Disruptive technology in the treatment of thoracic trauma

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Abstract The care of patients with thoracic injuries has undergone monumental change over the past 25 years. Advances in technology have driven improvements in care, with obvious benefits to patients. In many instances, new or “disruptive” technologies have unexpectedly displaced previously established standards for the diagnosis and treatment of these potentially devastating injuries. Examples of disruptive technology include the use of ultrasound technology for the diagnosis of cardiac tamponade and pneumothorax; thoracoscopic techniques instead of thoracotomy, pulmonary tractotomy, and stapled lung resection; endovascular repair of thoracic aortic injury; operative fixation of flail chest; and the enhanced availability of extracorporeal lung support for severe respiratory failure. Surgeons must be prepared to recognize the benefits, and limits, of novel technologies and incorporate these methods into day-to-day treatment protocols.

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It is a great privilege to present the Edgar J. Poth Memorial Lecture at the 65th Annual Meeting of the Southwestern Surgical Congress. I have greatly enjoyed my 30 years of involvement with this fine organization and consider it a great honor to give the Poth lecture. Dr Poth, the 16th president of this organization, was an outstanding surgeon and scientist. While many of the topics that I discuss today would be unfamiliar to Dr Poth, I am certain that he would recognize the importance of technological advances in providing outstanding care our patients.

The term disruptive technology has not been widely applied to surgery and medicine. However, this term seems particularly applicable to the impact of new technology on the treatment of surgical patients. The term disruptive technology was first coined in 1997 by Professor Clayton Christensen of the Harvard Business School. He defined disruptive technology as “a new technology that unexpectedly displaces an established technology.” A few examples of disruptive technology may be useful. The introduction of the printing press, the widespread availability of cellular telephones, GPS [Global Positioning System] technology, television, jet aircraft, the computer chip, and many others are examples of new technology that not only changed the world in which we live but rapidly displaced previously successful technological methods.

My purpose today is to discuss a few examples of technological advancement that have, and will, dramatically change the way we treat patients with thoracic trauma. While there are innumerable examples that might be appropriate for discussion, I have chosen to focus on a few advances that I consider particularly significant. These are the eFAST [extended focused assessment with sonography for trauma] examination, the use of thoracoscopy in trauma, the lung-sparing techniques of pulmonary tractotomy and stapled wedge resection, delayed and endovascular repair traumatic aortic disruption, operative fixation of rib fractures, and new miniaturized and simplified models of ECMO [extracorporeal membrane oxygenation].

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technology. Members of the Southwestern Surgical Congress have provided leadership in many of these advances in patient care.

**The Extended Focused Assessment with Sonography for Trauma Examination**

The use of ultrasound has been embraced in the evaluation of injured patients by many trauma surgeons. The FAST [focused assessment with sonography for trauma] examination for detection of fluid in the peritoneal cavity is standard procedure at most trauma centers.2,3 This technological application has largely replaced diagnostic peritoneal lavage and serves as an essential adjunct to computed tomography. The use of ultrasound for the detection cardiac tamponade is widely recognized as a superior method compared to other techniques such as pericardiocentesis and diagnostic pericardial window (Fig. 1). The routine use of ultrasound has facilitated the diagnosis of cardiac tamponade at a point much earlier in the course of patient assessment.2,3 The ultrasound diagnosis of tamponade is frequently made prior to alteration of the patient’s hemodynamic status. This improvement in the diagnostic timeline has permitted a more orderly and planned operative intervention for many patients with cardiac injury. There is little doubt that this technological advance as expedited and improved patient care.

