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Intraoperative monitoring during vascular surgery

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Physiologic monitors are tools that enable the "vigilance" described in the motto of the American Society of Anesthesiologists (ASA), become the guide for patient "safety" ("*securitas*," advocates noted) in the motto of the Association of the Anesthetists of Great Britain and Ireland [1]. The principal objectives of intraoperative monitoring are to improve perioperative outcome, facilitate surgery and reduce adverse events, using continuously corrected data of cardiopulmonary, neurological and metabolic function to guide pharmacologic and physiologic therapy. Although sophisticated and reliable apparatus may be used to collect these data, they are useless, or even harmful, without proper interpretation. Throughout this article the word *availability*, when applied to a monitoring method, includes the availability of all the necessary cognitive skills along with the apparatus itself. A comprehensive overview of the history, philosophy and the semantics of monitoring have recently been published [2].

Basic monitoring

It is axiomatic that all patients undergoing any form of anesthesia will be monitored to some degree. Definitive evidence of the value of monitoring is lacking, and a prospective trial would be unethical, however there is substantial surrogate evidence that leaves the issue beyond doubt (Fig. 1) [3,4].

The ASA has published standards for basic monitoring [5], and adherence to these may be assumed in all normal circumstances considered in this article. Adherence to standards is not controversial; guidelines similar in intent have been published by other organizations [1,6]. The reality, however, is that anesthesia must sometimes proceed under unusual circumstances, such as near a battlefield, at the site of a natural disaster (eg, an earthquake), or when resources are truly

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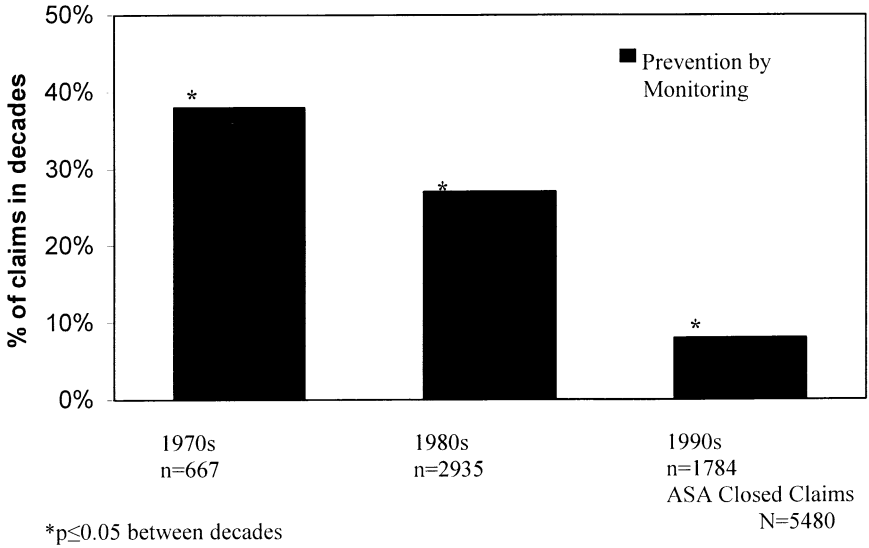

Fig. 1. Decline by decade of closed claims deemed preventable by further monitoring. (*From* Lee LA, Domino KB. The closed claims project. Has it influenced anesthetic practice and outcome? Anesthiol Clin N Am 2002;20:485–501.)

lacking. Although specific monitors are mentioned, the ASA emphasizes physiologic information gathering rather than just the application of devices [5]. Extensive information can be derived from a finger on a pulse and an educated hand manually ventilating a patient.

Of necessity, monitors that free the anesthesiologist to perform other tasks should be used whenever possible. The monitor displays should always be clearly visible to the anesthetist (and often the surgeons, for whom "slave" monitors may be helpful), the controls accessible, and the display of trends possible. A list of basic physiologic monitors (on which baseline values should be determined and recorded prior to the induction of anesthesia) normally used for all cases includes the following:

A 5-lead electrocardiogram, with 2 leads displayed
Continual blood pressure measurement
Pulse oximetry and plethysmography
Core thermometry
End-tidal carbon dioxide (CO2) analysis
Spirometry (with general anesthesia)

The use of automated record keeping and integrated information management is helpful for case reviews and performance improvement and has been endorsed by the Anesthesia Patient Safety Foundation [7]. This rapidly developing technology will at least offer an extended memory and manipulation of data and

trends, but commercial products now offer remote monitoring, and integration with laboratory data bases, computerized physician order entry, and digitized patient records.

Hemodynamic monitoring

Arterial blood pressure monitoring

Indirect measurement

Indirect measurement of blood pressure is most commonly accomplished either by sphygmomanometry, whereby the presence and quality of an arterial pulse distal to an occlusive pneumatic cuff is assessed by the clinician or a machine, or by plethysmography, in which the fluctuating volume of blood in a limb is detected by a pneumatic cuff and an oscillometer. Automatic devices using both principles have been marketed, although oscillometers are very reliable and are now used almost universally.

Direct (invasive) arterial pressure measurement

The numerical values for blood pressure that a monitor derives from a peripheral arterial cannula are often interpreted as being synonymous with the aortic root pressure and therefore to vital organ perfusion, but this is not so. A peripheral arterial pressure wave is not a simple quantity in its own right; it is a product of 6 to10 harmonics in a periodic complex wave, initiated by the contractile force of the left ventricle (LV) and transmitted down a fluid column in a compliant container [8]. Each of these structures has properties that modify the wave. The magnitude and morphology of the wave displayed through a monitor depends, furthermore, on the natural frequency and dampening of the transducer system and connecting tubing used [9] and the reflectance of the arterial tree [10]. Provided the system is not over extended (eg, by additional compliant tubing) or over-dampened (eg, by the presence of bubbles or additional stopcocks), modern commercial monitoring kits provide acceptable accuracy [11]. Arterial reflectance may change significantly, however, under the influence of anesthetic and vasoactive drugs, which must always be kept in mind when using an arterial line. Zeroing and transducer leveling errors also are a common source of mistakes [12]. Accurate recording of the pressure wave depends on the maintenance of a continuous fluid column from the aortic root to the transducer that remains uninterrupted throughout the cardiac cycle. This column or path may easily be occluded by direct manipulation during the procedure or by external pressure on a limb. The fluid path in an elevated limb may also be intermittently broken when the stroke volume is low or when there is profound vasoconstriction. An example is an arm suspended in a raised sling when the patient is in the lateral decubitus position. Regardless of posture, there commonly is a real or apparent pressure gradient between the aortic root and the peripheral arteries. Because of the effect of reflectance, direct measurements at the periphery are usually higher then those

