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special article

Optimizing the electrocardiogram and pressure monitoring

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Monitoring the electrocardiogram and directly measuring BP provide current and important data for intraoperative and ICU patient management. However, these physiologic measurements are not infallible; their accuracy is largely dependent on the careful set-up and use of the measuring instruments. This report integrates practical clinical and engineering information to provide a basis for optimizing ECG and pressure monitoring in the clinical setting.

Modern microcomputer-based bedside ECG monitors not only detect heart rate changes and signal an alarm during life-threatening situations, but also detect dangerous cardiac arrhythmias. However, if improperly set up or calibrated, this sophisticated monitoring equipment is useless. Optimizing the use of monitoring equipment is vital to provide reliable physiologic signals and minimize the need for troubleshooting. This study reviews methods for optimizing ECG, arterial pressure, and pulmonary artery pressure (PAP) monitoring. Such monitoring is particularly challenging in surgery, as there is interference from high-frequency electrosurgical equipment.

OPTIMIZING ECG MONITORING

Because ECG monitoring is used to detect arrhythmias, pacemaker function and myocardial ischemia (1), signal quality must be excellent. Two major frustrations in ECG monitoring are poor signal quality and the complete lack of an ECG. Other signal sources such as 60-Hz (50 Hz in Europe) power lines and electrosurgery equipment interfere commonly with the ECG signal, as do distortions caused by amplifier nonlinearity, noise, and inadequate frequency response (Fig. 1).

Patient

The electrical signal from the heart is only 0.5 to 2 mV at the skin's surface, and is best measured by properly preparing the skin and placing the electrodes in the best possible positions. Wet and oily skin should be cleaned with alcohol and dried to allow maximum electrode adhesion. Hairy skin should be shaved to optimize adhesion and to make electrode removal less painful. In surgery the electrodes should be covered with a sterile drape, to prevent surgical scrub solution from getting under the electrode and loosening the adhesive. Dead cells should be scratched from the skin surface, so that the conductive gel placed on the electrode can penetrate and disrupt the epidermis and reduce contact resistance, thus permitting the ECG signal to travel more efficiently to the electrode (Fig. 2) (2–9). Fifteen to 30 min are required for gel penetration. Because the protective skin layer has been disrupted, mild gels should be used to avoid skin irritation (3, 9).

The stratum granulosum has a resistance of about 50 kohm/cm^2 (3). There is also a skin potential of about 30 mV between the inside and outside of the stratum granulosum; however, stretching the skin can decrease this potential to about 25 mV; and abrading the stratum granulosum by vigorously rubbing it with cotton gauze further reduces the potential to near zero. Proper skin preparation reduces electrode resistance from as high as 200 kohm to as low as 10 kohm in 90% of patients (2, 3, 9).

Good electrode placement allows the electrodes to receive the maximum ECG signal with minimum noise. QRS amplitude is highest with the thoracic equivalent of lead II configuration (3). To reduce muscle and motion artifact, the electrodes should be placed over bony prominences such as the sternum or clavicles, not over areas of loose skin. In the operating room and ICU such optimum electrode placement may be impossible because of the operative or wound sites.

Other factors that may cause interference include muscle artifact (2, 3), skin movement, and respiration. The electromyogram (EMG) has frequency and voltage characteristics similar to the ECG. Shivering caused by hypothermia or Parkinson tremor may cause EMG artifact. Any EMG signal between the two electrodes shown in Figure 1 will add to the ECG signal and reduce signal quality. Motion artifact caused by move-

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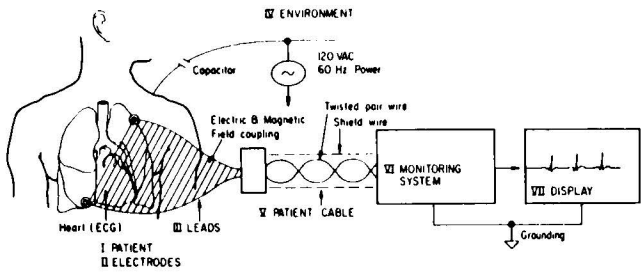

FIG. 1. Sources of artifact, interference, and distortion with ECG monitoring. Shown are the elements (I to VII) involved in signal degeneration.

