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Diagnosis and treatment of traumatic vascular injury of limbs in military and emergency medicine
A systematic review

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Abstract

Background: Traumatic vascular injury is caused by explosions and projectiles (bullets and shrapnel); it may affect the arteries and veins of the limbs, and is common in wartime, triggering bleeding, and ischemia. The increasing use of high-energy weapons in modern warfare is associated with severe vascular injuries.

Methods: To summarize the current evidence of diagnosis and treatment for traumatic vascular injury of limbs, for saving limbs and lives, and put forward some new insights, we comprehensively consulted literatures and analyzed progress in injury diagnosis and wound treatment, summarized the advanced treatments now available, especially in wartime, and explored the principal factors in play in an effort to optimize clinical outcomes.

Results: Extremity vascular trauma poses several difficult dilemmas in diagnosis and treatment. The increasing use of high-energy weapons in modern warfare is associated with severe vascular injuries. Any delay in treatment may lead to loss of limbs or death. The development of diagnose and treat vascular injury of extremities are the clinical significance to the tip of military medicine, such as the use of fast, cheap, low invasive diagnostic methods, repairing severe vascular injury as soon as possible, using related technologies actively (fasciotomy, etc).

Conclusion: We point out the frontier of the diagnosis and treatment of traumatic vascular injury, also with a new model of wartime injury treatment in American (forward surgical teams and combat support hospitals), French military surgeons regarding management of war-related vascular wounds and Chinese military ("3 districts and 7 grades" model). Many issues remain to be resolved by further experience and investigation.

Abbreviations: ABI = ankle brachial index, ATLS = advanced trauma life support, FSTs = forward surgical teams, MESS = mangled extremity severity score, PE = physical examination.

Keywords: diagnosis, limbs, traumatic, treatment, vascular injury

1. Introduction

Traumatic vascular injury may affect the arteries and veins of the limbs, and is common in wartime, triggering bleeding, and ischemia. If it is not treated properly, the wounded are likely to be disabled, and even death. Extremity vascular trauma poses several difficult dilemmas in diagnosis and treatment. The increasing use of high-energy weapons in modern warfare is associated with severe vascular injuries. In the Iraq War (at the beginning of the 21st century), the proportion of trauma victims attained 50% to 70%.[1–3] Vascular firearm injuries are associated with hemorrhage and ischemic issues. In the Second World War, patients treated via vascular ligation suffered amputation rates as high as 48.9%.[4] As treatment and vascular prostheses improved, the amputation rates in the Korean and Vietnam Wars fell to 13%.[5,6] In the recent Iraq War, the early amputation rate was only 5% to 10%.[7]

Detection and treatment of vascular injuries should take place within the context of the overall resuscitation of the patient according to the established principles of the advanced trauma life support (ATLS) protocols. Advances in the field, made mostly during times of war, have made limb salvage the rule rather than the exception. Teamwork, familiarity with the often-subtle signs of vascular injuries, a high index of suspicion, effective

communication, appropriate use of imaging modalities, sound knowledge of relevant technique, and sequence of surgical repairs are among the essential factors that will lead to a successful outcome.[7–9]

2. Factors influencing the amputation rate

Gifford et al,[8] studying the Iraq War, found that high-energy firearm injury, measured using an injury severity score (the mangled extremity severity score [MESS]), delayed treatment of venous injuries, and fractures affected the amputation rate.

2.1. High-energy firearm injury

High-speed projectiles damage blood vessels and other tissues more so than do low-speed projectiles.[9] In addition, an inflammatory response is often evident 2 to 3 days after injury, or even up to 5 days after injury if a ruptured blood vessel develops thrombosis or continues to bleed.

2.2. Mangled extremity severity score

The MESS is an objective posttraumatic criterion that predicts the risk of amputation.[10] The MESS considers 4 factors: the extent of damage to bone and soft tissue; the level of limb ischemia; shock; and the age of patient. Whether the MESS effectively predicts the amputation rate remains controversial but most authors consider that the MESS is useful.[8,11,12] Ly et al[12] found that a MESS ≥7 was associated with irreversible necrosis, and (often) a limb amputation rate of 100%. The MESS allows military doctors to carefully inform patients, to develop a comprehensive treatment plan over time, to make the best use the available resources, to form an evacuation plan, and, ultimately, to apply appropriate hospital treatment.