obtained more centrally, although this relationship may reverse when arterial tree compliance is increased, and hence, reflectance is reduced (vasodilation), by physiologic or pharmacologic factors [13]. Values may differ significantly from those obtained simultaneously from a pneumatic cuff method (different phenomena are being measured) and from right to left. For these reasons, a secondary method of blood pressure measurement should be available whenever possible, when an arterial line is being used; sometimes two and, rarely, three direct arterial cannulae may be indicated. The selection of the monitor or monitoring site on which to base clinical decisions, therefore, may well need to vary during the course of the procedure and will be determined by an understanding of the principles involved and the physiologic and pharmacologic factors that apply. Indications during vascular surgery for direct measurement of arterial pressure:

Potential hemodynamic instability exists, caused by comorbidity, rapid hemorrhage, or mechanical or pharmacologic manipulation of the cardiovascular system
Monitoring perfusion pressure from a bypass or assist pump
Arterial blood sampling is performed
Other methods are not available

Additional uses of the direct arterial waveform display include measurement of the systolic pressure variation (SPV) resulting from positive pressure ventilation for the indication of fluid volume requirements [14] and analysis of the waveform itself. Despite its limitations, a direct arterial pressure line is usually very reliable and provides the reassurance of continuous evidence of pulsatile blood flow. Arterial lines are normally indicated during aortic and carotid surgery and sometimes during peripheral vascular surgery.

Because of accessibility and familiarity, the radial arteries are most frequently used in the operating room. Extensive studies have shown, however, that complication rates are similar for ulnar, brachial, axillary, femoral, and dorsalis pedis cannulation and are very low [15], although embolization and arterial occlusion can occur, causing ischemic necrosis. Access is commonly by direct puncture with a simple intravascular needle and cannula, but wire-guided techniques offer advantages [16].

Central venous pressure

Neither guidelines nor a consensus concerning central venous cannulation has been published, however, the practice is ubiquitous and not controversial. Central venous catheterization is indicated:

For estimating right heart filling pressure to guide fluid replacement
For reflecting left heart filling pressure, in the absence of relevant cardiac disease [17,18]
For securing venous access when an adequate peripheral site is unavailable

When access is needed for pulmonary artery catheter or transvenous pacemaker
For the secure and central delivery of drugs
When access is needed for blood sampling

The mechanical considerations for transducer and tubing that apply to direct arterial pressure measurement apply also to central venous pressure (CVP) measurement. Because important clinical decisions may be based on relatively small pressure changes (eg, Weil's 5–2 rule [19]), particular care must be taken to avoid errors. The zero and the transducer positions are critical [12] and often must be adjusted during the procedure, and patient posture has a major effect on measurement. The effects of raising and lowering the head or legs in relation to the heart are generally understood, but there are very few studies that have formally examined the effect of the lateral position, or of isolated lung deflation, on real and apparent filling pressures [20,21]. Furthermore, it is the pressure gradient across the heart that actually determines filling pressure, whereas the transducer is zeroed to atmosphere, making the CVP reading a surrogate value. Although changes in CVP values usually reflect right ventricular filling pressure, and hence right ventricular end-diastolic volume and performance, this relationship may be lost in the event of cardiac or pericardial disease or abnormal intrathoracic pressure [17,22]. It is clear, therefore, that trends or the measured response to maneuvers such as a fluid "challenge" [19] should be the preferred data rather than isolated measurements. Central venous cannulation is frequently indicated during vascular surgery.

Line placement

Numerous techniques for obtaining central venous access have been described, from the placement of simple single lumen catheters by direct puncture to variations of the Seldinger technique for the placement of large and multilumen catheters. The right internal jugular vein is the easiest and most familiar site and is, therefore, most often chosen by anesthesiologists for access. Numerous approaches to this vessel have been described, but no one approach is clearly superior. Equipment for ultrasonographically-guided central venous cannulation (Figs. 2 and 3) is increasingly available, has real advantages [23], and may well become routine [24].

Complications from central venous catheterization

The frequency of serious complications is low but not inconsequential [25]. The most frequent, serious short-term complications are pneumothorax (0.5%) and those that result from unintentional carotid artery puncture. Delayed cardiac tamponade and nosocomial blood-borne infections are the most frequent, serious long-term complications. Evidence-based guidelines to reduce the incidence of infections have been published by the US Centers for Disease Control [26]. Guidelines include the use of an aseptic technique, including the use of gown, gloves, and a large fenestrated drape. Chlorhexidine in alcohol is the recommended antiseptic. Cardiac tamponade and late perforation of a central vein

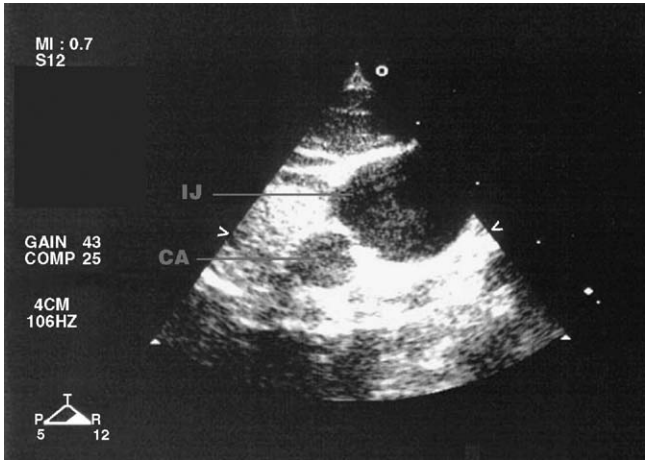

Fig. 2. Short axis two-dimensional ultrasonogram of the neck at the level of the cricoid. Probe is in the sagittal plane. IJ, internal jugular vein; CA, carotid artery.

caused by malposition of the catheter tip are rare but are often fatal when they occur. The issue is of sufficient importance that guidelines and instructional material, of which clinicians may not be aware [27], have been published by the US Food and Drug Administration. The orifice of the catheter should open into as large a vein as is reasonably possible. The tip of the catheter should ideally be situated outside the boundaries of the pericardium, and the axes of the vein and catheter should be parallel to avoid abrasions. The end of a catheter traversing the

