Vascular Injury: 50th Anniversary Year Review Article of *The Journal of Trauma*

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The selection of "landmark" articles about vascular trauma from 50 years of *The Journal of Trauma* is difficult because there are so many. The 12 articles selected will not please all but reflect the biases of clinical surgeons who have managed vascular trauma for the past 30 years. We have selected articles that have changed the way trauma vascular surgeons think, make decisions, and practice. The articles selected are intuitively practical and, for the most part, apply simple solutions to difficult problems.

In the 1960s, surgery for wounds to arteries and veins became more commonplace in civilian centers. This followed the pioneering efforts of American surgeons managing the vascular injuries of military personnel injured in combat during the Korean War. The techniques used in Korea were quickly adopted and advanced by civilian surgeons at busy urban centers throughout the United States resulting in improved limb salvage.

A vexing problem became apparent, however, in dealing with injuries to the carotid arteries leading to the brain. Although limbs could withstand a relatively protracted period of interrupted arterial inflow, the same was not true of the brain. And, despite repair of injured carotid arteries, some neurologic deficits did not improve, many worsened and asymptomatic patients occasionally developed deficits or died of cerebral ischemia. The need for more urgent and accurate diagnosis and a better understanding of the cervical and cerebral circulations became apparent. In 1969, Monson et al.[1] from Cook County Hospital in Chicago presented their division of the cervical region into three zones for evaluating and managing carotid and vertebral arterial injuries. Their schema has been widely adopted for management of cervical injuries and appears in every major surgical textbook. In describing their management of 24 patients with injuries to the carotid, vertebral, and innominate arteries, they "arbitrarily" divided the neck as follows: zone I—below the sternal notch and clavicles; zone II—from the sternal notch and clavicles to the angle of the mandible; and zone III—cephalad to the angle of the mandible. They made diagnostic and therapeutic recommendations based on the location of the wound relative to these zones, as well. Zone I injuries should not be routinely explored, and "clinical evaluation should be the primary determinant for exploration in this area."[1] Zone II injuries should be routinely explored. Management of zone III injuries should be "aided by angiographic evaluation."[1] Also, their written discussion provided a summary of the variations in the anatomy of the vertebral artery with references and figures. The discussion of the article at the 28th Meeting of the American Association for the Surgery of Trauma was led by Julian Youmans, a neurosurgeon, who described the classical clinical course of an unsuspected carotid dissection from blunt trauma. Ten years after the report from Monson et al., a recommendation was made to slightly modify the anatomic boundaries of zones I and II. Zone I was expanded to encompass the area below the cricoid cartilage, whereas zone II was narrowed to include the area between the cricoid cartilage and angle of the mandible. This modified anatomic classification is used in some centers. Finally, the recommendation by Monson et al. for routine exploration of zone II injuries continues to be debated, but represents a reasonable default when clinical examination and imaging studies are equivocal.[1]

In the late 1960s, it was commonly reported that cerebral infarction followed urgent revascularization of atherosclerotic carotid stenosis in patients with a fixed or evolving neurologic deficit. Stimulated by this observation, Bradley[2] from Emory University School of Medicine reported on 24 patients admitted to Grady Memorial Hospital in Atlanta, GA, with penetrating injuries to the carotid artery during a 10-year period to determine whether urgent repair in patients with existing neurologic deficits might worsen the outcome. In this report, 14 of the patients had no neurologic deficit after correction of hypotension. Repair of the injured carotid artery was performed in 12 patients, and all did well without neurologic sequelae. In the group of 10 patients who had some neurologic deficit before operation, six died, one had a worsened neurologic deficit, one remained unchanged neurologically, and two improved in the postoperative period. Of the two who improved one had ligation of the injured carotid artery and the other had a repair. Bradley observed that the degree of neurologic impairment before intervention seemed to affect the outcome. "Of seven patients with persistent flaccid hemiplegia or quadriplegia and profound coma, five