2.3. Venous injury

Earlier, venous injuries were simply ligated, often triggering thrombotic phlebitis and pulmonary embolisms. The risk of acute venous reflux disorders was ignored; amputation often followed. Rush et al[13] repaired 67 venous injuries; 9 patients developed venous thrombosis. Brusov and Nikolenko[14] considered that venous repair not only alleviated limb edema but also improved long-term arterial patency. Gifford et al[8] found that venous repair reduced the amputation rate. Veins should be repaired as soon as possible; ligation remains an option when encountering life-threatening injuries to large veins.

2.4. Additional fractures

About 33% of vascular injuries are combined with fractures, and about 17% with nerve injuries. Fracture is an independent risk factor for amputation.[8] Traditionally, the fracture should be treated 1st, followed by blood vessel repair to avoid further damage to blood vessels caused by the bone manipulations required to fixate the fracture. However, in wartime, this 2-step procedure extends the ischemia time and increases the risk of amputation. Thus, vascular injuries should be repaired 1st, followed by the fractures and any neural damage. When it is imperative to fix a fracture 1st, blood should be delivered via a temporary tube, followed by later vascular repair.[15]

3. Diagnosis of traumatic vascular injury

The blood vessels of all injured limbs should be mapped. Accurate evaluation of clinical status is critical in terms of rapid diagnosis. Most serious limb vascular injuries exhibit "absolute signs" in terms of absent pulses, ischemia, active bleeding, and pulsatile hematomas.[16] Such signs indicate that trauma surgery should be immediate; it is inappropriate to engage in time-consuming auxiliary examinations. "Relative signs" are vague symptoms, including the stabilities of small hematomas, unexplained hypotension, neural damage, and effects on large blood vessels adjacent to the trauma site.[17,18] The clinical significance of such signs should be explored when the emergency has been countered, and a detailed diagnosis made.[19,20]

Delay in diagnosis and treatment can be catastrophic, triggering aneurysms, arteriovenous fistulae, and/or gangrene, rendering it even more difficult to repair blood vessels, and increasing the risks of amputation and physical disability. Therefore, "fast diagnosis and treatment" (within 6–12 hours) is the fundamental principle when dealing with limb vascular trauma,[21] significantly improving survival.

It is essential to accurately evaluate all blood vessel damage to limbs, institute treatment rapidly to ensure the best possible outcome, and not spend too much time or money on auxiliary examinations.[22] Thorough familiarity with commonly used diagnostic methods and their clinical significance is required.

3.1. Physical examination

Prior to angiography, physical examination (PE) will often determine whether surgery is the only treatment option.[23] About 90% of vascular firearm injuries can be confirmed by PE revealing pulsatile bleeding, an expansionary hematoma, palpable tremor, audible noise, and "5P" distal ischemia (pain, paresthesia, paralysis, pulselessness, and pallor). Soft data include moderate bleeding, weak pulses adjacent to the wound, an expansionary hematoma, and peripheral nerve dysfunction.[24,25] Usually, no auxiliary examination is required, but it is important to note that distal artery pulsation does not entirely rule out arterial injury, especially in cases of upper limb trauma.[26] Also, even if no pulse is evident after vascular injury, the blood supply may be normal.[27] In the past, it was thought that "absolute signs" were sufficient to diagnose blood vessel injuries. When the major blood vessels lie remote from the site of injury, PE can exclude such injuries. If the injury is adjacent to the major blood vessels, or if the injury is blunt, a negative PE cannot rule out vascular injury. However, some authors consider that, in most victims, occult blood vessel injury is benign and self-limiting, thus not requiring surgery.[28]

3.2. Ankle brachial index

The ankle brachial index (ABI) is the ratio of ankle blood pressure to that of the upper arm (brachium), and is a very valuable and simple auxiliary datum. The patient must be placed supine, without the head or any extremity dangling over the edge of the table. Measurement of ankle blood pressure while seated will cause the ABI to be grossly overestimated (by approximately 0.3-fold).[29] A Doppler ultrasound blood flow detector, commonly termed a Doppler wand or Doppler probe, and a sphygmomanometer (a blood pressure cuff), are needed. The cuff is inflated proximal to the artery in question. Guided by the Doppler wand,

inflation is continued until the pulse ceases and the cuff is then slowly deflated.[30] When a pulse is redetected by the Doppler probe, the cuff pressure at that point is the arterial systolic pressure. The higher reading of the left and right brachial arteries is generally used in assessment. The pressures in the posterior tibial and foot dorsalis pedis arteries are then measured, with the higher of the 2 values used to calculate the ABI for that leg.