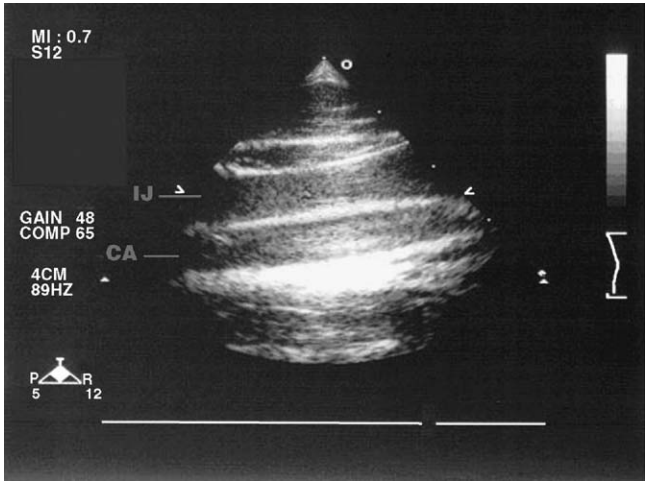

Fig. 3. Long axis two-dimensional ultrasonogram of neck at the level of the cricoid. Probe is in the oblique plane. IJ, internal jugular vein; CA, carotid artery.

brachiocephalic vein from the left should not, however, abut on the superior vena cava; therefore, occasionally a catheter tip located just within the right atrium may be preferred [28]. The location of a catheter must be confirmed if the catheter is to be used for any length of time. A radiograph is definitive, although transesophageal echocardiography (TEE) may also be useful. Guidance by electrocardiography (ECG) may locate the right atrium but is not reliable for localization of the tip in the great veins.

The use of alternative veins for central access is common, although this may have disadvantages. The left internal jugular vein may be smaller, is more awkward for the right-handed operator, and the catheter must transverse the brachiocephalic vein, which is vulnerable to damage and may subtend an acute angle with the superior vena cava, making further passage difficult. The external jugular veins are useful and safe, but in 10% of attempts the guidewire cannot be advanced past the subclavian vein. Direct puncture of the subclavian veins carries a higher risk of pneumothorax, which could be catastrophic on the occasion of a contralateral thoracotomy. The femoral veins are popular sites for central catheterization access when the patient is in the intensive care unit but are relatively inaccessible during surgery. Long catheters inserted through peripheral arm veins will enable CVP measurement and central administration of drugs but have high resistance to flow and often cannot be advanced beyond the upper arm.

Pulmonary artery pressure monitoring

Anesthesiologists are aware of the debate regarding the use of pulmonary artery catheters (PACs) [29,30]. In 1993, the ASA published practice guidelines (not standards) for PACs that emphasized the necessity for cognitive skills and suggested that ‘‘perioperative [pulmonary artery] catheterization should be considered in surgical settings associated with an increased risk because of complications from hemodynamic changes [31].’’ The elements contributing to that risk were patient status, the nature of the procedure, and the practice setting. In 1997, a consensus conference convened by the Society of Critical Care of Medicine [32] gave qualified support for the use of PACs in peripheral vascular and aortic surgery, noting, however, that the evidence was inconclusive. In 2000, an evidence-based consensus summarizing the continued debate was published by the National Heart, Lung and Blood Institute together with the Food and Drug Administration (the Pulmonary Artery Catheterization and Clinical Outcomes [PACCO] Group) [33] that recommended directions for future research. In 2003, Sandham et al [34] and the Canadian Critical Care Trials Group published a landmark study that answered one of the questions posed by the PACCO group, ‘‘Is there a benefit to the routine use of PACs for high-risk surgical patients?’’ The answer was no, but there was a higher rate of pulmonary emboli among the catheter group. This study included many patients undergoing major vascular surgery. In 2003, the ASA [35] published revised practice guidelines that do not support the use of PACs in peripheral vascular surgery unless indicated by comorbidity. The conclusion must now be that a PAC should not be used as a

routine monitor based on the type of surgery or group of patients but may be of value when used by skilled individuals in specific patients for a specific purpose (Box 1). There should be a reasonable possibility that the patient data obtained will influence clinical management and that the information should not be more safely obtained by other means.

Complications from pulmonary artery catheterization

Complications may be attributable both to the central venous access and specifically to the PAC itself. The rate of serious complications from the PAC

Box 1. Prerequisites and Indications for pulmonary artery catheterization

Prerequisites for pulmonary artery catheterization

- Procedurist with appropriate technical skills
- Available cognitive skills to interpret data
- Definable indication
- A reasonable expectation that data will aid in decision-making
- Facilities to manage the catheter
- The anticipated data is not obtainable by methods with a lesser risk of complications

Adapted from Practice guidelines for pulmonary artery catheterization. An updated report by American Society of Anesthesiologists task force on pulmonary artery catheterization [editorial]. Anesthesiology 2003;99(4):988–1014.

Indications for pulmonary artery catheterization

- Significant right or left ventricular dysfunction (causes include ischemia, cardiomyopathy, and the anticipated effects of trauma or surgery)
- Pulmonary hypertension
- Severe valvular disease
- Procedures associated with marked hemodynamic changes or fluid compartment shifts
- Pharmacotherapy titrated to derived hemodynamic variables
- Access for transvenous pacing

Adapted from Troianos CA. Intraoperative monitoring. In: Troianos CA, editor. Anesthesia for the Cardiac Patient. St. Louis: Mosby; 2002. p. 103.

alone is low, 0.2% [36], but when these complications occur, there is appreciable mortality [25]. The most dramatic complication is pulmonary artery rupture, which carries a 50% mortality [25], but infection [37] and misuse of data are also important complications. Destabilizing arrhythmias may occur during insertion, and a defibrillator and pacemaker should be available for their management.

Left ventricular function and prediction of fluid volume requirements

The limitations of CVP as an indicator of left ventricular preload has long been recognized, and for decades pulmonary artery wedge pressure, also referred to as the pulmonary artery occlusion pressure (PAOP), has been used in an attempt to measure quantities that are physiologically "closer" to the LV to guide fluid therapy [18,19]. The physiologic rationale is attractive. Against a constant after-load, LV output (stroke volume) is a product of inotropy and LV muscle fiber length, which is reflected by the LV end-diastolic volume. LV end-diastolic volume is determined by LV wall compliance and LV filling pressure, and under the right circumstances the measured PAOP approximates the LV filling pressure through an effectively continuous fluid path from the transducer through the PAC to the left atrium. The right circumstances do not occur often and, unfortunately, when guidance is most needed. The reasons why the PAOP may correctly predict LV function and volume requirements have recently been comprehensibly and succinctly reviewed [38], but the technical difficulties of PAOP measurement are also well understood [39].