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died after repair, one died after delayed ligation, and one survived after immediate carotid ligation."[2] Bradley also surveyed the existing literature and found 184 patients with injury to the carotid artery, but without severe associated injury to the brain or other confounding life-threatening injuries. He found only 15 "with stated preoperative neurologic deficits secondary to cerebral ischemia" in whom it was "possible to determine the postoperative course. Progressive cerebral ischemia after repair led to five deaths. Only four were restored to normal function; the remainder were either unchanged or developed an increased neurologic deficit as a result of surgery."[2] Bradley concluded his article with a scholarly discussion of the importance of restoration of systemic blood pressure in patients with evidence of cerebral ischemia to avoid what we now call "secondary injury." Based on his own series, his literature review, and data from patients with atherosclerotic disease and carotid occlusion, Bradley recommended, ". . . arterial repair of penetrating carotid injuries is definitely indicated in patients without preoperative neurologic signs after any co-existing hypotension has been corrected . . . repair should probably be undertaken in those patients with less severe cerebral lesions manifested by paresis" and that "the risk of hemorrhagic infarction after revascularization in patients with profound neurologic deficits appears prohibitive."[2]

Injury to the superior mesenteric artery (SMA) is rare, and experience with management is limited. By 1972, there were several reports describing repair, but none detailed the amount of ischemic bowel (if any) associated with the arterial injury. On the basis of their experience with eight patients seen at the University of Cincinnati during a period of 16 years, Fullen et al.[3] proposed a classification of SMA injuries based on the amount of intestinal ischemia and the injured anatomic segment of the SMA as follows: grade 1—ischemia was maximal and involved the entire jejunum, ileum, and right colon; grade 2—moderate ischemia involving a "major segment" of the small bowel or right colon; grade 3—minimal ischemia involved a "minor segment"; and grade 4—no ischemia. The SMA anatomic zones were described as follows: zone I—trunk to first major branch; zone II—between pancreaticoduodenal and middle colic arteries; zone III—trunk distal to middle colic artery; and zone IV—segmental branches. The authors recommended rapid resuscitation and perfusion of the distal circulation with the "use of a plastic shunt" while other injuries are repaired.[3] Most importantly, this is one of the first articles that proposed a classification schema of injury severity to compare outcomes. This article preceded the assessment of severity of organ injuries by the American Association for the Surgery of Trauma by 15 years.

The Vietnam War provided an opportunity to advance the management of vascular injuries, but to do so the leadership and foresight of Rich et al. were required in the war zone and at Walter Reed Army Medical Center. They made the observations and recorded the data that would eventually demonstrate that vascular repairs could be successfully performed in austere environments by a large number of individual surgeons. Lt. Col. Rich (at that time) and the 400 surgeons who contributed 4,000 patients to the Vietnam Vascular Registry generated numerous publications on the wartime experience with vascular injuries. In a sentinel publication, Rich et al.[4] reported on the operative management and outcomes of 1,000 arterial injuries. They reported that only 15 arteries were ligated, a remarkable change in the management of arterial injuries that had occurred since World War II and the Korean War. The amputation rate after repair of the 950 major arterial injuries of the extremities was only 13.5%. The authors attributed their success to rapid evacuation, adequate blood replacement, prompt arterial reconstruction, venous repair, wide local debridement, coverage of the vascular repairs, and early fasciotomy. They emphasized the importance of the Fogarty catheter in removing proximal and distal thrombus before repair. Virtually, all these recommendations have been adopted in current practice guidelines.

As expertise increased in the management of vascular injuries, the use of repair rather than ligation was expanded to those arterial and venous injuries that were previously ligated because of the extent of injury to local soft tissue. Rich et al.[4] had described the importance of coverage of the vascular repair with soft tissue so that the anastomosis, the vessel, or the vein graft would not become infected or desiccate, erode, and bleed. To prevent this disastrous complication, Ledgerwood and Lucas[5] from Wayne State University School of Medicine and Detroit Receiving Hospital described the use of porcine xenografts to provide temporary coverage of autologous vein grafts and prosthetic grafts in nine patients with vascular repairs and extensive loss of soft tissue. The xenografts prevented the need for primary wound closure, which might hide nonviable tissue or lead to ischemia because of tension. In his discussion of the article, Dr. William Moncrief (a well-known burn surgeon) suggested using the xenografts to temporarily cover the entire wound—not just the vascular repair. The use of xenografts (or homografts of cadaver skin) to cover major wounds has been applied repeatedly over subsequent years and represents another practical solution to a difficult clinical problem.

