History of temporary intravascular shunts in the management of vascular injury

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In 360 BC Plato wrote, "the true creator is necessity, who is the mother of our invention." Warfare by its nature creates extremes of wounding that surgeons have tended to over the millennia. Not surprisingly, it is through war that we have witnessed advances in care in response to this burden of injury. Often, however, the full utility of new operations or devices is not realized during or immediately after the period of initial description. Instead, inventions may be deemed crude or unrefined in the era of their conception and overshadowed by other developments of the day as relative need diminishes. Not until later when a burden of injury, often from an ensuing war, calls for refinement, is their potential realized.

The conception and use of temporary shunts in the management of vascular injury has followed this course over the past century (Fig 1). Few reconstructive options existed before 1950, and an era of necessity bore experimentation with crude intravascular tubes placed with an expectation of thrombosis but a hope that benefit would be gained from development of collateral circulation. The period from 1950 to 2000, in contrast, witnessed a remarkable proliferation of vascular reconstructive techniques. Sporadic use of the vascular shunt in this era was overshadowed by the propagation of all aspects of cardiovascular surgery, including definitive vascular repair. Enthusiasm surrounding this overall progress resulted in a relative lack of need for vascular shunts in trauma. And other than the notable transition from primitive intravascular "tubes" to more favorably designed plastic "shunts," advancement in the use of this technique for vascular injury was quiescent.

With a century of experience managing vascular injury behind them, military surgeons have now been faced with more than 40,000 extremity injuries after a decade of war in Iraq and Afghanistan, and the rate of treatable vascular injury is now five times that observed in previous wars.[1] The nexus of past experience and current injury burden has resulted in an era in which surgeons are attempting to refine aspects of vascular injury management. Specifically, attempts are being made in the current era to look beyond statistical limb salvage to the intricacies of ischemic injury and its effect on the quality of limb salvage. And as in past, the necessity to improve has driven a renewed interest in temporary vascular shunts.

1900-1950: AN ERA OF NECESSITY

Earliest expectations. The history of the temporary vascular shunt is inseparable from the earliest attempts to restore circulation through a disrupted vessel in the first decade of the 20th century. Importantly, the earliest attempts using hollow cylindrical devices in the arterial position were not expected to be temporary. Instead, the original use of prosthetic devices to restore flow through a vessel were intended to be permanent, given the absence of techniques to suture repair or interpose vascular conduit at the time. It was understood that these tubular devices would not remain patent for long periods but instead would function using a strategy of gradual occlusion while collateral circulation developed, hopefully mitigating the effect of acute arterial disruption. It was only as the techniques of vascular repair and bypass were subsequently developed by Carrel, DeBakey, and Linton that the concept of using a prosthetic tube as a removable device became possible.

Intravascular tubes and World War I. Among the first to introduce the principle of nonsuture anastomosis was Payr in 1900 when he published the description of

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Competition of interest: none.

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The editors and reviewers of this article have no relevant financial relationships to disclose per the JVS policy that requires reviewers to decline review of any manuscript for which they may have a competition of interest.

J Vasc Surg 2010;52:1405-9
0741-5214/$36.00
Published by Elsevier Inc. on behalf of the Society for Vascular Surgery.
doi:10.1016/j.jvs.2010.04.060