When hypotension, or a low cardiac output (CO), coincides with a low ($\leq$10 mm Hg) PAOP, a patient will likely respond well to volume, although this response is likely to be predictable without reference to the PAOP. An apparently normal or high PAOP may, however, be misleading. The PAC transducer is zeroed at a point outside the body, whereas the LV filling pressure is actually determined by the transmural pressure gradient across the heart, inside the chest. Poor or changing LV compliance and high or changing intrathoracic pressures may obscure the true filling pressure and indicate falsely high values. Similarly, the fluid path that establishes the relationship between the PAOP and the left atrial pressure may easily be impaired by incorrect catheter position, high alveolar pressure, and left atrial or mitral valve disease [39]. Trends and the measured responses to intervention are preferred to isolated measurements for making clinical decisions

Alternative measures of LV function may be available. Reference is made to the fact that TEE provides a more reliable measurement of LV filling than PAOP, and the recently defined concept of *functional* hemodynamic monitoring [40] has great promise. There is limited evidence, which is supported by widespread anecdotal experience, that the "delta-down" of the SPV that occurs during positive pressure ventilation is sensitive and specific in many circumstances in detecting functionally low LV filling pressures. A delta-down of greater than 5 mm Hg predicts that a fluid bolus will increase stroke volume and, thus, if the after-load remains constant, systemic blood pressure. In practice the SPV may be

helpful when used in conjunction with the CVP or PAOP [41]. More extensive perioperative studies are warranted.

Cardiac output and derivatives

A qualitatively adequate CO can usually be inferred by clinical observation and the data derived from basic monitors. When quantification is required, CO is commonly determined by thermal dye dilution through the PAC. Although other methods, such as TEE, can be used, thermal dye dilution remains the most common and best understood method. The CO measurement is used in both its own right and to derive other hemodynamic variables. Cardiac index, stroke volume index, and systemic vascular resistance are useful during aortic surgery because of the effects of cross clamping and unclamping and the frequent need for vasopressors and inotropes [42]. The following are useful calculations for cardiac index (*CI*), stroke volume index (*SVI*), and systemic vascular resistance (*SVR*): CI = CO/BSA, where *CO* is cardiac output and *BSA* is body surface area; SVI = CO/(PR × BSA), where *PR* is pulse rate; and SVR = (MAP − CVP) × 80/CO, where *MAP* is mean arterial pressure and *CVP* is central venous pressure.

Pulmonary artery pressure

Measuring the pulmonary artery pressure (PAP) is strongly indicated to monitor management of pulmonary hypertension or right ventricular failure. Both of these conditions may be precipitated by thoracic-level cross clamping or by fluid mismanagement, especially in cases of mitral or aortic valve disease [42]. In the absence of relevant heart disease, pulmonary artery diastolic pressure may often be used as a continuous monitor of the adequacy of volume replacement. If LV function is normal and does not change, PAOP and pulmonary artery diastolic pressure will usually change together [18], and once the relationship has been established, the effect of fluid therapy may be followed without the need for repeated pulmonary artery occlusion.

Monitoring for ischemia

It has long been recognized that the acute onset of myocardial ischemia causes immediate diastolic dysfunction and is accompanied by a rise in the LV end-diastolic pressure with consequent rises in the pulmonary artery diastolic pressure and PAOP. The PAP waveform may also change. The PAC has, therefore, been generally accepted as a monitor of myocardial ischemia [34], although the magnitude of the initial changes may be small and difficult to notice, and TEE is more sensitive [43]. There is no convincing study that shows routine PAP monitoring to be superior to optimal ECG monitoring, with or without the aid of TEE, in helping to reduce the frequency of perioperative myocardial infarction.

The more proximal the cross clamp, the greater the hemodynamic disturbance and the more likely a PAC will be useful. PACs are frequently indicated when the clamp is to be placed above the celiac axis but are often unnecessary when the clamp is infrarenal [42].

Transesophageal echocardiography

TEE is increasingly available in noncardiac operating rooms, and although bacteremia and pharyngeal, esophageal, and gastric injuries can occur, adverse outcomes are rare [44]. Guidelines for TEE that include evidence-based indications were published by the ASA in 1996 and have recently been updated by the American College of Cardiology and the American Society of Echocardiography (Box 2) [45].

Regional wall-motion abnormalities detected by TEE have consistently been shown to have superior sensitivity to ECG, PACs, and other hemodynamic monitors for detecting myocardial ischemia and to have greater positive predictive value for intraoperative and postoperative myocardial infarction [46]. There is evidence that under some circumstances, TEE is superior to PAP and PAOP as a guide to fluid therapy and LV performance [47]. In the experience of the author and others, TEE may assist with pulmonary vein cannulation [48] and with monitoring left atrial filling during partial left heart bypass (Fig. 4). Introduction of the probe is not usually more difficult with the presence of a double-lumen tube or with the patient in the lateral position, provided that access to the mouth is retained. Intuitively, there would seem to be a greater risk of pharyngeal trauma in this circumstance, although this has not yet been reported.

Training and skills

Although the American Board of Anesthesiology recommends that all residency programs offer an introduction to TEE, few clinicians will develop sufficient skills for clinical practice without substantial, specific training. The

Box 2. Indications for TEE in vascular surgery (Category I and II evidence)

- Intraoperative evaluation of severe hemodynamic instability unresponsive to treatment
- Perioperative monitoring of patients at increased risk of myocardial ischemia or with severe ventricular dysfunction
- Perioperative assessment of thoracic aortic aneurysms and stent placement
- Intraoperative evaluation of aortic atheroma
- Monitoring the placement and function of intracardiac and intravascular devices

Adapted from ACC/AHA Task Force on Practice Guidelines. ACC/AHA/ASE 2003 Guideline update for the clinical application of echocardiography: summary article. J Am Soc Echocardiogr 2003; 16:1091–110.