The vascular surgeon's mantra for success is "inflow, outflow, and conduit." Because trauma patients are frequently young and without the ravages of atherosclerosis, inflow and outflow are generally not a problem. However, the choice of a substitute vascular conduit remains controversial even today. Autologous vein may be unsuitable for a number of reasons including size, presence of strictures or dilatations, need for ipsilateral venous drainage (when there is an associated venous injury), or urgency. In the 1970s, prosthetic materials such as Dacron had been suggested for use as arterial replacements in injured patients, but there were ongoing concerns about infection because of the interstices in the weave or knit and thrombosis. This objection was overcome with the development of expanded polytetrafluoroethylene (PTFE) vascular grafts. The group at Baylor College of Medicine and Ben Taub General Hospital in Houston had noted that infection and desiccation of exposed vein grafts resulted in life-threatening hemorrhage and had published several reports of the successful use of prosthetic grafts in complex, partially open wounds. Their work culminated in a report by Feliciano et al.[6] on a 5-year experience with PTFE

Figure 1. Exposed 6-mm PTFE graft in superficial femoral artery and 12-mm PTFE graft in superficial femoral vein after avulsion injury of the thigh. Note the packing in the cavity extending down to a femur fracture.[6]

grafts in vascular wounds. From 1978 to 1983, they used PTFE almost exclusively and reported on the outcomes of 206 patients with 236 interposition PTFE grafts—206 arterial and 30 venous (Fig. 1). Prosthetic venous grafts were placed to avoid ligation with subsequent venous hypertension and increased bleeding in patients with large blast cavities. Early arterial occlusions (within 30 days) occurred in 12 grafts—five of which were 4 mm. The authors concluded that PTFE is an acceptable prosthesis for interposition grafting of arterial injuries provided that the graft is 6 mm or larger. They also suggested that "PTFE grafts inserted into proximal extremity veins are excellent temporary conduits, which decrease hemorrhage in blast cavities and fasciotomy sites."[6]

The need for conventional or surgeon-performed arteriography to diagnose peripheral arterial injuries was first questioned by Eric R. Frykberg, James W. Dennis, and co-workers from the University of Florida Health Science Center in Jacksonville in a series of articles from 1989 to 1991. In 1997, Dennis et al.[7] described their 5- to 10-year follow-up on the accuracy of physical examination alone in detecting arterial injuries in penetrating extremity trauma (PET). There were 287 patients with 309 asymptomatic proximity PET wounds, who were evaluated by physical examination alone from 1989 to 1991. Of the 287 patients, four patients (1.4%) returned with "hard signs" of an arterial injury (2 pulsatile masses, 1 pulse deficit, and 1 active bleeding) within 1 week of wounding and underwent successful arterial repair. The authors were able to contact 78 of the remaining 283 patients at a mean follow-up of 5.4 years, and these patients had 90 PET (90 of 305 = 29.5%). None had developed arterial insufficiency or the need for a delayed vascular evaluation or operation during the period since wounding.[7] The authors rightfully concluded that a physical examination alone without arteriography was appropriate screening in patients with PET. In the same article, the authors described the long-term follow-up of 43 patients with 44 clinically occult arterial injuries diagnosed by arteriography and managed nonoperatively. Four injuries (4 of 44 = 9.1%) worsened within the first month of follow-up and underwent successful arterial repair. Follow-up by ultrasonography (17 patients with 18 arterial injuries) or by telephone interview (6 patients with 6 arterial injuries) was completed in 23 of the remaining 59 patients (23 of 59 = 29%). One narrowing of the femoral artery was detected by ultrasound, but all 23 patients were asymptomatic at a mean follow-up of 9.1 years. The authors clearly validated their long-term nonoperative approach to clinically occult arterial injuries and, once again, changed the way minimal arterial injuries were managed around the world.