This method rapidly indicates the presence of vascular trauma and any lack of limb blood supply after treatment. Although the noisy environment of wartime renders accurate measurements difficult, this can be overcome by repeated testing, reliably identifying hidden vascular trauma. When the ABI is <0.9, both color Doppler ultrasound and angiography are required, as Johansen et al[11] has emphasized.

3.3. Angiography

Angiography is the "golden standard" for diagnosis of vascular disease, identifying the type and location of vascular injury, lesion size and extent, and any problem with the collateral circulation; treatment can then be planned.[31] However, angiography is complicated, time consuming, and requires special equipment; angiography is thus often reserved for the diagnosis of difficult cases. In addition, the negativity rates of exploratory operations attain 60% to 80%, unnecessarily increasing pain and wasting resources; therefore, the utility of angiography requires reevaluation. Some authors consider that arteriography detects asymptomatic problems adjacent to the injury more accurately than does conventional surgery. The true- and false-negative rates of angiographic surgical exploration are very low, ranging from 0.5% to 5%.[32] Angiography has become one of the important auxiliary diagnostic methods for vascular trauma.

In the mid-1980s, the fact that 95% of angiographic findings were negative when exploring problems adjacent to the injury became of concern. Other auxiliary diagnostic methods were explored. Hornez et al[33] showed that emergency center, percutaneous puncture, hand-push single-frame arteriography (performed in the emergency department or operating room), combined with frame arteriography, was as effective as multi-frame arteriography but much more rapid. When multiple trauma surgeries are required, this method eliminates arterial injuries quickly and accurately.

3.4. Ultrasonic examination

Ultrasound is noninvasive, safe, repeatable, and very flexible, in contrast with other imaging modalities. Blood flow velocities and waveforms are displayed in real time, revealing pathologic changes such as arterial thromboses and occlusions, artery dissection, pseudoaneurysm, and arteriovenous fistulae. Tisherman[26] found that ultrasonic diagnosis of vascular trauma was 98% accurate. A problem is that diagnosis is very subjective. Experienced operators are 96% to 98% accurate; the false-negative rate is 1% to 3%. Ultrasound is also used to diagnose venous injuries, but the sensitivity is only 50%.[34] DeBakey and Simeone[35] found that portable X-ray machines using monolithic imaging technology greatly improved the diagnostic accuracy of vascular injury.

Various diagnostic methods are used in special cases. Ultrasound can replace angiography, diagnosing, or excluding vascular injury in the vast majority of patients. Angiography has a role when noninvasive methods yield ambiguous results, and

for discovering thoracic outlet damage not evident on PE. Surgical exploration is the last resort. The accuracies of the various diagnostic methods are similar; therefore, future research should focus on specific cases to identify optimal methods.[36]

4. Treatment of traumatic vascular injury

4.1. Time window

Speed is critical when treating vascular trauma. Massive bleeding can rapidly trigger shock and endanger life. Lengthy, far-end limb ischemia can trigger necrosis, dysfunction, and even amputation. Rush et al[13] emphasized that muscles and nerves can tolerate ischemia for only 6 to 8 hours. Functional recovery is not ideal, and amputation may be required, if the blood supply is not restored within this time.

4.2. Operative treatment

In 1897, Murphy et al[34] was the 1st to show that vascular injuries could be repaired. However, until the development of antibiotics and blood transfusion technology in the 1950s, simple ligation was the conventional treatment for limb vascular trauma.[37] During World War II, the amputation rate of American soldiers was 35.8% after repair and 49% after ligation, emphasizing the superiority of repair.[38] In the Korean and Vietnam Wars, repair replaced ligation as the preferred treatment, and the amputation rate fell to 13%.[31] Since the 1970s, vascular trauma surgery in civilian hospitals has improved greatly. Limbs are preserved after limb artery injury in >95% of cases. Even popliteal artery damage, earlier often associated with amputation, is now associated with >90% limb survival.[39] The extent of blood vessel damage is often greater than evidenced by PE, and any role for debridement remains controversial. Some authors consider that tissue around high-speed bullet wounds should be removed within a diameter of 1 cm, and that around low-speed wounds within a diameter of at least 3 mm, so that microscopic damage will not compromise blood vessel wall repair.[40]