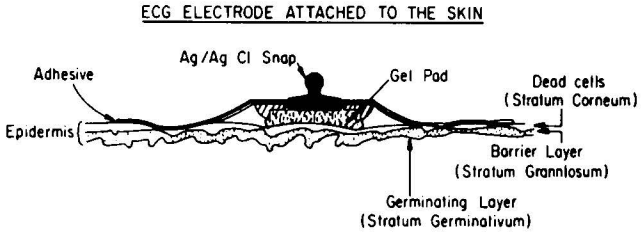

FIG. 2. Schematic drawing of ECG electrode attached to the skin.

ment of electrodes can be minimized not only by proper skin preparation, but also by taping a loop in the lead wires to prevent artifact caused by movement of the electrode wires. Electrode artifact induced by chest or abdominal wall movement due to respiration can be minimized by repositioning the electrodes.

Electrodes

Most electrodes used for monitoring are designed for single use. To minimize electrode problems be sure the proper type of electrode is used, one that has been designed for monitoring (not an exercise ECG electrode) (10, 11). Use of dissimilar types of electrodes can cause large half-cell (battery-like) potentials that may disable the ECG amplifier. Electrodes should be obtained from the same supplier and meet American National Standards Institute/Association for the Advancement of Medical Instrumentation specifications (10). Insufficient electrode gel or gel that has dried during improper storage can result in high-resistance skin contact, causing unstable traces and 60-Hz pick-up.

Unstable half-cell potentials can be minimized by coating the electrode's snap with silver/silver-chloride (Ag/AgCl) (12). ECG electrodes should be of the Ag/AgCl variety since the half-cell voltage for stainless-steel needle electrodes is large and unstable (11, 12). Also, stainless-steel electrodes have unacceptably long defibrillator recovery times (13). Needle electrodes, suggested as a solution to the electrode placement problems in surgery, should *not* be used because of the potential hazard of thermal injury resulting from high current densities associated with electrosurgery (3, 14). Cold electrodes may not adhere to the skin properly, and should be hand-warmed before application. Poor adhesive can result in premature detachment of the electrode.

Leads

Loose or corroded clips can result in poor contact between the lead wires and the electrode snaps. Increased resistance at this connection can increase interference from the 60-Hz power line. Poor connections between the lead wires and the patient cable going to the monitor sometimes may be improved merely by disconnecting and reconnecting these wires. Suspected intermittent breaks in the lead wires can cause sporadic ECG transmission and should be changed or carefully checked. Cable movement causing motion artifact or triboelectric noise is generated by friction and deformation of the insulation surrounding the wires (3). It can be minimized by repositioning the leads.

Shielded wire on the leads minimizes pick-up of alternating-current electric fields from 60-Hz power sources, electrosurgery machines, and other sources such as radiotransmitters (paging systems, CB radios) (15). The two leads which connect the patient form a loop (Fig. 1) through which magnetic fields can pass and induce unwanted voltages. Two ways to minimize this magnetic-field effect are to avoid draping the leads over motors, lights or other electrically powered instruments, and to decrease the loop area by keeping the lead wires close together, perhaps using twisted pair wires (15).

Environment

ECG recording is plagued frequently with interference from nearby power sources. The interference caused by a 60-Hz power line can be reduced by: (a) using lead wires which are shielded to minimize electrical field pick-up and twisted pairs to minimize magnetic coupling, (b) proper cable and equipment placement, (c) properly preparing the skin and placing the electrodes to minimize skin contact resistance, and (d) using an amplifier system that has excellent common-mode rejection (3, 15, 16). Voltage coupled to the patient from the power line, i.e., common-mode voltage, can be only a few millivolts if the patient is touching a grounded object, or up to 20 V if the patient grasps an insulated power cord. The common-mode voltage on most patients is typically 1 V (1000 times as large as the ECG) (17).