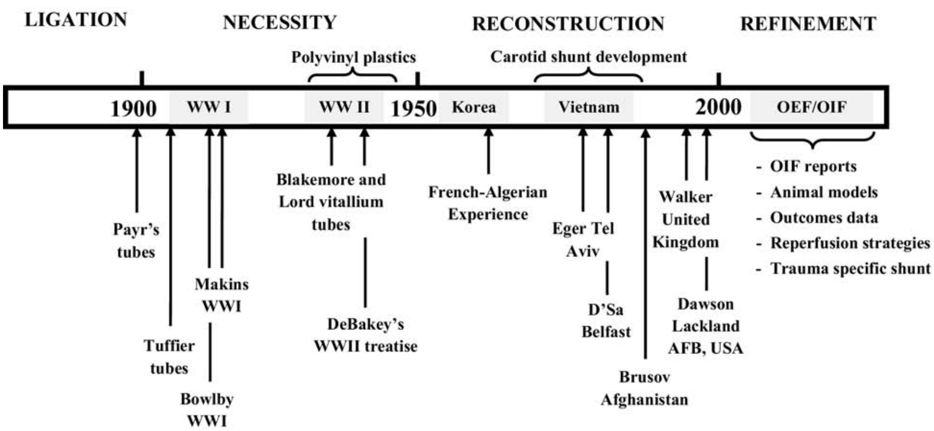

Fig 1. Timeline of temporary shunts depicts the four eras related to shunt development and usage. *OEF,* Operation Enduring Freedom; *OIF,* Operation Iraqi Freedom.

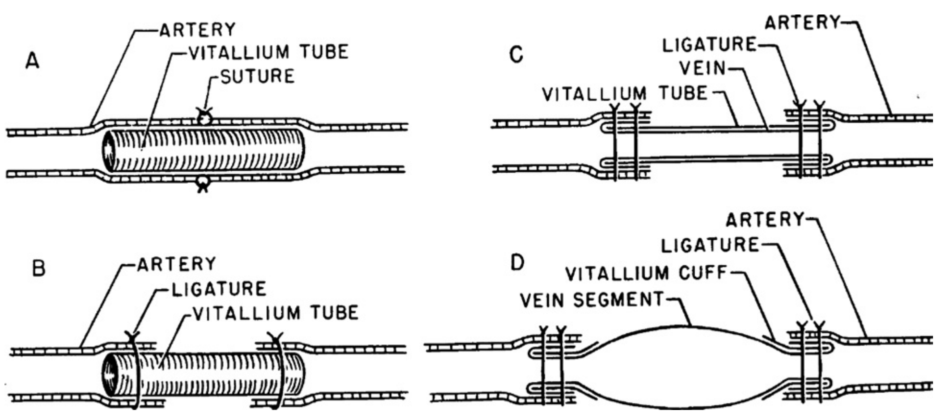

Fig 2. Illustration of the experimental and clinical application of the Vitallium tube techniques used by Blakemore and Lord. (With permission from Wolters Kluwer/Lippincott William and Wilkins; Annals of Surgery, 1945.)

absorbable extraluminal magnesium rings. In 1915 the French surgeon Tuffier described tubes to bridge arterial defects and maintain perfusion.[2] Tuffier tubes were hollow, silver cylinders lined with a paraffin mixture that were inserted into each end of the severed vessel and secured over the ends with ligatures. An early reference to the use of this technique during wartime is Bowlby's World War I account in which he used Tuffier's tubes to bridge arterial injuries.[3] Despite the recognition that these devices eventually occluded, there was benefit anticipated in short-term patency and gradual occlusion with development of collaterals. The expectation was this strategy would decrease the effect of acute arterial occlusion associated with the only alternative at the time, which was ligation. In 1922 Makins published his experiences from World War I and described lasting success with Tuffier tubes in two instances.[4] The tube remained patent for 21 days in one patient, and Makins eventually proposed using this method in acute vascular injury where suture was impractical.

The Payr and Tuffier tubes were inventions of necessity given the lack of options and the recognized severity of outcomes after ligation. Even their unrefined use represents the earliest damage control alternative to ligation. Use of these devices more than 100 years ago also emphasizes recognition of a common premise shared by surgeons today: the need to restore perfusion as early as possible in the setting of vascular injury to reduce neuromuscular damage. Experience with these devices paved the way for the use of flexible tubes made of polyvinyl plastics, invented in the early to mid-20th century.