4.2.1. Debridement. Debridement should be performed before infection develops, thus within 6 to 8 hours of injury. Nano-bashvili et al[41] emphasized that at least 1-cm lengths of injured blood vessels should be removed to ensure high-quality vascular anastomosis. Rich et al[42] suggested that 2- to 3-cm lengths were preferable. However, most surgeons simply remove the visible portions of the vessels.[1,15]

4.2.2. Surgical decompression of the deep fascia. After vascular injury, muscles of the forearms, legs, and other regions develop prolonged ischemia fascia compartment syndrome that may be fatal. Rush et al[13] listed the indications for preventative, deep fascial decompression surgery: blood flow to the ischemic limb is restored later than 6 to 8 hours after injury; a tourniquet is applied for >1.5 hours; soft-tissue injuries are extensive, accompanied by limb edema; venous injury is apparent; and a limb artery experiences long-term low-pressure blood flow. The indications are significantly expanded in wartime: hospital arrival after an ischemia time >4 to 6 hours; any arteriovenous injury; any crush injury; a high-velocity bullet injury; prior vascular repair; prior arterial or venous ligation; coma; a closed craniocerebral injury; epidural analgesia; increased myofascial gap tension; and prior preventative surgery.

4.2.3. Vascular ligation. Prior to the Korean War, arterial ligation was the main treatment for firearm injuries. The operation is simple but the outcomes very poor. Lovrić[43] reported that, during the Korean War, the amputation rate after such ligation was 51.4%, similar to that in the Second World War. Popliteal and femoral arterial ligation was associated with a 70% amputation rate. Ligation is now very rarely used. In emergency situations[44]: double ligation is better than transfixion, avoiding slippage; after ligation, any incompletely fractured artery should be removed, to prevent arterial spasms that may propagate; the artery should be ligated as far as possible from distally open regions of the main branch, thus allowing blood flow through collateral vessels, protecting limb nutrition and survival (thus, after brachial artery injury, ligation distal or proximal to the deep arterial branches is associated with significantly different amputation rates); arterial ligation of vessels of infected wounds should be proximal, and with normal tissue, to prevent secondary bleeding caused by the infection; and the residual blood vessels should be covered with muscle tissue to allow a good blood supply, and to prevent exposure, rupture, and hemorrhage.

4.2.4. Blood vessel prostheses. Blood vessel prosthesis placement is the optimum treatment for vascular injury. The 1st device was developed in 1952, and reduced the amputation rate from 51.4% to 13.0%.[6] Side-wall repair may be accompanied by vascular anastomosis, grafting, and prosthesis placement. Dewitt and Prough[45] reported that the extent of direct anastomosis was 38% after debridement, and about 56% of all damaged blood vessels required prostheses.

4.3. Grafts

At present, it remains controversial whether the autogenous great saphenous vein or artificial blood vessels should be used for grafting. Use of the vein as a graft has a long history, pioneered by White et al[46] in the Vietnam War. However, venous grafts can be placed in only certain places and are short, increase wounding, prolong the operation time, and are not easy to match to targeted blood vessels. Lau et al[47] found that while the early limb salvage rate was higher when a venous rather an than an artificial graft was placed, the cumulative patency and limb salvage rates did not differ significantly, suggesting that artificial grafts should be used for 1st aid or when the vein is not available. However, artificial blood vessels are expensive and exhibit poor histocompatibility. Avery et al[48] reported that about two-thirds of wounds can be treated by placing bypass grafts in the original anatomical locations. However, high-speed bullets often cause soft-tissue damage and are associated with deep exposure. Vascular transplantation in the absence of a good tissue bed and healthy cover, combined with the presence of foreign bodies and pollution, often cause vessel-repair surgery to fail. Extra-anatomical aortic bypass grafting is much more successful. Johansen et al[49] successfully repaired 8 vascular injuries (10–20 cm in length; mean 14 cm) in this manner. As long-term cryogenic vessel preservation is now possible,[40] allogeneic blood vessels can be used to repair arterial defects.[50] After allograft repair, long-term clinical follow-up has shown that the outcomes are excellent.[42] Allogeneic arteries used to repair firearm injuries to the great vessels of the limbs exhibit clear organization; have dense walls; more luminal support than veins; better histocompatibility and flexibility properties; are associated with low

incidences of thrombosis; are easily sutured; afford high success rates; can be matched to the length and diameter of the defect; require no new incision; save operation time; and can even be used as 1st aid. Lovrić [43] used 15 cryopreserved allograft arteries to repair 14 instances of vascular injury, with good outcomes, showing that such repair is feasible. However, few allogeneic libraries are yet available, and the long-term outcomes of such repair require further study.

