Minimally Invasive and Noninvasive Diagnosis and Therapy in Critically Ill and Injured Patients

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In this review, both the newer noninvasive (ie, those that pose no breach of an epithelial barrier) and minimally invasive techniques relevant to the treatment of the critically ill or injured patient will be discussed. In some cases, the development of the technology is so recent that published data describing their clinical applications may be scant. The emphasis herein is on newer technologies; therefore, the discussion of certain established noninvasive techniques, such as pulse oximetry, and minimally invasive therapies, such as percutaneous abscess drainage, will be deferred.
Arch Surg. 1999;134:1189-1196

Critically ill and injured patients are some of the most difficult patients to treat in the hospital. These patients frequently harbor complex multiorgan pathologic processes that require close monitoring of hemodynamics and critical organ function to avoid further morbidity or mortality.[1] The primary derangements to avoid are impaired tissue perfusion and cellular hypoxia, which have been associated with nosocomial infection and multiple organ failure. The occurrence of these morbidities severely impairs the chances of a good outcome. Therefore, timely intervention for any physiologic perturbation is often crucial.

To treat these patients, clinicians have long relied on the practice of supporting failing organs, while the patient attempts to recover from the primary traumatic or septic insult contributing to the critical illness. Over the last 20 years, advances in ventilator treatment, monitoring, and antibiotics have decreased the mortality rate in many surgical intensive care units (ICUs). However, many of the standard monitoring modalities create morbidity themselves, either by their invasive implementation or by inaccurate interpretation of the derived data.

Minimally invasive technologies have had a tremendous impact in modern medicine. These technologies allow diagnostic and therapeutic interventions with diminished tissue trauma, discomfort, and a presumably expedited recovery. These interventions generally contribute to a significantly decreased length of stay and cost to the institution. From a cost-benefit standpoint, the cost savings from the intervention will often offset the cost of the intervention itself. Subsequently, ICUs are increasingly using these technological advances to optimize care for their patients in many different areas. In some cases, these techniques permit the earlier diagnosis of pathologic processes and allow the institution of meaningful interventions that can prevent further organ failure.

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ADVANCES IN MONITORING AND ASSESSMENT OF TISSUE PERFUSION

Point-of-Care Testing

An advance that is increasing the rapidity by which many blood tests can be obtained is point-of-care testing.[2] These portable testing devices can perform many common laboratory tests, including blood chemistry concentrations, blood gas values, and tests of hematology or coagulation. Accuracy has been validated for these tests and the clinician can be confident in their results. The attraction of these devices lies in their ability to perform blood tests in 90 seconds with as little as 500 μL of blood. Because of the portable nature of these devices, tests may be performed at the patient's bedside. Consequently, these devices can be used in the operating room, the emergency department,[3] and the ICU.[4]

The greatest potential of point-of-care devices is in critically ill and injured patients. Rapid turnaround times will render crucial laboratory data immediately available. Trauma patients or those with life-threatening bleeding may have their hematologic status monitored in real time, avoiding dangerous delays.[5] Potentially serious physiologic conditions requiring immediate resuscitation, such as hyperlactatemia, can now be diagnosed more quickly.[6] Additionally, troponin concentrations can be determined by point-of-care testing so patients acutely suspected of myocardial infarction[7] or blunt cardiac injury may also be treated more expediently.[8]

Gastric Tonometry

Perhaps the noninvasive device garnering the most attention in recent years is the gastric tonometer. This device determines the gastric intramucosal pH of the patient through a special nasogastric tube, an extra port of which leads to a semipermeable membrane. Investigators have focused on both the absolute intramucosal pH and the tissue carbon dioxide (CO_2) to arterial CO_2 gradient as being potential surrogates of splanchnic perfusion and therefore markers of effective resuscitation.[9] Proponents of the device believe it is such a valuable tool because gastric mucosal ischemia is an early sign of impaired perfusion. Recently, the technology has evolved to the use of a continuous tonometer with the assistance of an infrared capnograph that can provide more frequent readings than previously available.[10-12]