Recently, routine application of the eFAST examination has become more widespread at trauma centers. The eFAST examination utilizes same bedside technology to provide the early diagnosis of pneumothorax.4,5 The diagnosis pneumothorax by ultrasound is accomplished by using a high-frequency ultrasound transducer to examine the anatomic relationship of the pleural interface. In the presence of a pneumothorax, there is loss of the “lung-sliding” finding and the absence of a ring-down or comet-tail artifact (Fig. 2). This technique is learned rapidly and performed quickly. The use of M-mode ultrasound further increases the utility of this technique. Several large series performed at prestigious level 1 trauma centers has validated sensitivity, specificity, and accuracy of this technique. Dulchavsky et al4 showed that there were no false-positive examinations in a series of 382 patients. This group reported a 95% sensitivity for the eFAST examination. Knudtson et al5 documented that surgeon-performed eFAST had a sensitivity of 99.7%, a negative predictive value of 99.7%, and accuracy of 99.4% compared to chest radiography. In summary, eFAST is the premier method for the detection of cardiac tamponade and in some centers is replacing conventional chest x-ray for the diagnosis of pneumothorax.

**Thoracoscopy in Trauma**

Use of minimally invasive techniques for diagnosis and treatment dates back to the 10th century, when Abdulkasim used reflected light to examine the cervix of women. And in the early 20th century, Jacobaeus6 first reported the utilization of “laparothorakoskopie” for evaluation of the pleural cavities. Jones et al,7 at Charity Hospital in New Orleans, provided an early report demonstrating the effectiveness of thoracoscopy in the trauma setting. This group used a rigid proctoscope, under local anesthetic and without endotracheal intubation, to perform examination of 36 patients with traumatic hemothorax. These examinations were performed at the bedside in the emergency department. They found that this simple technique altered the management of 44% of their patients. They were able to achieve hemostasis in several patients with intercostal artery hemorrhage with electrocautery. More recently, a number of groups have demonstrated the benefits of thoracoscopy in evaluation and treatment of injured patients.8–14 As of February
of 2013, at least 120 English-language articles have addressed this topic. Wong et al described 41 hemodynamically stable patients with thoracic injury. This group reported consistent success in the treatment of bleeding from intercostal artery injury, identification and repair of diaphragmatic injuries, and evacuation of retained hemothorax. Ben-Nun et al recently compared the use of thoracoscopy to traditional thoracotomy. This group demonstrated that patients treated with thoracoscopy had less postoperative pain, a shorter recovery period, and were more likely to return to preinjury levels of activity. Milanichi et al reported the successful use of thoracoscopy in 25 injured patients and further reported the use of this technique for the removal of a foreign body, creation of a pericardial window, ligation of the thoracic duct, and lobectomy in addition to previously reported indications. Smith et al recently reported the use of thoracoscopy by an acute care surgery service for the treatment of retained hemothorax, empyema, and persistent air leak. This group appropriately emphasized that utilization of thoracoscopy early in the course of treatment provided improved results.

In summary, the use of thoracoscopy in the trauma setting has both diagnostic and therapeutic utility. In the diagnostic category, thoracoscopy has been useful in determining the cause of persistent pneumothorax, diagnosing injuries to the intercostal arteries, the diaphragm, the heart, pulmonary parenchyma, the esophagus, and the great vessels. Thoracoscopy has been demonstrated as an effective intervention for removal of clotted hemothorax, decortication, treatment of persistent pneumothorax, hemorrhage control, repair of the diaphragm, foreign body removal, drainage of pleural and pericardial effusions, and other indications. In summary, thoracoscopy has largely replaced thoracotomy as front line treatment for persistent pneumothorax, evacuation of retained hemothorax and continued bleeding from intercostal artery aneurysm. The indications for the thoracoscopy in the trauma setting continue to expand.

Pulmonary Tractotomy and Wedge Resection

Penetrating pulmonary injury is associated with the high rate of morbidity and mortality. A recent study performed by the Western Trauma Association multicenter trials group documented progressively more extensive pulmonary resection following injury is associated with a corresponding increase in mortality. Therefore, techniques that achieve hemostasis while preserving the maximal amount of pulmonary parenchyma are desirable. In the past, deep lobar injuries were preferentially treated with major pulmonary resection such as a lobectomy. A major advance in the treatment of pulmonary penetrating injuries was introduction of pulmonary tractotomy by Wall et al in 1994. This group showed that utilization of this straightforward technique facilitated definitive control of bleeding while preserving lung parenchyma. This approach was modified by Asensio et al in 1997. This group conclusively demonstrated that the use of linear stapling devices for tractotomy was not only faster but was equally effective (Fig. 3). Subsequently, the use of linear stapling devices to facilitate the wedge resection was found to be equally efficacious (Fig. 4).