Interference created by the electrosurgical equipment is a combination of radio frequency current (800–2000 kHz) and AC line frequency (60 Hz) (14). Many ECG monitoring systems are disabled by this interference, particularly when caused by spark gap electrosurgery units. Several passive electrical filters and electronic methods have been implemented in bedside monitors to minimize interference (3). An additional way to

reduce the artifact of the electrosurgery unit is to place the indifferent (right-leg) electrode close to the electrosurgery ground pad. The ECG bedside monitor should also be plugged into a separate power outlet from the electrosurgery unit.

Because defibrillator discharges can destroy ECG monitors or force the amplifier into a nonlinear region, the Association for the Advancement of Medical Instrumentation suggests that the ECG monitor should withstand defibrillator discharges and recover within 5 sec (13, 18).

Because motors and electrical transformers emit magnetic fields, it is important to keep leads, cables, and patient away from bypass pumps (which have motors in them), infusion pumps (3, 19), static charge sources (such as a nurse who has walked across a carpeted floor) (19), and fluorescent lights (16).

Patient Cables

Since patient cables have problems similar to those of ECG leads, they should have good connectors and an intact shielded wire to minimize electric field pick-up. Also, their internal wires should be twisted to minimize magnetic field pick-up. Cable movement can cause triboelectric pick-up, so the same precautions that apply to locating patient leads apply to patient cables. Cables from different pieces of equipment should be individually coiled and not draped over each other (15).

Monitor

The properly designed modern ECG amplifier seldom causes signal distortion (20). Because low-amplitude ECG signals may be due to low gain of the ECG amplifier, the monitor should have an amplifier gain control. However, if not carefully done, changing the gain may affect the ischemia detection (ST-segment analysis) available with newer systems (1). The problem of low QRS amplitude (usually under 0.5 mV) can often be solved by better skin preparation or by changing or moving the electrodes.

A heart-rate detector, used to monitor the QRS complex, will sometimes improperly double-trigger on T waves or pacer spikes. Changing the position of the ECG electrodes or switching to a different monitoring lead may circumvent the problem. Recently introduced monitoring systems can monitor and display calibrated signals from multiple ECG leads simultaneously (20), so that continuous ECG monitoring is not affected by the loss of one lead. Single-lead ECG recording may thus become a thing of the past. An alternative to determining a false heart rate from the ECG signal has been to derive the heart rate from the arterial blood pressure signal.

The American Heart Association has specified two ECG frequency response ranges: (a) 0.5 to 50 Hz for monitoring use, and (b) 0.05 to 100 Hz for diagnostic use (21). The diagnostic frequency response must be available when monitoring for ischemic changes (1). The monitoring mode may improve the quality of the ECG tracing by decreasing baseline wander, but it may also falsely depress or elevate the ST segment or even shift an abnormal ST back toward the isoelectric line (4). Thus, the diagnostic mode is required for monitoring ischemic changes in the ST segment. Bringing a conventional 12-lead ECG system to the bedside or to surgery to detect ST-segment changes is no longer necessary with the new bedside monitor technology. Indeed, ECG signs of ischemia are now monitored intraoperatively.

Because pacemaker spikes may be as short as 0.1 msec and have amplitudes of 50 to 700 mV, they are especially difficult to detect, display, and count (20). Special analog circuits must condition pacer spikes to make them visible to the digital sampling system (20); otherwise, pacer spikes may appear to come and go, and the pacemaker may seem not to be working properly.

A recent advancement in ECG monitoring systems is the lead continuity detector. By injecting small, high-frequency alternating currents into each of the leads, the monitoring system can detect if a given lead has too large a resistance, and can give warning before the lead is completely disconnected or dried out.