World War II. Activity exploring the potential of Tuffier's tubes and other vascular conduits was renewed in World War II. In his pioneering work with heparin in 1940, G. Murray used glass cannulae in larger vessels and found that patency could be extended to 24 hours, raising the possibility of tubes being placed to maintain perfusion during casualty evacuation.[5] Arthur H. Blakemore and Jere W. Lord, Jr focused on technique, trying to elucidate the most efficient method by which to repair vascular injuries.[6] In these endeavors, they too experimented with prosthetic tubular devices to, as DeBakey wrote, "bridge the arterial gap by intubation to provide maintenance of blood flow."[7]

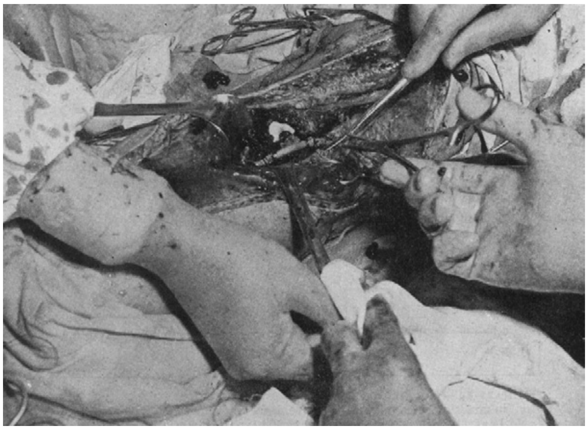

Fig 3. Completed nonsuture vein graft anastomosis of the popliteal artery using the "double tube vein graft technique with Vitallium tube."[7] (With permission from Wolters Kluwer/Lippincott William and Wilkins, Annals of Surgery, 1946.)

Blakemore and Lord compared the Carrel suture method with a Vitallium tube nonsuture technique to bridge femoral artery injuries. Vitallium, a lightweight alloy composed of cobalt, chromium, and molybdenum, was developed in 1932. Initially, the Vitallium tube technique involved a single tube lined with vein graft that had been cut, brought out both ends, and secured to the external aspect of the tube using ligatures (Fig 2). Blakemore and Lord later modified this technique using two short tubes at either end of an intervening segment of vein. This was called the "two-tube method" and, like the single tube, allowed contact of the vein and arterial intima without sutures (Fig 2). The experiments by Blakemore and Lord demonstrated improved limb salvage using the nonsuture technique compared with suture repair and these surgeons eventually recommended an amalgam of both techniques.[6]

During World War II, Vitallium tubes were distributed by the Office of the Surgeon General for use at forward locations and were used in at least 40 cases (Fig 3). Concurrently, British and Canadian surgeons used glass tubes for the same purposes.[7] Charles Stewart also described the need for an alternative method to restore arterial blood flow amidst the Tunisian campaign, where it was observed that popliteal artery ligations resulted in amputation. Stewart used the nonsuture, two-tube approach described by Blakemore with some success and even reported the use of plastic tubing to restore perfusion in one patient with extremity vascular injury.

Despite sporadic successes, DeBakey noted there were drawbacks to the nonsuture technique, including time needed to perform the procedure and the potential to cause injury to normal arterial segments. DeBakey wrote that in some instances, Vitallium tube placement took 3 hours even when performed by "an above average surgeon." And he noted that, "additional arterial substance may be destroyed in the course of attempting to insert the tube."[7] This concern was particularly relevant in an era that preceded use of interposition vein grafts that could be fashioned to a range of lengths, thus allowing débridement of damaged arterial segments.