In summary, pulmonary tractotomy is a fast and effective technique for the treatment of deep lobar injuries. Tractotomy allows preservation of lung parenchyma and is associated with lower mortality rates. This technique and wedge resection obviate the need for major pulmonary resection in many patients. This crucial technique should be in the armamentarium of any trauma or acute care surgeon.

Delayed and Endovascular Repair of Thoracic Aortic Injury

One of the most devastating injuries is that of blunt injury to the thoracic aorta. A 10-year retrospective review of autopsy and clinical data reported a mortality rate of 84%. The majority of patients with this injury die at the
Figure 4  Stapled wedge resection of the lung following a gunshot wound.

Scene of the accident or shortly thereafter. However, many patients arrive at trauma centers with stable vital signs. Survival rates of 80% for this subgroup of patients have been reported. It has been appropriately noted that prompt recognition and treatment of this injury results in acceptable rates of morbidity and mortality. In the past, therapeutic approaches included immediate operative repair with interposition grafts. Operative strategies included the “clamp and sew” technique, the use of cardiopulmonary bypass, partial bypass techniques, and heparin-bonded shunts. These open operative procedures, while reasonably effective, were associated with significant complications and mortality. Complications included alarmingly high rates of postoperative paraplegia, recurrent laryngeal nerve injury, and death. A paradigm shift in the treatment of this injury has occurred over the past decade. Demetriades et al18 have recently described this change in philosophy in an observational multicenter trial comparing early versus delayed repair of thoracic aortic injury. In this study of 178 patients, 109 patients received early repair, while 69 patients received a planned delayed repair. An open technique was utilized in 63 patients, while 115 patients underwent a TEVAR [thoracic endovascular aortic repair] procedure. Patients undergoing an early repair at a higher mortality rate (18% vs 4%, P = .034), while patients undergoing delayed repair and longer ICU [intensive care unit] and hospital lengths of stay. No differences noted in complication rates for mortality rates between the 2 groups. Specifically, the rate of paraplegia was equivalent. In 2013, Azizzadeh et al19 compared endovascular repair to open techniques. This retrospective study examined the course of 106 patients. Open repair was formed in 56 patients, and 50 patients were treated with an endovascular technique. Patients treated with an open technique had higher morbidity and mortality rates. An open repair was associated with a 3 times higher odds of complications or death. Patients that received a TEVAR were more likely to have undergone delayed management, a longer length of stay during the preoperative period, and higher costs. This group noted that in the final year of the study (2010), 100% of patients had been treated as endovascular repair. Khoynezhad et al20 recently reported the results of the RESCUE trial. This was a prospective randomized multicenter trial examining 30-day and 5-year outcomes for TEVAR. This study involved 20 different centers, and 50 patients were enrolled over a 2-year period. This group reported an all-cause mortality rate of 8% at 30 days. The TEVAR was successfully deployed in 100% patients. The origin of the left subclavian artery was occluded by endovascular graft placement in 40% of patients. Subsequently, 4 patients required subclavian revascularization for symptoms of upper extremity ischemia. No patients developed either postoperative paraplegia or stroke. Five-year follow-up of these patients is pending, and these results are greatly anticipated. The TEVAR procedure for aortic injury is now preferred by most thoracic and vascular surgeons. However, the long-term complications and outcomes for this technique are not known. Areas of concern include progressive aortic dilation with aging, inadequate stent graft characteristics, stent graft durability, the cumulative radiation exposure secondary to surveillance radiography, and the risk of the necessary treatment of trivial aortic injuries.

In summary, the endovascular repair has largely replaced open techniques in the treatment of thoracic aortic injury. Additionally, strategies involving planned delayed repair have displaced the standard approach of immediate surgical intervention. However, long-term results are needed before open repair is permanently abandoned.