Display

Displays are typically either oscilloscopes or strip-chart recorders. Most oscilloscopes display digitally stored waveforms either in a scrolling mode or frozen on the screen. Problems can occur because of improper connections or improper grounding, and frequency response limitations (especially when displaying pacemaker spikes). Also, imperfect computer algorithms can prevent proper heart rate determination as a result of artifact on the ECG signal, and distortions can be caused by limited display resolution. For example, stair-step changes in the ECG signal on some computer-driven displays can be distracting and prevent proper waveform interpretation.

OPTIMIZING BP MONITORING

Arterial pressure can be measured by both direct or indirect methods. However, CVP, PAP, and pulmonary capillary wedge pressure are currently measured only by direct methods. Although indirect measurement of arterial pressure is imprecise compared to the direct method (22), errors in direct pressure measurement are still very common.

Indirect BP Measurement

The American Heart Association has made recommendations regarding how indirect arterial pressure

should be measured (22). Auscultatory measurement of arterial pressure usually underestimates systolic pressure. Cohn (23) showed the serious limitation of the auscultatory and palpatory methods for hypotensive patients in shock. Since most indirect pressure measurement techniques require cuff inflation, measurements can be made only at intervals. Only recently have prototype devices that allow continuous noninvasive pressure waveform monitoring been tested clinically (24).

Despite automated oscillometric, stopped flow and auscultatory techniques (25–28), there are problems and questions about their accuracy (26, 29–38). The Dinamap (Critikon, Tampa, FL), a popular automated oscillometric device, underestimates systolic and mean pressures at high arterial pressure and overestimates them at low arterial pressure (30, 31). Finnie et al. (33) recommended for an indirect BP method on a critically ill patient that the oscillometric method be used for systolic and mean pressures and that the K5 Korotkoff sound method be used to determine diastolic pressure. Johnson and Kerr (31) found that five automated noninvasive devices gave unreliable readings on patients with low BP (radial artery systolic pressure less than 80 mm Hg). If they did obtain a pressure it tended to be an optimistic result. They also reported that invasive techniques were clearly preferable in the critically ill shocked patient.

In spite of the well-established safety and convenience of the automatic oscillometric BP systems, a few clinically important problems are reported, such as ulnar neuropathy (39) and venostasis (40), which occur when the cuff is inflated too frequently. Recommendations (41) for automated oscillometric BP measurements include the following: (a) Always verify the heart rate/pulse by a second method. (b) If the oscillometric BP seems low, immediately compare the oscillometric determined pulse rate with that from the ECG monitor (for patients without bigeminy); if the pulse rates agree, then hypotension exists. If the oscillometric rate is considerably lower that the ECG rate, there might be a malfunction in the BP instrument. (c) Observe the patient's cuffed extremity for signs of impeded blood flow, especially when cycling quickly (every 1 to 2 min). (d) Use the cuffs and connections provided by the manufacturer. The most important factor to determine accurate indirect BP measurement is the selection of the proper cuff size (42), based on the limb circumference (22).

As a general rule, if there is a rise or a fall in BP measured by any indirect method, no precipitous clinical action should be taken until a repeat measurement has been made (30). Any indirect methods for determining pressures in patients with arrhythmias may give inaccurate results. When a rapidly acting drug such as nitroprusside is given, indirect pressure measurements may not be available often enough.

Direct BP Measurement

Two major purposes for inserting an arterial or a pulmonary artery catheter are to measure intravascular pressure and to withdraw blood samples. Direct measurement of BP requires a catheter, stopcock(s), connecting tubing, continuous flush device, pressure transducer, and a pressure monitor with display (Fig. 3). The major problems of BP measurement with a catheter system are: (a) improper zeroing and zero drift, (b) improper transducer/monitor calibration, (c) inadequate dynamic response, and (d) improper determination of derived data from the available pressure signals (34, 43–47).