The value of a Doppler arterial pressure index (API = systolic arterial pressure in the injured extremity divided by the arterial pressure in an uninjured upper extremity) as part of a diagnostic work-up was comprehensively described by Johansen et al.[8] from the University of Washington and Harborview Medical Center in Seattle in 1991. The study analyzed the use of an API of 0.9 as a diagnostic filter in 100 injured limbs (84 penetrating trauma and 16 blunt or other) in 96 patients. There was clinically normal perfusion in 17 limbs, but an API < 0.90, and 16 of these (16 of 17 = 94%) had a "positive arteriographic" finding resulting in seven arterial repairs. There was an API > 0.9 in 79 limbs, and no exclusion arteriography was performed; however, duplex ultrasonography (DUS) was performed in 64 of these as the lead author is a vascular surgeon. Five "minor arterial lesions" were detected in the duplex studies (4 small pseudoaneurysms and 1 profunda arteriovenous fistula), and only the arteriovenous fistula required operative repair. In the remaining four patients with a normal physical examination and an API > 0.9, the arteriograms subsequently performed in violation of the protocol were normal. The authors noted that 88 of the original patients (88 of 96 = 92%) returned for follow-up to the Vascular Clinic at least once after their original evaluation by API. The authors emphasized the accuracy of 0.9 as a diagnostic filter in patients with trauma to the extremities and noted that their need for exclusion arteriography in an injured extremity decreased from 10 per month to 3.2 per month after instituting the use of API. API is now routinely used to determine the need for further diagnostic studies in patients with injuries to an extremity and normal, possibly decreased, or clearly decreased clinical perfusion to a hand or foot.

Another diagnostic modality described in *The Journal of Trauma* during the past 25 years has been duplex ultrasonography (DUS). This modality is commonly used in the evaluation of patients with atherosclerotic occlusive disease of the extracranial carotid and peripheral arteries. In the only experimental study described in this 50-year review, Panetta et al.[9] from the Louisiana State University Medical Center in New Orleans compared arteriography and DUS in evaluating "surgically created" arterial lesions in the femoral and carotid arteries of dogs. Injuries created included 25 arterial lacerations, 24 blunt injuries, 19 occlusions, and 13 arteriovenous fistulas, while there were 19 arteries that were not injured (sham group). After closure of the incision, a vascular surgeon (without knowledge of the presence or type of the arterial injury created) performed DUS. Biplane selective arteriography was performed on the 100 arteries being studied, as well, and the results were interpreted by a staff radiologist. DUS was more sensitive (90.1% vs. 80.2%, $p = 0.002$) and better at identifying injured arteries, whereas arteriography had greater specificity (94.7% vs. 68.4%, $p = 0.04$) and was more accurate in identifying normal arteries ($p = 0.04$). The authors noted that the validity of DUS "increased in the latter half of the study." Because of its ability to detect the specific type of injury, condition of the arterial wall, and hemodynamic pattern, the authors recommend that DUS be evaluated in clinical trials. Subsequent clinical reports in *The Journal of Trauma* and other surgical journals have confirmed the accuracy and cost effectiveness of DUS and the added value of color flow DUS in injured patients. Widespread use of the technique continues to be limited because there is often not a vascular surgeon certified in DUS or a Registered Vascular Technician available in the trauma center 24 hours a day.