Operative Fixation of Rib Fractures

In the United States each year, more than 150,000 patients have fractured ribs from traumatic mechanisms. In this population of patients, more than one third require hospital admission, primarily for advanced methods of analgesia and significant associated injuries. At least 30% of patients admitted to a hospital due to rib fractures and chest wall trauma developed significant and potentially life threatening complications. The most prominent of these complications are respiratory failure and nosocomial pneumonia. Many of these patients do not recover. Additionally, a significant proportion of patients with rib fractures develop chronic disability secondary to pain. The average recovery from time of injury to resumption of normal activities is 70 days. Approximately 60% of patients with rib fractures develop chronic debilitating pain. Only about 60% of patients admitted with rib fractures returned to preinjury levels of employment and activity. The significance and severity of chest wall trauma is a public health issue that is generally unappreciated by surgeons and physicians of other specialties.

The indications for surgical stabilization of rib fractures are in evolution. Patients with severely displaced and overlapping rib fractures are very likely to develop chronic
pain secondary to rib and pseudoarthrosis and intercostal nerve neuralgia. Until recently, these patients were rarely considered candidates for surgical correction. Anecdotal reports and some additional literature indicates that these patients may benefit from operative treatment. The majority of patients undergoing operative fixation for rib fractures are treated in the acute setting, and the primary indication for treatment is respiratory failure. This group of patients can be divided into several categories. In patients with flail chest and pulmonary contusion, if ventilator weaning is not possible after a period of support of mechanical ventilation, operative fixation of rib fractures may be useful. Additionally, patients who initially do not require intubation but have progressive respiratory decline despite optimal non-surgical therapy, may benefit from operative fixation. Another category of patients that should be considered for operative fixation are those patients with multiple rib fractures that require thoracotomy for associated injuries. Patients that are hemodynamically unstable are not candidates for operative fixation of rib fractures.

Operative treatment of patients with flail chest and multiple rib fractures is not a new concept. A number of techniques and approaches have appeared in the surgical literature for the past half century. These techniques include the use of plates, intramedullary devices such as Kirschner wires, vertical bridging devices including the use of synthetic mesh, and the use of sternal wires for rib fixation. To date, none of these techniques have proven superiority to randomized prospective trials. In fact, most of the previously described techniques have fallen into disuse because of inconclusive results or surgeon dissatisfaction. In the past decade, 2 novel plating systems have been introduced. Both of these systems involve the use of titanium plates specifically designed for the fixation of rib fractures (Fig. 5). The systems have the advantage of ease of use and a very straightforward operative technique. As a result, the frequency of operative fixation of fractured ribs increased exponentially in the last decade (Fig. 6).

Balci et al, 21 in 2004, reported their group’s experience with 64 patients with flail chest who required mechanical ventilation. In this retrospective nonrandomized trial spanning 9 years, 27 patients received operative management, while the remainder received continued medical therapy. The operative group appeared to have improved results outcomes, as evidenced by a decrease in the number of days of mechanical ventilation, a decreased length of stay, decreased morbidity, and decreased mortality. In 1 of the few randomized prospective trials of operative fixation, Tanka et al22 reported their experience with 37 patients with flail chest. In this well-designed randomized trial, all

![Figure 5](image)

**Figure 5** Operative fixation of flail chest.

![Figure 6](image)

**Figure 6** Algorithm for the operative treatment of flail chest.
patients initially received standard medical management, including mechanical ventilation, for 5 days. After 5 days, if patients could not be weaned from ventilator support, they were randomized to either a surgical treatment group or a group that received continued medical management. The surgical surgically treated group was found to have a lower incidence of pneumonia, a decrease in the number of days of mechanical ventilation, a decrease in ICU length of stay, and improved pulmonary functions 1 month after discharge.