Although the availability of heparin, antibiotics, and transfusions provided hope that progress could be made in the use of these luminal devices, DeBakey stated well the primary limitation to their use, "To achieve the desired result using these tube techniques, the patients must be seen early, and the current irreducible time-lag makes this impossible in the majority of cases."[7] In World War II, when these techniques were attempted, the average medical evacuation time was 12 to 15 hours, a fact that seems inconceivable today when evacuation to surgical capability often occurs in less than 60 minutes.[1,7]

1950-2000: AN ERA OF VASCULAR RECONSTRUCTION

Transition to the temporary vascular shunt. Rotary wing evacuation during the Korean War reduced the time from injury to operation to 5 hours, which allowed the development of vascular reconstruction in the theater of war. Frank Spencer, Carl Hughes, and others established the feasibility not only of suture repair but also of interposition grafting for vascular injury.[8] Hughes documented this shift from ligation to repair with a notable decrease in amputation rate compared with World War II. Interestingly however, Hughes did not document instances of the use of the previously described nonsuture vascular reconstruction techniques.[9] At about the same time, experience was reported by Daniel Rignault on the use of temporary intravascular devices by the French in the Algerian Wars (1959-1961).[9]

At home, cardiovascular surgery was bourgeoning with remarkable progress in the operative management of age-related disease. Publications appeared reporting the first carotid endarterectomy, aortic aneurysm repair, and vein bypass procedures for occlusive disease in the coronary arteries and lower extremity arteries. These developments were in lock step with the development of prosthetic vascular graft materials as well as polyvinyl plastic and silicone rubber tubing. Within a decade, it was now possible not just to ligate or suture repair an injured vessel but to replace it with an autologous or prosthetic interposition graft. In addition, these advancements made it possible to "shunt" or divert blood from one channel to another with a favorably designed plastic or rubber tube while an intervening segment was repaired or replaced. Although the foundation had been laid decades before, the reality of temporary vascular shunting surely came to fruition in the 1950s and 1960s.

Although the prosthetic temporary vascular shunt was realized, the successes of the day in cardiovascular surgery, including definitive vascular repair, overshadowed study into the shunt's most effective use. Even well-designed shunts by Hushang Javid in Chicago, TM Sundt Jr at Mayo, and others during this era were designed not for vascular injury but instead to maintain perfusion to the brain during carotid endarterectomy.

Military experience. Although the doctrine of vascular reconstruction was extended greatly in Vietnam, the use of temporary vascular shunts was limited. The focus at the time was refinement of definitive vascular injury repair using techniques described only a decade earlier.[9] In 1971, Miklos Eger provided the first detailed account of the use of temporary vascular shunts to treat combat-related injuries at Negev Central Hospital in Beer-Sheba Israel. Eger's report listed potential benefits to the use of this technique and offered a description of vascular shunts used in conjunction with an abbreviated (ie, damage control) operative strategy.[9]

The experience and expertise of Russian surgeons should not be overlooked when surveying the history of vascular shunts. During their experience in Afghanistan between 1981 and 1985, Brusov and Nikolenko reported using 33 shunts in forward echelon damage control situations and 38 shunts at higher echelons of care. This approach resulted in only two amputations, which were attributed not to failure of vascular reconstruction but to the severity of soft tissue injury. Similar experiences demonstrating the effective use of temporary shunts by Russian military surgeons have been reported in the treatment of casualties from the military conflicts in the Northern Caucuses (personal communications).

During the British experience with the paramilitary conflict in Northern Ireland, popliteal gunshot injuries as a result of "knee-capping" were emblematic. Operating at the Royal Victoria Hospital, Belfast, where transport times were short, Borros D'Sa used shunts in vascular injuries to minimize ischemic time.[9] Borros D'Sa also reported the use of shunts in venous injuries and documented an early amputation rate of only 5%.

Building on the experience of Borros D'Sa, Walker, a colleague and United Kingdom military surgeon, developed an animal model to test the patency of shunting before the first Gulf War (Fig 1). Using this model, Walker demonstrated prolonged patency of a heparin-bonded shunt without the use of systemic anticoagulation.[10] Five years later, Dawson at Lackland Air Force Base in Texas reported the 24-hour patency of a non-heparin-bonded carotid shunt in the peripheral arterial circulation.[11]

These studies showed the feasibility of temporary shunts during damage control operations without the need for systemic heparin. This work also opened the door for a strategy that included placement of shunts to maintain perfusion at forward surgical locations as part of abbreviated operations. Despite these and other reports that began to refine the use of vascular shunts, further interest waned because the injury burden from the Gulf War was low and the perceived need diminished.