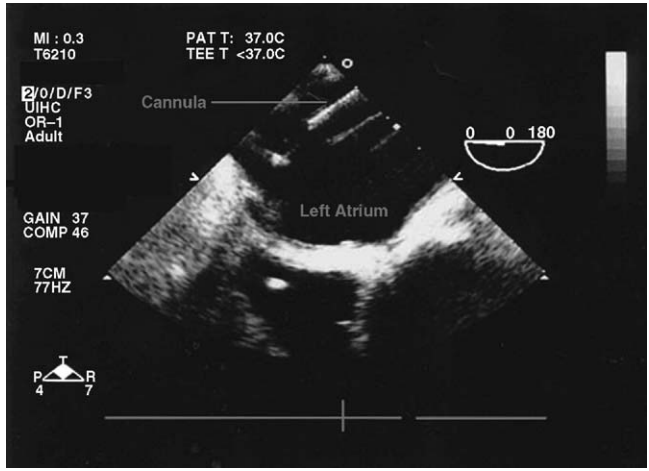

Fig. 4. Short axis TEE image of left atrium during partial left heart bypass.

Society of Cardiovascular Anesthesiology and the American Society of Echocardiography have recently published guidelines for minimum training requirements [49], and a similar program is being developed in the United Kingdom [50]. A clear distinction is made between basic training that is sufficient for ''indications that lie within the normal practice of anesthesiology'' (ie, physiologic monitoring) and advanced training that would allow an opinion that might alter a surgical plan (Table 1).

Qualifications for a supervisor and training program are specified. Although a letter from the program director of a recognized training program certifying completion of an arbitrary course of study may be acceptable for granting credentials, a formal examination of cognitive skill, such as that organized by the National Board of Echocardiography, is clearly more objective.

Electrocardiography

All vascular surgery patients should be monitored by ECG for the detection and management of cardiac arrhythmias and ischemia. Important arrhythmias are

Table 1
Training recommendations for perioperative transesophageal echocardiography

Training	Basic	Advanced
Minimum number of archived examinations studied under supervision	150	300
Minimum number of examinations personally performed under supervision	50	150
Minimum hours of additional study time devoted to TEE	20	50

Data from Thys DM. Clinical competence in echocardiography. Anesth Analg 2003;97:313–22.

common, and by definition, most patients in this population are at high risk for coronary artery disease. New-onset junctional rhythm is a frequent cause of hypotension at induction, and ventricular tachycardia or significant ectopy occurs intraoperatively in up to 16% of cases [51]. Landesberg et al [52] showed that the widely used display of the standard leads II and V5 detects 80% of ST segment changes caused by ischemia, although V4 is preferable to V5, and that the observation of three leads is required for a sensitivity of 95% or higher. There is some evidence that the modified leads CS5 and CB5 are more sensitive than the II–V5 combination [53]. Standard placement of lead V is not possible during a left thoracotomy. Given the mediastinal shift that occurs when the patient is in the right lateral position with a deflated, isolated left lung, there is a modification of the CB5 placement that is out of the surgical field and is intuitively attractive. A negative electrode (eg, right arm) is placed over the right scapula, a positive electrode (eg, left leg) is placed over the *right* sternal edge at the fourth interspace, and an appropriate lead (eg, ''Lead I'') is selected on the monitor. The sensitivity of this arrangement for detecting ischemia, however, has not yet been validated. An esophageal lead may also be useful [54]. To optimize the recognition of ischemia, automated ST segment analysis can be an aid to maintaining vigilance, although the technology is imperfect and continues to evolve.

Neurophysiologic monitoring

Discussion of neurophysiologic monitoring is limited here to monitoring that pertains to spinal cord ischemia during aortic surgery and cerebral ischemia during carotid artery surgery. Many of the monitoring methods require special expertise and equipment and substantial expense. Neurophysiologic monitoring is useless unless the data generated is actually used in an attempt to correct ischemia. If the surgical plan will not or cannot be altered in the event ischemia is detected, the 'quick, simple clamping' technique, monitoring is valueless.

Spinal cord ischemia

The number of reported incidents of paraplegia following aortic surgery varies from approximately 1 in 1000 for elective repair of uncomplicated abdominal aortic aneurysm to 30% when the entire thoracic aorta is replaced emergently [55]. Strategies to minimize ischemic cord damage during thoracic aoratic surgery include:

Aggressive reattachment of segmental arteries
Selective perfusion of segmental arteries
Sequential aortic clamping
Distal perfusion with partial left heart bypass
Cerebral spinal fluid drainage

Systemic or epidural cooling
Induced hypertension

Selective perfusion and reattachment of intercostal arteries is technically demanding, time consuming, and is associated with greater blood loss. Some centers, therefore, undertake these measures only if they are indicated by the identification of spinal cord ischemia by neuropsychologic monitoring [56]. Other centers use all available protective techniques whenever possible and forego monitoring [57]; and still others operate as fast and as skillfully as possible without special protective measures or monitoring [58]. Satisfactory outcomes have been achieved with all three approaches.

Neuroanatomic basis for spinal cord monitoring

Blood is supplied to the spinal cord from one anterior and two posterior spinal arteries (PSA). These three arteries originate from the vertebral arteries bilaterally. There are two continuous PSAs supplying the posterior one third of the cord, each originating proximal to the posterior inferior cerebellar artery from a vertebral artery. The blood flow to the PSAs is augmented throughout their length. The PSAs in the cervical region receive variable contributions from posterior cervical segmental medullary arteries also derived from the vertebral artery, in the thoracic region from intercostal arteries, and distally from a lumbar–sacral plexus. The central and anterior two thirds of the cord, with the ischemia-sensitive anterior horn cells, is supplied by the anterior spinal artery, which is inconsistent and may sometimes be effectively discontinuous [59]. The single anterior spinal artery has a bilateral origin from the vertebral arteries just distal to the posterior inferior cerebellar artery. In the cervical region, the anterior spinal artery receives variable contributions from anterior segmental medullary arteries derived from the cervical and vertebral arteries. In the thoracic region, segments of the anterior spinal artery are supplied by a varying number (averaging five) of segmental medullary arteries derived from intercostal or lumbar vessels, the largest of which is named the *artery of Adamkiewicz*; and there is also a distal contribution from a lumbar–sacral plexus. Because of the possible discontinuity of sections of the anterior spinal artery, corresponding sections of the cord may depend entirely on a blood supply from their segmental medullary vessels. These segmental vessels may be interrupted by aortic disease or surgery and made ischemic during aortic cross clamping. The posterior one third of the cord containing mostly sensory tracts and supplied by the two PSAs may be functionally monitored by somatosensory-evoked potentials (SSEPs); the anterior two thirds of the cord, with mostly motor tracts and supplied by the single anterior spinal artery, may be functionally monitored by motor-evoked potentials (MEPs).