Althausen et al.23 recently reported on a 5-year experience with 50 patients with flail chest. In this retrospective study, the mean follow-up was 18 months. Twenty-two patients received operative management based on the assessment and preference of the surgical team that included both trauma surgeons and orthopedic surgeons. Locking plates (2.7 mm) were utilized for rib fixation. The operative group appeared to have better outcomes. The group treated with fixation had fewer ICU days, a shorter period of mechanical ventilation, a decreased length of hospitalization, required tracheostomy less frequently, had a lower rate of pneumonia, were less likely to require reintubation, and had decreased requirements for supplemental oxygen at the time of discharge. This group reported no operative complications.

Slobogean et al.24 recently performed a meta-analysis of operative versus nonoperative management of flail chest. This group reviewed 11 manuscripts that included data from 753 patient records. This analysis appeared to favor operative management. Patients treated with operative fixation had fewer days of mechanical ventilation, decreased rates of pneumonia, a shorter ICU length of stay, a lower mortality rate, a decreased incidence of sepsis, fewer tracheostomies, and decreased chest wall deformity. This group concluded, “Surgical fixation may have substantial benefits, but additional randomized prospective trials are still necessary.”

In summary, there has been an exponential increase in the utilization of operative techniques for the fixation of rib fractures, despite the paucity of randomized prospective trials. This treatment modality may be a good option for patients with chronic pain secondary to pseudoarthrosis or in patients with severely displaced rib fractures. Further randomized prospective trials are sorely needed to delineate the most appropriate utilization of this operative technique.

Advances in Extracorporeal Membrane Oxygenation and Pumpless Extracorporeal Lung Assist

I have had the honor and privilege of visiting the United States military hospital at Landstuhl, Germany, on several occasions. The period of time that I spent as a senior visiting surgeon at this excellent facility is 1 of the most meaningful experiences of my career. The men and women who staff the hospital are the finest group of medical professionals that I have ever had the pleasure of meeting. Landstuhl Regional Medical Center [RMC] is an American College of Surgeons–verified level 1 trauma center and tertiary care facility. Landstuhl RMC has the responsibility of providing state-of-the-art trauma care for our men and women injured in the conflicts in Iraq and Afghanistan, after initial lifesaving treatment is provided in those theaters of operations. During 1 of my visits to Landstuhl, I had the opportunity to review the medical record of a desperately injured soldier who received outstanding treatment, not only during the early phases of care but also during a long distance, intercontinental transport and subsequent definitive interventions. This man had suffered extensive combat-related injuries that caused severe respiratory failure. All conventional approaches to treatment of his respiratory failure had been inadequate and unsuccessful. In an extraordinary effort to save this young man’s life, he was placed on a novel device that provided extracorporeal lung support. After a prolonged course of extensive treatment, including extracorporeal lung support during transport and subsequently at Landstuhl RMC and Regensburg University Hospital, this man recovered from these devastating injuries. This extraordinary care was the result of close and productive collaboration between military surgeons and intensivists and the lung rescue team at Regensburg University Hospital, also in Germany. Without the use of extracorporeal lung support, this patient would have certainly succumbed to respiratory failure. This remarkable case provides an excellent example of the advances in technology that now make extracorporeal lung support strategies feasible in a variety of clinical settings.

ECMO may be described as an extracorporeal device that provides cardiac or respiratory support. The use of extracorporeal membrane oxygenation techniques in the treatment of injured patients began in 1972, when Hill25
first reported the use of this therapeutic modality for a young man with posttraumatic ARDS [acute respiratory distress syndrome]. In the 1970s, ECMO devices were essentially cardiopulmonary bypass machines. Subsequently, in 1977, Bartlett reported the first series of 28 patients with ARDS treated with ECMO. This group of patients included 14 adults and 14 children. In this severely ill group of patients, 5 of 28 survived with support from ECMO. All would have expired otherwise. Unfortunately, an initial randomized controlled trial reported in 1979 did not demonstrate a survival advantage. Since that time, ECMO and related techniques have been used at a limited number of trauma centers for the purpose of lung assist and lung rescue therapy for respiratory failure secondary to trauma, postoperative ARDS, and some influenza strains, such as H1N1. Despite the impressive anecdotal experience of several unexpected survivors, the literature remains inconclusive and up to this time has demonstrated minimal or mixed survival benefit. However, recent technological advances have resulted in simplification and miniaturization of several extracorporeal support devices. For example, the Novalung iLA is a compact gas-exchange system that does not include an extrinsic pump (Fig. 7). In this system, blood flow through the extracorporeal circuit is powered by the patient’s cardiac output and blood pressure. This device is completely self-contained, aside from an external source of oxygen. A polymethylpentene hollow-fiber diffusion membrane provides effective gas exchange. Due to reliance on the patient’s cardiac output, the device is more effective for correcting hypercarbia as compared to hypoxia. The entire system is bonded with high–molecular weight heparin, which prevents clot formation and greatly reduces the need for systemic anticoagulation. Utilization has been further simplified by the availability of percutaneously placed femoral arterial and venous catheters that are usually placed with ultrasound guidance. Devices such as this have led to the concept of pumpless extracorporeal lung support. Other miniaturized ECMO devices with extrinsic centrifugal pumps are now commercially available.