Zeroing the pressure monitoring system is the single most important step in setting up a pressure measuring system, since errors can make a large difference in recording all pressures, particularly CVP, PAP, and wedge pressure. Pressure monitoring systems should be zeroed frequently and always before initiating treatment changes based on the pressure data. Zeroing is done by opening an appropriate stopcock to atmosphere and aligning the resulting fluid-air interface with the midaxillary line (Fig. 4). Although other methods have been proposed (such as zeroing to the transducer dome position), positioning the fluid-air interface point at the midaxillary line is crucial to correct zeroing. Zero changes can be caused by many factors, including: (a) patient position change in relation to the pressure transducer (hydrostatic effect), (b) drift due to membrane dome coupling problems (48, 49), (c) transducer electrical zero change, and (d) pressure amplifier drift.

Many calibration problems associated with trans-

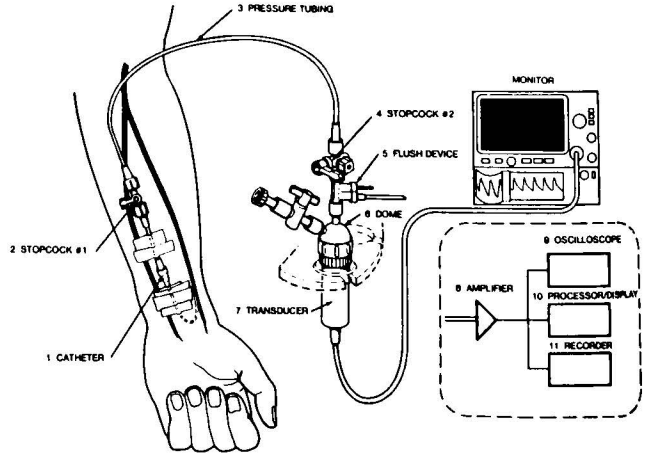

FIG. 3. The ten components used to monitor direct BP. The monitoring components are nearly the same independent of whether the catheter is in an artery (radial, brachial, or femoral) or in the pulmonary artery. (Size of transducer and plumbing components were enlarged for illustration purposes.)

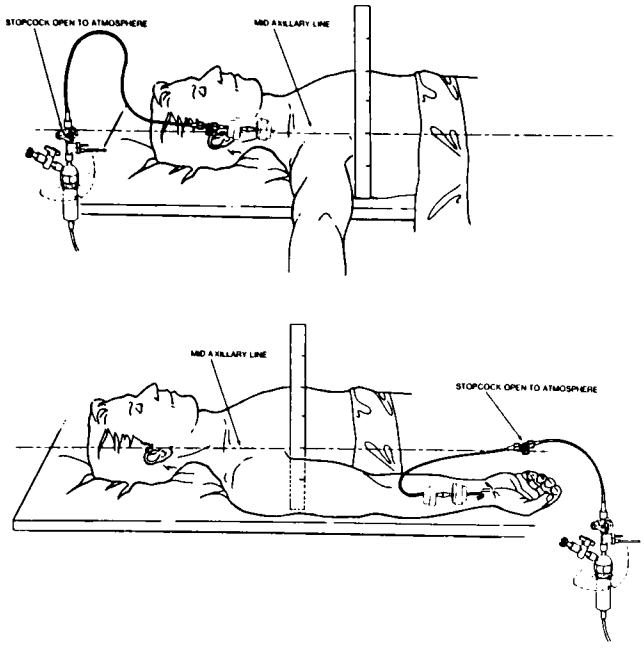

FIG. 4. Two methods of zeroing a pressure transducer. Note the place at which the water-air interface occurs should always be at the midaxillary line when zeroing. *Top*: The stopcock is placed near the transducer at the midaxillary line. *Bottom*: The stopcock near the catheter of the midaxillary line.

ducers, caused by improper application of disposable domes and improper transducer setup (34, 48–51), can be eliminated by recently introduced disposable pressure transducers which meet newly established industry standards (52, 53). Most pressure transducers are standardized to a fixed sensitivity of 5 μV/V of excitation per mm Hg pressure applied. If standardized pressure transducers are used, there is no need for a sensitivity adjustment on the monitor. If pressure calibration or checking must be done, calibration against a mercury manometer is preferable. When a calibration check with a mercury manometer is used, extreme care should be exercised to prevent arterial air embolism from the pressurized manometer.