Somatosensory-evoked potentials

The perioperative use of SSEPs to monitor spinal function is well established. The technique is usually unavailable outside major centers because of the special

equipment and skilled staff necessary to obtain reliable results, although a traveling monitoring service may be obtained in some areas.

Electrical stimulation is usually applied to the posterior tibial or common peroneal nerves in the leg, although methods of directly stimulating the cord have been developed. The neuronal potentials evoked are detected by surface or needle electrodes at the cervical spine and scalp, filtered, and, after 300 or more signals are electronically averaged, the resulting waveforms are analyzed for magnitude and latency. Users determine the significance of any changes [60]. The latencies are increased, and the magnitude of SSEPs is reduced by benzodiazepines and normal clinical concentrations of volatile anesthetic agents, especially in combination with nitrous oxide. Responses may also be impaired by coexisting disease, ischemia of the stimulated peripheral nerve or by cerebral ischemia. The method is very sensitive to electromagnetic interference although it remains useful during mild ($\geq 32^{\circ}C$) hypothermia. Although the occurrence of false-negatives and -positives is well documented, SSEPs remain an integral component of the cord protection regime in some centers [60,61].

Motor evoked potentials

Introduced more recently, MEPs have a penetration similar to SSEPs in specialized centers [62] because of the requirement for special skills and equipment. Either the motor cortex of the brain or the spinal cord itself is stimulated, and the potential evoked is recorded distally from a peripheral nerve such as the popliteal (a neurogenic recording) or a muscle such as the tibialis anterior (a myogenic recording) through a percutaneous needle. The cortex is stimulated using either a transcranial (tc) electrical current (much less than that used for electroconvulsive therapy) through standard surface electrodes (tcE MEP) or a transcranial magnetic stimulus (tcM) from a coil in contact with the scalp that generates a 1.5- to 2.0-Tesla magnetic field (tcM MEP). Transcranial MEPs are exquisitely sensitive to anesthesia but are maintained during mild and moderate hypothermia. The dosages of benzodiazepines, volatile anesthetic agents, and nitrous oxide must be minimized or eliminated, and neuromuscular blocking agents must be carefully titrated to reduce motion artifact while retaining the compound muscle action potential [63]. Automated, calibrated neuromuscular function monitoring is helpful. Anesthetic techniques using infusions of ketamine and opioids are favored. Like SSEPs, MEPs are susceptible to mechanical and electromagnetic interference in the operating room, and the extracranial magnetic coil is unwieldy. Neurogenically evoked potentials (not to be confused with neurogenic recordings of tc MEPs) induced by direct electrical stimulation of the cord are more robust in the surgical environment and much less sensitive to anesthesia. Neurogenic MEPs are more common in the context of spinal surgery when the vertebrae or cord are exposed, but the use of percutaneously placed extradural electrodes during vascular surgery has been reported [64]. Despite the technical demands, both tcE and tcM MEPs have been incorporated as vital components of integrated programs of spinal cord protection [60].

Monitoring for cerebral ischemia

The carotid artery must be occluded by a cross clamp during carotid endarerectomy (CEA). Because the internal carotid artery is an end artery, during carotid cross clamping blood flow to the anterior portion of the ipsilateral hemisphere is dependent on collateral flow through the circle of Willis. The potential for cerebral ischemia, infarction, and stroke exists if collateral flow is inadequate. The most common technique to restore flow to the territory of the occluded carotid is a temporary shunt. One purpose of intraoperative cerebral monitoring is to aid in the decision as to which patients should receive a shunt [65]. (Other purposes are to detect emboli and early or impending thrombotic occlusion of the reconstructed artery.) Although they are possible, direct measurements of cerebral blood flow and the regional availability of oxygen to the brain are not routinely available in the operating room. Consequently, two approaches for surrogate monitoring are used. Either the function of parts of the brain are monitored (and the assumption is made that continued function implies an adequate oxygen supply) or the blood flow or pressure, at one or more points in the brain are measured (and the assumption is made that the flow or pressure is equivalent elsewhere). Neither assumption is always correct, and despite monitoring, ischemia may sometimes occur without detection, and a stroke occurs.

Although intraoperative stroke due to carotid cross-clamping is disastrous, it is uncommon. Any other procedure, including shunt placement, that may detach embolic material also carries a risk of stroke. It has always been intuitively attractive, therefore, to reserve shunts for only those patients who truly need them. Many papers describe and compare different approaches to this problem. Although 90% of neuroanesthesiologists, responding to a 1997 survey reported using some form of neurophysiologic monitoring during CEA [66], the skills and equipment required have only gradually become available over the past 25 years. CEA is a commonly indicated procedure that has been widely performed, and the earlier limited availability of monitoring led to three alternative approaches. One approach is to place a shunt in all patients receiving general anesthesia; the second is to never place a shunt. Both of these approaches have ‘‘acceptable’’ outcomes, with total rates of stroke less than 2.5%. The third approach is to proceed under regional anesthesia and allow patients to be their own monitor.

The similar outcomes from these contrasting approaches have led to an authoritative analysis suggesting that a large prospective trial is required to assess the indications for and fundamental value of shunting itself, and that further trials of methods of monitoring to aid selective shunting are not currently merited [67]. This opinion notwithstanding, there is substantial evidence that (1) monitoring reliably detects intraoperative ischemia caused by cross clamping [68,69]; (2) the cause of most perioperative strokes is related to technical factors [70]; (3) stroke is rare in centers with skilled and experienced staff [71]; and (4) shunts may themselves cause ischemia because of emboli or occlusion [72]. Regional anesthesia for CEA is gaining in popularity [73], but the majority of procedures

in the United States are still likely to be performed under general anesthesia [66]. Monitoring for cerebral ischemia during CEA may be of more value in the instructional setting and in hospitals with low volumes of cases or historically high complication rates [74].