The few published controlled trials have focused on its use in critically ill and injured patients.[13] In some centers, attempts are made to correct intramucosal pH with the use of inotropic agents and antioxidants in addition to standard resuscitation fluids.[14] The device has been used as an intraoperative marker of resuscitation. More optimal splanchnic perfusion during surgery has been suggested to decrease complications after major abdominal surgery,[15] cardiac surgery,[16,17] and aortic aneurysm surgery.[18]

Despite the popularity of the gastric tonometer in certain centers as a monitor of resuscitation and perfusion,[19-23] questions regarding its true benefit persist. To our knowledge, no large prospective, randomized trials demonstrating superior outcomes with the device have been published. If the tonometer conferred such outstanding information as purported by its proponents, it would be anticipated that some convincing multicenter data would strongly support its use in trauma, critical care, or perioperative patients. Until such data are available and show its benefit over other markers of resuscitation, such as base deficit, acidosis, mixed-venous oxygenation values, or even clinical intuition, many clinicians feel unjustified incorporating the device into their practice.

Esophageal Doppler Monitoring

The esophageal Doppler monitor (EDM) device is a soft 6-mm catheter that is placed noninvasively into the esophagus. A Doppler flow probe at its tip allows continuous monitoring of cardiac output and stroke volume. A 4-MHz continuous-wave ultrasound frequency is reflected to produce a wave form, representing the change in blood flow in the descending aorta with each pulsation. The history and physics of the EDM have been fully described.[24,25] Although the EDM has been approved by the Food and Drug Administration and has numerous studies documenting its accuracy as a monitoring device, its use has been sporadic, particularly in North American centers.[26-28]

The EDM poses several advantages over the pulmonary artery flotation (PA) catheter, the primary bedside device used to determine cardiac output. Unlike the invasive PA catheter, the EDM does not require percutaneous insertion, which can be complicated by pneumothorax or arrhythmia. The EDM does not rely on an indwelling catheter that has obvious infectious risks. An EDM may yield more accurate hemodynamic data than a PA catheter in patients with cardiac valvular lesions, septal defects, arrhythmias, or pulmonary hypertension. Also, the continuous cardiac output display is less labor intensive than PA catheters (there are no injections of a thermal indicator, which are subject to error), and may thereby stimulate quicker responses to hemodynamic disturbances than intermittent cardiac output monitoring devices. Conceivably, the EDM could be used on standard hospital floors for patients whose therapy might benefit from cardiac assessment without the delay and cost associated with an ICU transfer.

The primary disadvantage of the EDM is that the device may sometimes lose its wave form with only a slight positional change and render dampened, inaccurate readings. Additionally, because some manipulation is frequently required to achieve the optimal wave form necessary for accurate data, great potential exists for misinterpretation of the readings by the inexperienced health care worker.[29]

A small amount of literature has detailed the clinical use and accuracy of the EDM.[30,31] Its primary use will be in the operating room and in the ICU. In cardiac surgery, the device has been shown to assist in optimizing gut perfusion in conjunction with a gastric tonometer and to decrease perioperative complications.[32] Similarly, the EDM has proven a beneficial device for perioperative monitoring as a means to decrease morbidity in elective femur fracture fixation in a prospective, randomized trial.[33] This device has also been proven capable of yielding beneficial information for treatment of sepsis in humans.[34]

Further experience with the EDM is necessary before it can be considered equivalent to the PA catheter as a monitoring device, especially because familiarity with the EDM seems crucial for its proper use. Nonetheless, as a perioperative and critical care monitoring device, it may develop into a widely used tool.

Thoracic Bioimpedance Cardiac Output Monitor

Thoracic bioimpedance cardiac output monitoring systems are being developed for clinical use. This noninvasive device gains information from topical electrodes placed on the anterior aspect of the chest and neck that estimate cardiac output by incorporating a modified form of the Kubicek equation and by estimating the left ventricular systolic time interval based on time-derivative bioimpedance signals. The time for the system to provide values is approximately 2 to 5 minutes from initial lead placement and activation.[35]

The cardiac outputs gained from the bioimpedance device have been correlated with those of the PA catheter in animal models and clinical trials. Compared with conventional thermodilution in a healthy porcine model,[36] the bioimpedance system correlated accurately over a wide range of cardiac outputs in 199 measurements with an r of 0.87. In another study, this device was compared with a standard thermodilution monitor as a perioperative monitor for 23 adults undergoing extensive oncologic surgery.[37] The correlation coefficient between the 2 methods was 0.89. Finally, in a large multicenter study of emergency department patients, the bioimpedance system was found to correlate with thermodilution, with an *r* of 0.85 over 2192 simultaneous measurements.[35]