PRESENT AND FUTURE: AN ERA OF REFINEMENT

The burden of extremity injury resulting from the wars in Iraq and Afghanistan has reestablished a necessity to hone vascular injury management. This fact is made poignant by the positioning of forward surgical teams receiving casualties within a short time after injury and reports that the rate of vascular injury is increased.[1] Unlike in previous wars, however, modern-day surgeons have the benefit of history from which to learn; specifically, decades of work on vascular adjuncts and reparatory strategies. Not surprisingly, this combination of past experience and current injury burden has resulted in a reappraisal of the use of vascular shunts.

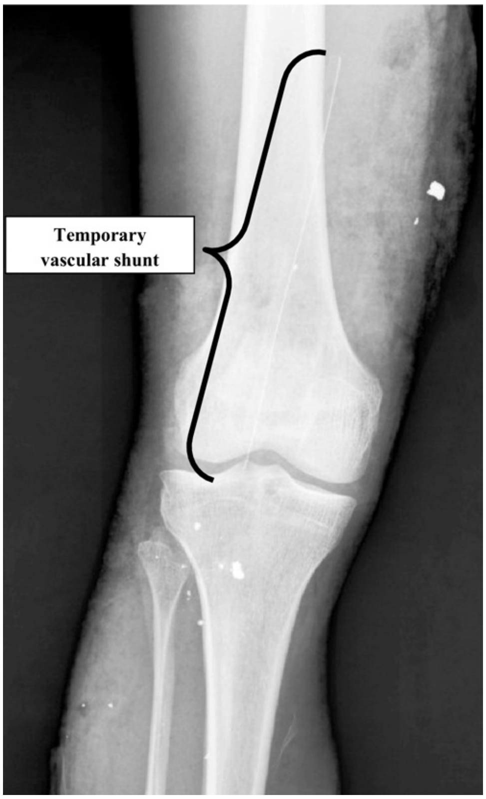

Fig 4. Radiograph of a right thigh and knee with a patent Argyle shunt positioned in the superficial femoral artery. This shunt was placed in early 2010 at a forward level II surgical facility in Afghanistan and was found to be patent and was removed with subsequent definitive repair 3 hours after insertion.

Early reports from Iraq indicated that shunts were being used effectively at forward level II facilities. At such locations, the concept of abbreviated or damage control operating is the intent, keeping surgical time to <1 hour. Specifically, Javid (Bard Peripheral Vascular Inc, Tempe, Ariz), Argyle (Kendall Healthcare Products, Mansfield, Mass), and Sundt (Integra, Plansboro, NJ) shunts were used as part of a triad of vascular injury exploration, thrombectomy, and restoration of flow. Shunts remained in place during medical evacuation to higher levels of in-theater care where they were removed and definitive reconstruction performed.[12] During times of high casualty flow, shunts were used in up to 50% of femoral/popliteal injuries, a pattern that is substantiated today in Afghanistan (Fig 4). Complications have been rare, and patency approaches 90%

at 4 to 6 hours when placed in larger arteries, although longer indwelling times have been observed (unpublished observations).

In an effort to ensure *primum non nocere,* outcomes after the use of vascular shunts have now been reported. Work presented by military surgeons at the 33rd annual meeting of the Southern Association for Vascular Surgery demonstrated that the use of shunts did not result in worse outcomes but, in fact, extended the window of opportunity for limb salvage.[13] Future efforts are focused at refinement of techniques to restore extremity perfusion after injury. Development of a trauma-specific vascular injury shunt is underway, as are studies to evaluate the potential of therapeutic reperfusion to mitigate the impact of ischemia on nerve, skeletal muscle, and bone. With history as a guide, surgeons are well poised to maximize experience gained from these uncommon times to once again advance the management of vascular injury.

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Submitted Apr 19, 2010; accepted Apr 21, 2010.