Electroencephalography

Continuous perioperative electroencephalography (EEG) monitoring has been used for decades to detect focal, hemispheric, and global dysfunction resulting from ischemia. Studies confirm the high sensitivity, specificity, and predictive value of EEG to detect ischemia resulting from carotid cross clamping, and EEG monitoring is the gold standard of comparison with other monitors and approaches. These studies demonstrate that EEG is a valid component of surgical programs that incorporate selective shunting and that the cross clamp-derived ischemic stroke rate can be kept below 1% [68,69]. It must be emphasized that in these large studies, full 16-channel or 10–20 montage EEG was used and that experts interpreted the results. The need for expert interpretation is highlighted by major disparities with other series, with some centers reporting that their sensitivity for the detection of ischemia using EEG is as low as 70% [75]. In attempts to reduce dependence on elaborate equipment and skills, computer processing of simplified EEG data has been used to produce derivatives that might be successfully interpreted by clinicians with a minimum of special training. These derivatives include compressed spectral array, density spectral array, and the spectral edge frequency. Several small studies and anecdotal experience have shown that a processed EEG derived from only one or two pairs of electrodes will detect many ischemic changes that are reversible by shunting or raising the mean blood pressure, but there is insufficient data to support a conclusion that the sensitivity and specificity of these derivatives is equivalent to a full EEG [76]. Processed EEG may be of value in some circumstances in which there are limited resources and regional anesthesia is contraindicated. Regardless of technique, surface EEG may be profoundly affected by anesthesia and does not always detect ischemia in deeper cerebral structures [77].

Somatosensory-evoked potentials

The use of SSEPs for monitoring spinal cord function has already been described. SSEPs also have an established use for monitoring cerebral function to detect ischemia [78]. The investment in equipment and skill is similar to that required for EEG. Stimuli are commonly applied to the median and posterior tibial nerves, and surface electrodes on the cranium detect responses. The responses from 300 or more stimuli at 4 Hz are filtered and electronically averaged, and the resulting wave is analyzed for changes in amplitude and latency. The user decides the significance of any changes. SSEPs have been shown to be less sensitive then EEG in predicting the need for shunting [79].

Transcranial doppler

First described in 1982, the use of transcranial Doppler (TCD) ultrasonography to monitor cerebral blood flow has been well studied [80] and is achieving increasing popularity. In a 2000 survey, 25% of anesthetists in the United Kingdom reported routine use of TCD perioperatively [81]. The middle cerebral artery (MCA) is insonated through the temple bone by a Doppler probe of specialized design. The blood flow velocity is measured, and the passage of emboli may be detected and counted. The underlying assumption is that blood flow velocity through the MCA is predictive of global cerebral blood flow. Although these quantities are clearly related, however, flow velocity in one cerebral artery is not directly indicative of oxygenation in other parts of the brain. A variety of indices derived from the measured velocities have been used to predict the risk of clamp-derived ischemic stroke, including a post-clamp mean velocity MCA (mvMCA) less than 30 cm/sec; clamp–preclamp mvMCA ratio less than 0.6 or 0.4; post-clamp mvMCA less than 50% of pre-clamp value [82]; changes in peak systolic velocities; and changes in a complex pulsatility index [80]. Several studies have attempted to validate these indices, but most suffer the weakness of comparison made with another surrogate criterion of ischemia (often EEG changes) rather than a neurologic outcome. An mvMCA ratio of less than 0.6 has been shown to correlate with a global cerebral blood flow of less than 20 mL/100 g/min [83]. An mvMCA ratio of less than 0.4 has been shown to correlate with EEG changes of severe ischemia, and an mvMCA velocity of less than15 cm/sec with a regional cerebral blood flow of less than 9 mL/100 g/min has been shown to correlate with EEG suppression [83]. One large retrospective review suggested a benefit from selective shunting determined by "persistent ischemic changes" of these indices, and, in the same study, TCD detected a profound reduction in blood flow whereas the EEG remained unchanged [84]. Despite this evidence and the obvious attraction of correcting a dramatic drop in flow velocity when a clamp is applied, like other monitoring methods, TCD must too be interpreted with caution. Two studies using the deterioration of the neurological status of awake patients as the standard of "real" ischemia showed poor specificity in the predictive value of three of the standard velocity indices (unnecessary shunts would have been placed), although the negative predictive value (high flows indicating shunt unnecessary) was good [85,86].

It has already been noted, however, that the majority of perioperative strokes are caused not by cross clamp-related ischemia but by emboli, the hyperemic syndrome or by early occlusion of the reconstructed vessel by thrombus [72]. This finding strongly suggests additional roles for TCD monitoring [74]. TCD has been used successfully to guide post-reconstruction antiplatelet treatment for patients with high embolic counts and to detect and allow management of incipient hyperemia [80,87]. Urgent re-operation for occlusion of the reconstructed carotid is often dramatically successful and may prevent stroke or mortality. An important implication is that TCD monitoring might usefully be continued in the postoperative phase [88].

Table 2
Electroencephalography and transcranial Doppler

Function	Electroencephalography	Transcranial Doppler
Ischemia detection	Functional	Surrogate
Limitations	Abolished by cerebral "protection"; monitors superficial structures; affected by prior morbidity	Unobtainable in 15% of patients
Lag time between onset and detection of ischemia	Yes	No
Quantification of emboli	No	Yes
Detection of hyperemia	No	Yes
Postoperative monitoring	Logistically difficult	Technically easy

Some of the characteristics of TCD and EEG monitoring are compared in Table 2. Rather than considering them as competitors, when the resources are available TCD and EEG may be considered complimentary in the context of a surgical program that uses selective shunting under general anesthesia [89].

The awake patient

The most specific monitor of cerebral function is the mental status of a responsive patient; the avoidance of general anesthesia allows patients to act as their own monitors. Although anxiolytics may be used, verbal communication and visual contact are maintained with the patient throughout the procedure and the response to command or conversation is assessed. Motor function may be demonstrated by the patient squeezing a squeaking toy or a bulb connected to a pressure transducer or manometer, with the contralateral hand. Neurologic deterioration is obvious and usually responds immediately to shunt placement, occurring in 6% to 14% of cases. This is approximately half the percentage of patients who exhibit "significant" EEG changes under general anesthesia. Several studies reporting the synchronous use of EEG monitoring with conscious neurologic evaluation have shown that EEG changes are not detected in 19% to 30% of the patients who exhibit an actual neurologic deterioration that responds to shunt placement [75,90]. That the number of patients with the EEG changes when awake is half that of those under general anesthesia and that the nature of these EEG changes is different have led to the intriguing suggestion that EEG changes represent different phenomena when awake or under general anesthesia or that general anesthesia itself may perhaps predispose to ischemia [90].