The main drawback of thoracic bioimpedance cardiac output monitoring is that the technique is sensitive to any alteration of the electrode contact with the patient. Therefore, minor changes in lead placement or changes in tissue water content that can occur with perioperative fluid shifts may degrade the signal and produce error. Because the electrodes may need to provide data over several days, depending on the critical nature of the patient, the issue of lead placement with this technique is a substantial problem.

Signal-Averaged Electrocardiographic Assessment of Heart Rate Variability (HRV)

Analysis of HRV is a promising new technique for noninvasive quantification of autonomic function. Here, a signal-averaged electrocardiographic signal is captured by a bedside computer and subjected to fast Fourier transformation for spectral analysis. This technique may have particular applicability to assess prognosis in critically ill and injured patients.

In a recent study, Winchell and Hoyt[38] examined HRV using spectral analysis in patients in the surgical ICU over a 6-month period. They studied HRV measurements every 6 hours on all patients in the ICU and recorded the total spectral power in the signal, which represented a measure of overall autonomic activity. They found loss of normal sinus HRV to portend a poor prognosis and also showed the ratio of high frequency to low frequency HRV components to be of particular significance. The ratio of high frequency to low frequency indicated the degree of parasympathetic to sympathetic balance in individual patients. Low sympathetic tone and vagal predominance, or an increased high frequency to low frequency ratio, were associated with increased mortality, whereas sympathetic predominance with a lesser high frequency to low frequency ratio predicted survival.

In a subsequent study of patients with head injuries in the ICU, these same authors found that low HRV was associated with increased mortality and a decreased rate of discharge home.[39] Furthermore, loss of normal HRV was associated with episodes of increased intracranial pressure and decreased cerebral perfusion pressure. Monitoring HRV may improve outcome by allowing earlier detection and treatment of intracranial pathology.

Decreased HRV has also been described in endotoxemic volunteers, suggesting that uncoupling of biologic oscillators may contribute to the pathophysiology of multiple organ failure.[40] Because of this potential association, the signal-averaged electrocardiogram may develop a role as a monitor of sepsis in the ICU.

Tissue Spectroscopy

Tissue spectroscopy is an exciting new area of patient monitoring. This technology relies on the principle that mitochondrial cytochrome aa–redox shifts can be determined by near-infrared wavelength reflection, which can penetrate skin and bone. Consequently, mitochondrial oxidation can be measured noninvasively using near-infrared spectroscopy (NIR) from which perfusion can be inferred. In trauma, NIR has potential importance as a method to diagnose acute compartment syndromes. Fiberoptic devices using NIR wavelength reflection determine the redox state of certain light-absorbing molecules. This wavelength can be adjusted to monitor venous hemoglobin saturation in tissues as a method of detecting cellular ischemia that corresponds to the low-flow state. Investigators created a porcine model of acute compartment syndrome by the instillation of albumin into the hind limb. The monitor positioned cutaneously over the anterolateral hind limb detected a relative decrease in tissue oxygen saturation, which accurately diagnosed the compartment syndrome.[41] In another study by the same group, significant correlations among mitochondrial cytochrome aa–redox state, cardiac output, and oxygen delivery were observed throughout hemorrhagic shock and resuscitation with NIR probes placed directly on the stomach, liver, kidney, and skeletal muscle of rabbits.[42]

Near-infrared spectroscopy should also develop a variety of other clinical uses. This technology has already been described as a noninvasive method for the early detection of ischemia after free-tissue transfer.[43] Similarly, NIR should be useful in the postoperative monitoring of lower-extremity vascular bypass grafts. Near-infrared spectroscopy monitoring of small bowel pH may be used to gauge the adequacy of resuscitation. This technique has been compared directly with electrode-derived small intestinal pH in a porcine hemorrhagic shock model, and was found to correlate favorably.[44]

Using a related technology, McKinley et al[45] demonstrated the use of fiberoptic sensor probes for concurrent measurement of tissue oxygenation, pH, and tissue CO_2 in a canine model of hemorrhage. These sensors are contained in 0.5-mm flexible probes that measure light transmission emitted by fluorescent indicators depending on the amount of molecular oxygen in the medium around the sensor. The ability of a single probe to capture simultaneously skeletal muscle oxygen, CO_2, and pH may yield more information than any single derived variable.