Bein et al recently described the use of portable extracorporeal lung support for the treatment of severe respiratory failure in 10 combat casualties. This collaborative effort from Landstuhl Regional Medical Center and the Regensburg University Hospital provided extracorporeal support for a total of 10 patients, including long-distance aeromedical transport. All of these patients had severe ARDS, and all other conventional interventions for respiratory failure had failed to stabilize the respiratory status of these patients. In addition to extracorporeal lung support, a lung protective ventilator strategy was utilized. In all 10 cases, hypoxia and hypercarbia improved dramatically. The mortality rate for this high-risk group of patients was only 10%. One patient died secondary to multiple-system organ failure. This group concluded that extracorporeal lung support should be considered in severe respiratory failure secondary to trauma.

Haneya et al recently published their initial experience with a portable ECMO device for severe respiratory failure in an adult population. In this series, 22 patients with severe ARDS were treated with this device. In 15 patients, vascular access and initiation of extracorporeal lung support were initiated at the referring hospital prior to transportation to the regional lung rescue center. Lung protective ventilator strategies were used. This group reported an immediate improvement in both hypoxia and hypercarbia in all patients. The median duration of extracorporeal support was 13 days (range: 8 to 19 days). There were no device-related complications, and 73% of patients were weaned from ECMO. The survival rate was 68%. In nonsurvivors, multiple-system organ failure and sepsis were the causes of mortality.

Percutaneous extracorporeal lung assist approaches have also been used to facilitate thoracic operations in patients with severely compromised respiratory function. Wiebe et al reported their experience in 10 patients who required complex thoracic operations but who, because of circumstances such as contralateral pneumonectomy, planned tracheal resection, severe bronchopleural fistula and a contralateral bronchial stump leak, would not tolerate conventional operative or anesthetic approaches. Using extracorporeal lung support, all 10 patients had successful completion of their operative procedures. In 6 patients, there was discontinuation of ventilation during the operative procedure. In the remaining 4 patients, ARDS had made standard ventilatory techniques ineffective. In all cases, hypoxia and hypercarbia were controlled or were improved, even during extended periods of apnea.

In summary, recent advances in technology have resulted in the simplification and miniaturization of extracorporeal membrane oxygenator systems. These advances have, for the first time, provided truly portable extracorporeal lung support capability that is applicable to the interfacility transport setting. Additionally, intraoperative support for complex thoracic operative procedures in patients with severely compromised pulmonary function is a growing reality. Results of recent trials with contemporary ECMO and PECLA [pumpless extracorporeal lung assist] technology are impressive, but not conclusive. The need for additional randomized controlled trials utilizing current technology is obvious. We may be on the verge of an altered paradigm and new treatment algorithms for the treatment of posttraumatic respiratory failure.

Conclusions

Technological innovations and novel applications of existing technology have markedly altered the therapeutic approach to the treatment of common thoracic injuries. Many of these changes were unexpected or unplanned. Surgeons who care for injured patients, through thoughtful consideration, have driven the development of improved methods of treatment. With the accelerated introduction of
new technology, long established paradigms of care are likely to be “disrupted” at an equally rapid pace.

References