The catheter, tubing, continuous flush device, and the transducer (plumbing) system used for pressure monitoring can distort the pressure signal (34, 43–50). A fast-flush test assures that the recorded waveforms and derived parameters are adequate (43). Two methods are used to characterize dynamic response of catheter, tubing, and transducer systems. The first specifies that the system's frequency response be unvarying up to a specified cutoff frequency determined by the number of harmonics of the original pulse wave (usually ten harmonics are specified) (Fig. 5). The second method uses the specification of the natural frequency (Fn) and damping coefficient (zeta). The Fn and zeta parameters are convenient to use because they can be measured in the actual patient pressure monitoring system and have recently been used to define catheter-transducer system dynamics (43).

Most catheter, tubing, and transducer plumbing systems are underdamped, and a few have unacceptably low natural frequencies. If the Fn is less than 7.5 Hz, the pressure waveform will be distorted no matter what the damping coefficient is (Fig. 6). However, if the Fn can be increased to 24 Hz, the zeta can range from about 0.15 to 1.1 without distorting the pressure waveform. Therefore, to optimize the dynamic response of any pressure monitoring system, the Fn should be as high as possible and can be obtained theoretically in systems with short tubing, catheters with large internal diameters, and by using transducers and other components which are noncompliant.

Fast-flush dynamic response testing should be performed at regular intervals and always after manipulation of the plumbing sytem, such as after drawing a blood sample. A fast flush is produced by opening the fast-flush valve of the continuous flush system (for example, by pulling the pigtail on a continuous flush device) (Figs. 3 and 5). The rapid valve closure generates a square wave which permits measurement of the plumbing system's Fn and zeta (43). The fast-flush method is superior to other techniques for ascertaining the plumbing system's dynamic response because it is

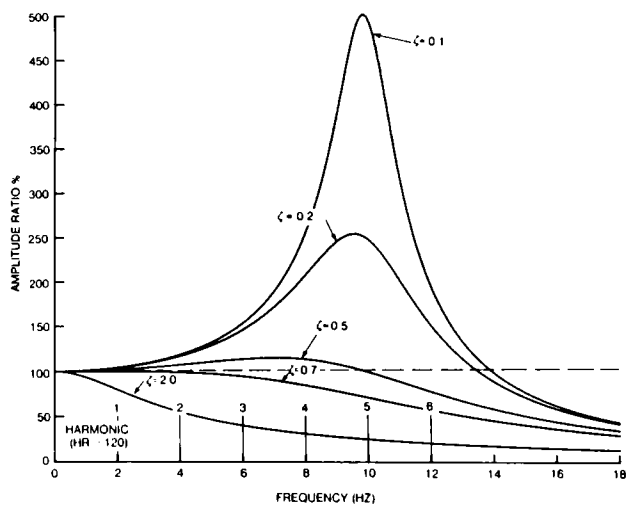

FIG. 5. Family of frequency vs. amplitude ratio plots for five different zetas (ζ). Fn of the plot shown is 10 Hz. A zeta of 0.1 occurs when a system is very underdamped, and a zeta of 2.0 occurs when it is overdamped. The *dashed line* shows the frequency vs. amplitude characteristic which would occur if the system had a flat frequency response. Along the frequency axis are plotted the harmonics of the pressure wave if the heart rate were 120 beat/min (2 beat/sec). Note that by the fifth harmonic (10 Hz) if the zeta were 0.1 the true signal would be amplified five times. If the zeta were 2.0 there would be an attenuation to about one-fourth of the amplitude. In both cases there would be gross waveform distortion because neither situation reflects a high fidelity systems dynamic response. Fidelity of the system can be improved by increasing the Fn or adjusting the zeta to be in the range of 0.5 to 0.7.