Stump pressure

Measurement of the mean intra-arterial pressure just distal to the cross clamp (stump pressure) has long been used to guide the need for shunt placement [91]. Values below 50 mm Hg, or alternatively 25 mm Hg, are used as triggers for shunting [92]. A mean pressure at one point in the cerebral vascular tree, however, is not proof of flow in another, although a real predictive relationship between a low stump pressure and global ischemia undoubtedly exists [93]. Stump pressure

has been shown to have a poor negative predictive value (unnecessary shunts used) but, more importantly, a relatively poor positive predictive value (shunt not used when possibly needed) compared with the development of ischemic EEG changes or changes of neurologic status of awake patients [92]. Despite its relatively poor predictive value, however, measuring stump pressure requires little equipment and no extra skill and may have application when regional anesthesia is contraindicated and resources are scarce.

Blood chemistry

There have been preliminary studies as to the value of monitoring changes in jugular venous oxygen saturation [94] and blood chemistry [95], but it is too early to draw conclusions.

Monitoring in specific circumstances

The following lists are procedural suggestions based on the preceding references and are offered only for convenience (Box 3).

Endovascular aortic surgery

Abdominal aortic stenting

Devices and techniques for endovascular stenting are in a state of active evolution, making generalization difficult. Because of the possibility of rupture of the aorta, which requires emergent primary conversion to an open procedure, many centers have routinely fully monitored all patients as though the procedure was open [96]. Although there is a primary conversion rate that averages 2% [97], recent experience shows that catastrophic aortic rupture is very uncommon. Three recent series with a total of 531 patients did not report a single rupture that required emergent primary conversion for repair [98–100]. For procedures to the abdominal aorta, therefore, there is likely time for placement of all lines should conversion to an open procedure be necessary. Unless special difficulty is anticipated, therefore, it is reasonable to use initially only basic monitoring. Additional monitoring may be indicated if a transitory cardiac arrest is planned [101].

Thoracic aortic stenting

Presentation of thoracic aortic disease for stenting may vary from an emergent type A dissection of an extensive aneurysm to an entirely stable, progressively narrowing coarctation. Patients with a large or dissecting aneurysm either are or are likely to become unstable and require general anesthesia and full monitoring. TEE may be required to localize an intimal tear, assist stent placement, and to monitor for endo leaks [101–104]. Furthermore, some types of thoracic stent require a relatively long period of circulatory arrest for stable placement, and

facilities for fibrillation, defibrillation, and external or transvenous pacing with attendant hemodynamic monitoring are required [101]. On other elective occasions, when the pathology is more benign, the stent may be placed under local or regional anesthesia, and basic monitors are sufficient [105]. Although neurologic deficits may occur after endovascular aortic stents are placed, the devices currently available are ''all or nothing,'' without the opportunity to revascularize segmental arteries. Therefore, neurophysiologic monitoring is not indicated.

Cranial vessels

Percutaneous stenting of the cervical carotid arteries is becoming a more frequently used procedure [106]. The intraoperative complication rate is low and usually proceeds with the patient awake, often with monitored anesthesia care using basic monitoring [107].

The imaging techniques for obliteration therapy, angioplasty, and stenting of intracranial vascular disease require virtual immobility. Intraoperative complica-

Box 3. Surgical procedure and monitoring recommendations

Extracranial carotid surgery

ASA basic monitors
Arterial line
CVP line if indicated by comorbidity or the need for ''central'' access for drug administration
PAC only if indicated by comorbidity
Monitoring for cerebral ischemia if selective shunting under general anesthesia is planned
TCD, if available, continued into the postoperative phase

Direct arterial pressure monitoring is strongly indicated. Hemodynamic instability requiring vasoactive management is common during this procedure, although less so if general anesthesia is avoided, and may continue well into the postoperative period [94].

Open abdominal aortic surgery

ASA basic monitors
Arterial line
CVP line
PAC if indicated by comorbidity
TEE if indicated by comorbidity or unresponsive hemodynamic instability

The more proximal the cross clamp, the more often a PAC is useful. Hemodynamic instability is common even in otherwise healthy patients and the arterial line is strongly indicated. Central venous access is frequently useful to infuse vasoactive drugs and as a guide of fluid volume requirements. Easy access for blood sampling is essential. CVP used in conjunction with SPV may avoid the need for a PAC.

Open thoracic aortic surgery

ASA basic monitors
Arterial line proximal to cross clamp
Second arterial line distal to cross clamp if distal profusion is planned (partial left heart bypass)
PAC
TEE
Neurophysiologic monitoring if indicated

Neurophysiologic monitoring is required if the surgical plan bases the selective reimplantation of intercostal arteries, sequential cross clamping or selective distal profusion on evidence of spinal cord ischemia. PAC data must be interpreted with extra care when the patient is in the lateral position and the upper lung is collapsed and unventilated. TEE is very helpful for accessing left atrial or pulmonary vein cannulation and left ventricular function [48]. Surgical manipulation near the beginning of the descending aorta may interfere with flow to the left subclavian artery (and therefore usually to the left vertebral artery) so the proximal arterial pressure line is commonly placed in the right arm. If, however circulation to the right arm is already compromised, for example by peripheral vascular disease or the hematoma of a dissection, a third line in the left arm is justified. This has the added benefit of indicating interference with the left subclavian and vertebral arteries.

Peripheral vascular surgery

ASA basic monitors
Arterial line if indicated by co-morbidity or special circumstances
Access for blood sampling if no arterial line

Direct arterial pressure monitoring from an upper limb is occasionally helpful to quantify the pressure drop across an arterioplasty or stent. Some centers prefer to base heparin dosage on quantitative data, requiring repeated blood sampling.

tions including aneurysm rupture and vessel spasm or dissection can be devastating [108]. A recent review is not available, but it is likely that the majority of these procedures are conducted under general anesthesia in North America (John Chalupka, personal communication, 2003). In the author's institution, hemodynamic manipulation is required in approximately 30% of procedures, and post-procedural hypertension must be avoided. Basic monitoring with the addition of an arterial line is used and is continued in the intensive care unit for the first postoperative night.

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