Near-infrared spectroscopy has also been used to evaluate cerebral oxygenation during periods of tissue hypoxia and impaired perfusion. In a recent study in newborn piglets subjected to transient global hypoxia and cerebral ischemia by bilateral carotid ligation, NIR monitoring was able to detect decreased cerebral perfusion.[46] Near-infrared spectroscopy has also been used as a monitor of reperfusion in a patient who underwent guided thrombolytic therapy for a stroke.[47] In a study of healthy volunteers, NIR detected small changes in cerebral oxygenation associated with different anesthetic agents.[48] Further studies could further establish NIR as a cerebral oxygen monitor in patients with head injuries or stroke, or intraoperatively during craniotomy.

NEW MONITORING AND THERAPIES IN TREATMENT OF LUNG DISEASE AND INJURY

Noninvasive Ventilation

Securing access to the subglottic airway by endotracheal tube or by surgical means has been an integral aspect of assisted ventilation. Recently, different methods of noninvasive ventilation have been used successfully for selected patients with respiratory failure without the use of an airway cannula.[49-52]

A possible method for gas exchange in critically ill patients is the use of noninvasive positive pressure ventilation via a face or nasal mask.[53] The attached mask with auxiliary pressure can be used for several days in certain patients. Different types of support can be applied to the mask to augment respiratory excursion. The most popular pressure modes with noninvasive positive pressure ventilation have been continuous positive airway pressure or intermittent positive pressure. In selected patients with respiratory compromise who need only short-term support, noninvasive positive pressure ventilation may be able to avert the need for endotracheal intubation.[54] Patients who may benefit from noninvasive positive pressure ventilation include those with difficult airway access and those with certain reversible pathologic processes of moderate severity, such as exacerbations of chronic obstructive pulmonary disease. In a systematic review, continuous positive airway pressure in lieu of intubation was shown to decrease mortality in patients with cardiogenic pulmonary edema.[55] Noninvasive positive pressure ventilation has also been described as therapy for acute respiratory distress syndrome as well.[51] Disadvantages of this technique include the lack of a secure airway, inability to suction the airway or perform bronchoscopy, and patient compliance with wearing the mask.

Recently, the use of bilevel positive airway pressure (BiPAP) has become more popular. Bilevel positive airway pressure operates as a noninvasive mode of ventilation applied by mask. Unlike continuous positive airway pressure, BiPAP also includes an exhalation valve that permits maintenance of expiratory positive pressure as well. This aspect of the modality improves the exhalation of CO_2. For short periods, this technique can be used effectively to increase ventilation and alveolar recruitment, while possibly diminishing nosocomial infection and patient discomfort.[56] The greatest success rate of BiPAP for preventing the need for intubation has been in patients with hypercapnia rather than hypoxemic respiratory failure.[57] Notably, BiPAP failure (ie, need for intubation) was associated with an increased likelihood of in-hospital mortality, suggesting that patients with BiPAP need close monitoring to avoid a serious delay when intubation becomes necessary. Bilevel positive airway pressure has also been used successfully to temporize patients who develop respiratory failure in the period after endotracheal extubation and can prolong survival in patients with amyotrophic lateral sclerosis whose forced vital capacity has decreased below 50% of the predicted level.[58]

Monitoring the Work of Breathing

Once the primary pathologic processes of patients who are intubated and mechanically ventilated have been treated effectively, patients can be weaned from mechanical support. Depending on the mode and level of respiratory support, mechanical weaning entails decreasing the volume or frequency of machine breaths, having the patient assume a progressively higher proportion of the work of breathing, and decreasing the fraction of inspired oxygen. In most patients, conventional respiratory parameters such as a high negative inspiratory force or an f/V_t (number of spontaneous breaths per minute divided by the generated tidal volume) of less than 200 bpm/L reflect a generalized ability of the patient to sustain adequate respiratory excursion without mechanical support. However, these parameters are not reflective of patient effort if the patient is not able to cooperate or if the resistance in the ventilator circuit and the endotracheal tube imposes a hindrance to patient breaths.[59]