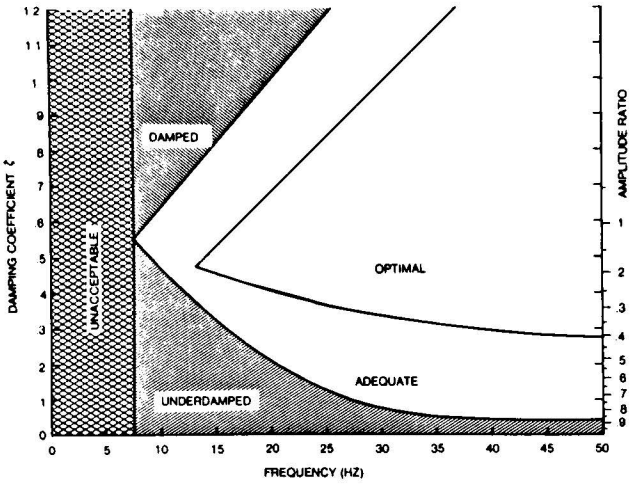

FIG. 6. Fn vs. zeta (ζ) plot which illustrates the five areas into which catheter-tubing-transducer systems fall. Systems in the optimal area will reproduce even the most demanding (fast heart rate and rapid systolic upstroke) arterial or pulmonary artery waveforms without distortion. Systems in the adequate area will reproduce most typical patient waveforms with little or no distortion. All other areas will cause serious and clinically important waveform distortion. Note the scale on the right can be used to estimate the zeta from the amplitude ratio determined during fast flushing (43). See Figure 7 for example waveforms.

applied quickly, safely, and easily in the clinical setting (Fig. 7). The method tests the entire pressure monitoring system from the catheter tip to the display device.

Several factors lead to poor dynamic response: (a) air bubbles in the system; (b) kinked tubing, particularly tubing with T connections; (c) pressure tubing that is too long; (d) pressure tubing that is too compliant; (e) pressure transducers or continuous flush devices that are too compliant; (f) clot formation in the catheter.

Although air bubbles are frequently intentionally added to the plumbing system to damp the waveform, they decrease the Fn as well as increase the zeta. Adding air to pressure systems can thus create waveform distortion and also increases the likelihood of blood clotting at the catheter tip since more blood enters the catheter. Clinically the best method of improving the plumbing system's dynamic response is to improve the Fn. Techniques of increasing the system's Fn include eliminating air bubbles by using transparent tubing and fluid pathways so air can be seen and removed. A tiny air bubble of only 1 mm diameter in the transducer can result in serious waveform distortion. Place the continuous flush device on the downstream side of the transducer to prevent air coming out of the flush solution from being trapped in the transducer dome (50). Also keep the plumbing system simple by using the fewest components possible, preferably preassembled pressure monitoring plumbing kits. Use only short lengths of high quality, low compliance pressure tubing and do not use injection sites or compliant stopcocks. Use continuous flush systems to prevent clot formation by keeping the catheter patent, and prevent flap valve clots (43, 54, 55). If the plumbing system still does not perform adequately, use an adjustable damping device (43, 56). Although pressure monitoring systems are tested in the laboratory to determine their dynamic characteristics (43, 44), because of individual set-up variability, fast-flush tests of each system's dynamic response in the clinical setting are essential.

Various electronic filters and processing algorithms built into pressure monitors may improperly extract data from the pressure waveform (55, 57). Pressure amplifiers should have a frequency response which extends from 0 (DC) to 50 Hz so that the patient's pressure waveform is not distorted. A calibrated oscilloscope or a recorder provides the best way to view blood pressure waveforms. These display devices allow visualization of each pressure waveform in real time so that respiratory variations, arrhythmias, and artifact can be seen.