The "newest" diagnostic study in evaluating cervical, truncal, or peripheral arteries in injured patients is computed tomography angiography (CTA). Although its use was originally described in patients with possible blunt injury to the descending thoracic aorta and subsequently for evaluating cervical carotid and vertebral arteries, radiology departments in trauma centers have recently adopted the technique for evaluating peripheral arteries. Their enthusiasm is based on evolving CT technology (i.e., 64 slice), the use of CT in evaluating increasing numbers of injured patients, the ease in completing the study as compared with conventional or digital subtraction arteriograms, and the unvalidated accuracy. The recently published prospective trial by Seamon et al.[10] from Temple University in Philadelphia has been of great help to trauma centers considering the adoption of this new technology. CTAs were performed on 22 injured extremities (20 penetrating and 2 blunt) in 21 patients with an ankle-brachial index < 0.9. A "diagnostic" CTA resulted in 21 of the 22 studies, and the result was confirmed by a follow-up conventional arteriogram (#18), operative exploration (#2), or both conventional arteriography and operative exploration (#2). Final results included 11 CTAs demonstrating an uninjured artery, nine arterial injuries, and one arterial vasospasm. The authors stated that the "sensitivity and specificity of diagnostic CTA for the detection of clinically significant extremity vascular injury in our study population was 100%."[10] Less than ideal CTAs occurred in three instances related to problems with an intravenous catheter (#1) or suboptimal dosages of contrast (#2); however, both the latter studies were diagnostic and concordant with a follow-up conventional arteriogram. Of interest, eight of the 22 CTAs that were "limited by shrapnel or bullet artifact" were still accurate when compared with a conventional arteriogram. In addition to the accuracy of CTAs in assessing for arterial injuries, the authors described significant decreases in patient charges (84%) and hospital costs (85%) when comparing CTAs with conventional arteriograms. If confirmed in other prospective studies, the accuracy, ease, speed, and cost savings described with CTA in assessing for peripheral arterial injuries will significantly decrease the use of conventional arteriograms in trauma centers.

The increasing use of temporary intravascular shunts in managing peripheral or truncal vascular injuries was described by Subramanian et al.[11] from Emory University School of Medicine and Grady Memorial Hospital in 2008. Shunts have been historically used in patients with an urgent need to restore inflow or outflow, with multisystem injuries including a major vascular injury, with Gustilo IIIC open fractures, or as part of the preparation for replant of a limb. Their use has expanded significantly as "damage control" operative procedures are now used frequently in near-exsanguinated patients with vascular injuries that should not or cannot be ligated. During a 10-year period, patients with vascular injuries who survived beyond the day of injury or who had a potentially salvageable extremity had 99 temporary intraluminal vascular shunts inserted. Carotid-type arterial shunts were used 78% of the time and thoracostomy tubes in 20% (13 venous injuries and 3 arterial injuries). The most commonly inserted shunt was a 14 Fr Argyle shunt (C.R. Bard, Billerica, MA), and the most commonly shunted vessels were the superficial femoral and popliteal arteries (16 = 53%) and the superficial femoral and popliteal veins (12 = 40%). "Damage control" was the most common indication for insertion of a shunt in patients with penetrating trauma (57%), and patients in this group had a mean base deficit of -13.3. The overall survival rate was 88% with a limb salvage rate of 74%.The authors concluded that temporary shunts should be used liberally in patients with appropriate indications and that anticoagulation was not indicated as only three thromboses occurred (2 SMA and 1 distal brachial artery).

The use of a saphenous vein graft as a vascular conduit to repair 192 extensive arterial injuries in 191 patients was reviewed by Mitchell and Thal[12] from the University of Texas Southwestern Medical School and Parkland Memorial Hospital in 1990. Thrombosis of the saphenous vein graft occurred in 16 patients (8.3%) within 8 days of the original repair, reoperation was performed in 14, and 12 had a "good outcome." Clinical evidence of infection was noted in seven patients (3.6%), and five required amputations. A total of 18 patients (9.4%) required amputations, but 10 were unrelated to the saphenous vein graft. Overall, 87 of the patients (45.5%) had follow-up greater than 3 months after injury and 168 (88%) had no graft-related complication. When the saphenous vein was available and there was not a damage control situation, the authors concluded that "autogenous tissue should still be the primary source of interposition grafts for arterial injuries."[12] Also, they noted the absence of long-term thromboses of the saphenous vein grafts in their extensive follow-up as compared with the higher rate in patients who had small PTFE grafts inserted in other series.

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