For those patients whose parameters are poorly reflective of their intrinsic effort or who are going to require a longer-term weaning process, a commercially available work-of-breathing monitor (CP-100; Bicore Monitoring Systems Inc, Riverside, Calif) is available.[60] This device is an easily placed esophageal balloon catheter (for estimation of intrapleural pressure) with pressure and flow transducers placed in the ventilator circuit for calculation of the work of breathing.[1] Physiologic work of breathing is normally about 0.5 to 0.6 J/L and successful extubation is likely when physiologic work of breathing is less than 0.8 J/L. The clinician can regulate the ventilator so that patients are using no more than this level of energy for their respirations and therefore the inability to wean does not become a function of excessive patient fatigability.

Weaning From Mechanical Ventilation

Oxygenation and ventilation are each vital elements of mechanical support, and therefore both require evaluation prior to the withdrawal of respiratory support.[61] To monitor the effect of these changes, clinicians have relied on standard arterial blood gas determinations that require 3 mL of blood and a turnaround time of approximately 1 hour. Several innovations have decreased the cost and time associated with this regimented approach, including point-of-care testing and pulse oximetry.[62-67]

A vital monitoring advance from a respiratory standpoint has been the increased use of capnography, or end-tidal CO_2 monitoring in expired gas. Capnography relies on either mass spectroscopy or infrared light absorption to detect the presence of CO_2 during different phases of the respiratory cycle. Capnography has been found useful in assessment of tracheostomy or endotracheal tube placement, weaning, and ongoing monitoring. With its ability to detect hypercarbia during ventilator weaning of patients who are intubated, capnography use has diminished the need for blood gas determinations.[68] In conjunction with pulse oximetry, many patients can be weaned successfully from mechanical ventilation entirely without arterial blood gas determinations.[69]

Other information is acquired from the end-tidal CO_2 monitoring as well. Prognostically, an end-tidal CO_2–pCO_2 gradient of 13 mm Hg or more after resuscitation has been associated with an increased mortality rate in trauma patients.[70] Additionally, a sudden perturbation of the end-tidal CO_2 can be correlated with some undetected pathologic finding, such as low cardiac output or pulmonary embolism. Finally, the characteristics of the wave form can indicate information about the patient's pulmonary status and in particular whether obstructive disease is present.[70]

Heimlich Valve

A traditional device that has enjoyed a resurgence of popularity is the Heimlich valve. This device, essentially a needle with a 1-way flutter valve, has been employed increasingly in the treatment of uncomplicated pneumothorax in lieu of standard thoracostomy tubes.[71] The introducer needle is placed percutaneously into the pleural cavity and then the device is attached to the chest wall of the patient. Because the Heimlich valve does not require a large collection apparatus or application of a vacuum, reexpansion of lung parenchyma is much less invasive. These valves have been successful in the treatment of bilateral pneumothoraces,[72] lung reduction surgery,[73] and in decreasing the length of stay for lung resections in selected patients to 1 day.[74]

MINIMALLY INVASIVE SURGICAL TECHNIQUES

In all realms of surgery, less-invasive operative techniques are making inroads. For example, laparoscopic cholecystectomy has now become the standard of care for patients with biliary colic or acute cholecystitis. Similarly, in the critically ill and injured patient, endoscopic surgical techniques are being more frequently employed.

Laparoscopy

Laparoscopy has become an important diagnostic and therapeutic tool in the treatment of both blunt[75] and penetrating traumatic injuries.[76-79] In penetrating left-sided thoracoabdominal trauma, approximately one third of patients with diagphragmatic injuries will demonstrate no signs of occult injury on physical examination or plain chest radiography. Missed diaphragmatic injuries in this situation could lead to severe patient morbidity, including life-threatening respiratory failure.[80,81] Noninvasive imaging has shown some promise in the detection of occult intra-abdominal pathology, but previously, no study short of laparotomy has diagnosed all intra-abdominal injuries with 100% sensitivity. Laparoscopy has been shown to be valuable in detecting occult diaphragmatic injuries in locations where computed tomography (CT) scanning and diagnostic peritoneal lavage have recognized limitations.[82]