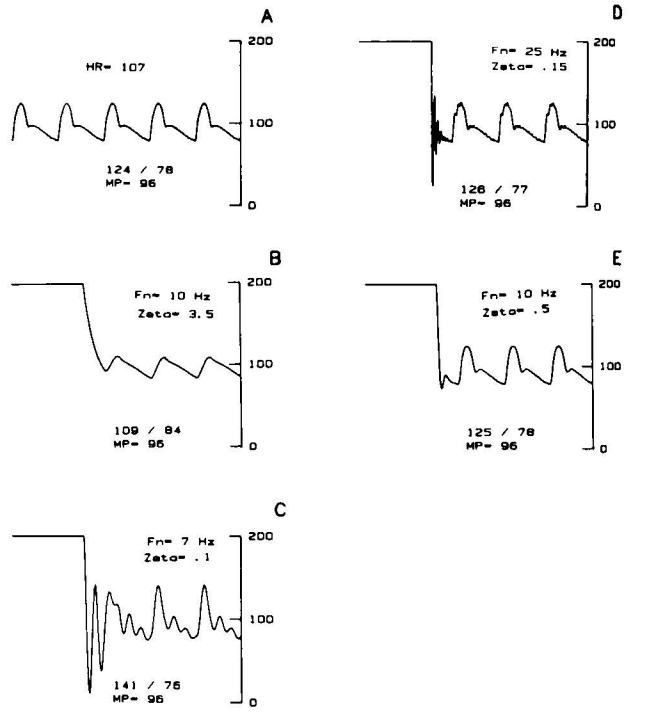

FIG. 7. Arterial pressure waveforms obtained from the same patient. *Panel A*: Patient's actual arterial pressure waveform as if recorded with a catheter tipped transducer. MP-Mean pressure. *Panel B*: The same patient's arterial waveform recorded with an overdamped system. Note the fast-flush signal (*upper left*) returns slowly to the patient waveform. Systolic pressure is underestimated and diastolic is overestimated and mean pressure (MP) is unchanged. *Panel C*: An underdamped condition with low Fn. After the fast flush, the pressure signal oscillates rapidly (rings). Systolic pressure is overestimated, diastolic is slightly underestimated, and mean pressure is correct. *Panel D*: An underdamped condition but with high Fn. Waveform is only slightly distorted and systolic, diastolic, and mean pressures are close to the actual ones. *Panel E*: An ideally damped pressure monitoring system. The undershoot after the fast flush is small and the original patient waveform is adequately reproduced.

Respiratory variations affect arterial pressure and especially PAP (57–60). Digitally displayed results are available on most monitors and present systolic, diastolic, and mean pressures, and sometimes give heart rate determined from the pressure waveform. Systolic pressure is not the same for each heart beat and as a result the digital readout will appear unstable, a problem facing the monitor manufacturer. Most manufacturers filter or smooth the beat-to-beat variability to get a representative systolic pressure. Although filters stabilize the display readings, most monitoring systems do not reject artifact or handle artifact properly (58–62). Therefore, it is important to compare pressures displayed on a calibrated oscilloscope or recorder with values displayed on the digital readout.

Even if the mechanics are properly checked out, there can still be differences between the direct and indirect pressure measures. In addition to the variability caused by respiration, arrhythmias, and artifact, there are known physiologic differences (32, 33, 36, 63). There are real differences between arterial pressures measured in different locations in the arterial system. For example, there is usually an amplification of systolic pressure as one moves to peripheral vessels, similar to that seen in the underdamped system (Fig. 7, *panel C*). To measure arterial pressure, it is desirable to have the catheter tip advanced to a central location such as the thoracic aorta or subclavian artery. Pressures measured at peripheral sites may not accurately indicate pressures at the central arterial location (35, 36). Often, femoral arterial catheters are inserted and advanced to measure abdominal or thoracic aortic pressures (64). Central pressures are those which supply the driving force and cause flow to the vital organs, heart, kidney, and brain, and are thus most important. If an invasive arterial catheter is placed, great care should be taken to assure that accurate pressure monitoring data are obtained and that it is removed promptly when not in use. Any invasive procedure increases the risk of infection and inserting a catheter includes the risk of thrombosis (46).

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