronary circulation have been fatal.[24] Air embolism is best prevented by using continuous-flush systems and keeping the plumbing systems closed.[24,28]

THROMBOSIS

Thrombosis can be caused by an invasive catheter, but it is an infrequent complication of arterial or pulmonary artery catheterization. Embolization of clots formed on a catheter can be flushed retrograde into the central circulation from radial arterial cannulation sites. To minimize thrombus formation, continuous-flush systems have been developed to keep catheters patent and prevent the need to use syringes to flush catheters.[28,29] Some pulmonary artery catheters have had heparin bonding added to their surface to minimize thrombus formation.[30] There has been considerable discussion about the use of heparin in the flush solution and its effects on minimizing clot formation in the catheter tip.[31,32] There are conflicting reports on the need to heparinize the flush solution.[31,32] In our experience over the past 2 years, heparin was not used in the flush solution for arterial catheters. Since my colleagues and I eliminated heparin, we have not seen an increased rate of thrombus formation or loss of catheter function. If heparin is used in the flush solution, clinicians must be aware that a discard volume of five times the dead space of the catheter and tubing must be withdrawn to minimize effects on coagulation studies.[33]

INFECTION

Although invasive pressure monitoring provides valuable monitoring information, it also can result in bacteremia due to contamination of catheters, stopcocks, pressure transducers, and flush solutions.[34–40] Early pressure transducers were reusable, and when they were not properly sterilized, they caused epidemics of bacteremia.[34,35] Based on experience with re-usable pressure transducers and domes, the Centers for Disease Control have recommended changing domes and

other disposable components every 48 hours.[38] Several studies, however, support the safe and cost-effective longer replacement interval if disposable components are used.[36–41] To prevent contamination, the sterility of the monitoring plumbing system must be maintained.

SIGNAL AMPLIFICATION, PROCESSING, AND DISPLAY

After the pressure signal has been transmitted to the transducer, the bedside monitor operates on the signal. Most monitors digitally display the heart rate and systolic, diastolic, and mean pressures. Applying the same pressure waveforms to each of three monitors in one study gave different results.[42] Moreover, none of the monitors recognized and rejected several artifact conditions: zeroing the transducer, fast-flushing the system, and drawing blood from the patient. These conditions occur several times a day during normal patient care and result in false alarms and erroneous data.[42]

To help eliminate these problems, new algorithms are being developed for bedside pressure monitors. Preliminary testing has shown that these enhanced algorithms produce dramatic improvements in the bedside monitor's ability to evaluate pressure waveforms in the clinical setting.[43] Present monitoring systems allow far too much artifactual data to reach the monitors' display, trend buffer, and alarm logic. The enhanced pressure artifact rejection algorithm eliminates most of the false alarms caused by zeroing, flushing, and blood drawing. The trend displays of the new algorithm are more representative of actual patient conditions. Because data sent from the bedside monitor to the computerized patient data management system are more accurate, patient data management computer systems can be programmed to acquire patient data automatically.

Algorithms for enhancing the quality of data derived from pulmonary artery pressure waveforms have recently been developed.[44]

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