Notably, laparoscopy can also provide therapeutic interventions in certain circumstances as well.[83] Simultaneous gastric and diaphragmatic injuries have been repaired using this approach.[84] Laparoscopy has been used to repair blunt traumatic solid organ injuries, including a subcapsular splenic hematoma.[85] Blunt hepatic injuries have been successfully treated laparoscopically with the instillation of fibrin glue.[86] A duodenal hematoma has been decompressed laparoscopically.[87] Importantly, in trauma patients with potential intracranial injuries, laparoscopy should be used cautiously because of the risk of increased intracranial pressure.[88] Laparoscopy is also potentially hazardous in patients with acute respiratory distress syndrome, because lung compliance and effective gas exchange may be further decreased by the pneumoperitoneum.

In critically ill patients, laparoscopy has become a valuable tool to assist in the diagnosis of emergent abdominal pathology, such as ischemic bowel or perforated hollow viscus. Sometimes, this modality can be performed in the ICU itself. In a recent study of ICU-based interventions, laparoscopy detected significant intra-abdominal pathology with the same accuracy as diagnostic peritoneal lavage.[89] For acalculous cholecystitis, laparoscopy has been shown to be particularly beneficial in diagnosis and definitive therapy.[90]

Thoracoscopy

Thoracoscopy has also become a valuable part of the surgeon's armamentarium in elective thoracic surgery. To treat pleural pathology, many uses for thoracoscopy have evolved in critically ill patients, including the treatment of recurrent malignant effusions,[91] empyema, or pneumothorax.[92] As with laparoscopy, thoracoscopy can be used to treat penetrating thoracoabdominal injuries.[93] Thoracoscopy has supplanted thoracotomy for a variety of thoracic surgical procedures in trauma patients, including empyema drainage,[94] repair of pleuropericardial rupture,[95] and partial lung resection.[96] Thoracoscopy has also been used to assist with the safe removal of an impaled intrathoracic knife from a stab wound.[97]

The most important recent role thoracoscopy has acquired is in the examination of the thoracic cavity for hemothorax after blunt or penetrating chest trauma.[98] Previously, most trauma surgeons would perform thoracotomies on patients with ongoing thoracic bleeding or a large hemothorax present after a traumatic injury. This intervention would assess the injury, evaluate airway leak, diagnose active bleeding, and evacuate residual blood clots that could predispose a patient to empyema. Thoracoscopy can now accomplish all these aims with substantially less morbidity. Thoracoscopy should remain an important part of trauma care and help to eliminate post-traumatic empyema as a complication of trauma.

ADVANCES IN RADIOGRAPHIC IMAGING AND INTERVENTION

Ultrasound

One of the most notable changes in trauma care during the last decade has been the methods of evaluation for the blunt trauma patient. Before 1990, the safest, most prevalent method for evaluation of the abdomen in these patients was diagnostic peritoneal lavage. In the early 1990s, CT scanning became used increasingly in stable patients with blunt trauma. Since then, the use of ultrasound in the emergency department for both the stable and unstable trauma patient has become an increasingly standard procedure.

Most trauma centers use torso evaluation by the focused assessment by sonography in trauma (FAST) technique.[99] To diagnose potential truncal injuries from any mechanism, the FAST technique has been proven to detect hemopericardium or hemoperitoneum in the emergency department setting. Performed by surgeons, emergency personnel, or radiologists,[100] the FAST technique sequentially surveys for blood in the pericardium, right upper quadrant, left upper quadrant, and pelvis.[101] Trauma ultrasound is most beneficial in large-volume centers where the operators have been properly trained and supervised. Further studies need to be performed to show that smaller centers can duplicate the sensitivity in detecting injuries before the technique can become applied universally.

Ultrasound has also facilitated many nonoperative interventions in critically ill and injured patients. Vena cava filters have been placed at the bedside in the ICU for trauma patients.[102] Unruptured ectopic pregnancies can be now treated with ultrasound-guided percutaneous drainage.[103] Improvements in resolution have allowed many vascular surgical procedures to be performed with preoperative ultrasound instead of the more invasive arteriography.[104] In the ICU, portable ultrasound machines assist in the diagnosis and therapy of a variety of conditions, including blood flow studies for portal hypertension, deep venous thrombosis, or acalculous cholecystitis.[90,105,106] Ultrasound has also assisted in vein localization for difficult central venous access.[107]

Computed Tomography

The advent of helical CT scanning has dramatically increased the speed and accuracy of cross-sectional imaging. Consequently, a plethora of new diagnostic and therapeutic indications for CT scanning have developed.[108] With improved software, the grading of solid organ injuries after blunt trauma has been substantially improved and the number of nontherapeutic laparotomies has decreased.[109] No longer do patients with mediastinal widening or other signs of traumatic aortic injury from blunt trauma require aortography to clear the suspicion of this injury.[110] Computed tomography scanning can also assist in clearance of the cervical spine in blunt trauma patients with inadequate plain film radiographs.[111] With thin cuts of the first 2 cervical vertebrae and a complete normal helical evaluation from C1 to T1, many centers will remove an immobilizing cervical collar and decrease the morbidity associated with these devices. Patients with signs of blunt carotid injury at many centers are being evaluated with a CT scan using 3-dimensional reconstruction instead of a 4-vessel arteriogram.[112]

Computed tomography scanning is now also being used to assess intra-abdominal injury in penetrating abdominal injuries. Previously, all transperitoneal wounds were explored with laparotomy. Now, some centers are evaluating stable patients without signs of peritonitis and a low suspicion of visceral injury with CT scans.[113] This strategy has also been employed for penetrating transmediastinal injuries in lieu of arteriography coupled with bronchoscopy and a separate esophageal evaluation.[114] Evaluating abdominal and transmediastinal injuries by CT scans can only currently be recommended in centers familiar with the potential complexity of these injuries and only where 24-hour patient evaluation and intervention are available.

In critically ill patients, CT scanning has decreased the need for more invasive tests in a variety of areas. Helical CT scanning has proved expedient and accurate for the diagnosis of pulmonary embolism and has emerged as its initial test of choice.[115] Unlike nuclear medicine evaluation of pulmonary emboli, the CT scan usually yields a definitive diagnosis and can guide therapy, while being far less invasive than a pulmonary arteriogram.

In neurosurgical patients, percutaneous ventriculostomy with CT guidance has been described in severe brain injury.[116] In this technique, the ventriculostomy catheter can be placed in very narrow ventricles despite substantial brain edema. This intervention has been performed successfully at multiple centers when standard methods of ventriculostomy drainage were not possible.

A new type of CT scanning using xenon enhancement has been used to quantitate cerebral blood flow.[117,118] This technique has been applied to patients with cerebral steal syndrome and at least 1 patient with a traumatic carotid-cavernous fistula in which the area where the blood flow was altered was identified for subsequent craniotomy.[113]

Interventional Radiology

Advances in interventional radiology have improved the treatment of critically ill and injured patients in many ways. Bleeding that is surgically inaccessible and previously required major surgery can now be treated nonoperatively. Selective embolization has been successful in many instances, including gastrointestinal bleeding, retroperitoneal[119] or pelvic hematomas, pancreatitis, intercostal arteries,[120] and craniofacial trauma.[121]

The likelihood of successful nonoperative treatment of liver and spleen injuries has been enhanced by selective arterial embolization.[122] After a CT scan has identified certain hepatic injuries from blunt trauma, some centers would then proceed to hepatic artery embolization to maximize successful nonoperative therapy.[123,124] Some grade V hepatic injuries have required a combination approach with operative packing and interventional techniques.[125] For splenic injuries in stable patients, embolization of patients with an angiographic blush increases the likelihood of successful nonoperative treatment.[126,127] Selective embolization has also been noted to control bleeding from splenic pseudoaneurysms[128] and intrasplenic arteriovenous fistulas.[129]

In certain vessels, embolization is not recommended because the patency of flow is critical to the patient. Interventional techniques have allowed the control of bleeding in these vessels using arterial stenting. A variety of arteries have been stented successfully after traumatic injury, including the coronary,[130] carotid,[131] renal,[132] subclavian,[133] and craniofacial vessels.[134,135] Using similar technology, stenting has also successfully controlled bile duct injuries after trauma.[136]

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