4.4. Temporary vascular pathways

After wartime blood vessel damage, vascular reconstruction will often not be a priority, attributable to the environmental conditions; a need to 1st fixate a fracture; or the need to perform laparotomy, exploratory thoracotomy, and/or other procedures.[51] Thus, a tourniquet or vascular clamp will be used to initially control proximal vessel bleeding; a vascular shunt rapidly inserted; a Rummel tourniquet or silk employed to ligate the vessel; a temporary blood flow path established; the blood flow restored in a timely and effective manner; and, ultimately, the amputation rate reduced. In the past, various types of vascular shunt were used. Callcut and Mell,[52] using temporary shunt tubes, reported a 23.5% success rate. Rush et al[13] treated 38 patients with silicone tubes or a disposable transfusion apparatus establishing temporary access; the indwelling time was ≤12 hours, and only 2 patients required amputations. Medina et al[15] advocated the use of the Sund vascular shunt tube, characterized by a supporting ring preventing distortion and collapse. A clamped ring-free shunt can be used to treat small injuries when necessary. Early shunt tube techniques varied widely; comparisons are impracticable. Temporary vascular shunt tubes were widely used during the Iraq War, and played important roles in reducing early amputation rates.[1–3,15] Gifford et al[8] retrospectively evaluated patient outcomes. Those of patients who did not receive shunts, or who received interim shunts only, did not differ significantly. However, the cited authors pointed out that those who did receive shunts were more seriously injured than the others, emphasizing the utility of the temporary shunt.

4.5. Nonoperative treatments

Some useful nonsurgical treatments are now available. Angiography has been widely used since the 1970s to evaluate limb trauma, but the clinical utility of the technique remains controversial. Angiography may be overly sensitive, detecting tiny asymptomatic arterial damage. For many years, all arterial anomalies evident on angiography have been repaired; it is widely believed that such damage might cause blood clots that imperil the limbs.

Conservative treatment should be applied only when no "absolute sign" is apparent and angiography is negative. Points that are not "absolute signs" should undergo arteriography and surgery. Neither anticoagulation nor antiplatelet therapy is necessary. If continued follow-up confirms the utility of this approach, the avoidance of unnecessary surgery is of great benefit, especially in patients with multiple severe traumas.[49–52]

5. A new model of wartime injury treatment

Currently, given the predominance of local wars seeking to counter terrorism, the American approach is to form forward surgical teams (FSTs) of 20 persons and combat support hospitals each with 300 personnel. The FSTs are responsible for emergency assistance

and limb-salvage surgery. The French researchers indicated the practice of French military surgeons regarding management of war-related vascular wounds was comparable to those published on the conflicts in Iraq and Afghanistan. Revascularization on the front-line saved limbs and so improved functional prognosis. Reversed saphenous graft associated with prophylactic fasciotomy should be the golden standard technique. Indications for arterial shunts should be more clearly defined. The special training of French general surgeons in vascular traumatology seemed particularly effective. However, it could still be improved as shown by the gaps between implemented practices and those taught. Moreover, this training should be implemented for civilian surgeons as civilians can also be victims of assault rifles and explosive devices even in countries at peace as observed in France during the terrorist attacks of January and November 2015.[51] The Chinese military currently employs the "3 districts and 7 grades" model; most patients with vascular firearm injuries are sent to a unit with the capacity for vascular repair surgery. This may take 6 to 8 hours, compromising limb survival. As vascular trauma increases in modern wars, it is essential to strive toward the "injury without disability or disability without death" goal.

6. Conclusion

No matter in military or emergency medicine, in summary, the key factors in successful management are optimal sequence of the repair, adequate exposure and vascular control, debridement of the injured vessel wall to healthy intima, proximal and distal balloon catheter thrombectomy, tension-free end-to-end repair or appropriately sized interposition graft, good soft-tissue coverage, stable but expeditious fracture fixation, and adequate fasciotomies.[52,53] Incisions for fasciotomies or vascular control should preserve perforating vessels, taking into account the future potential need for fashioning flaps for soft-tissue coverage. Finally, a bed in the intensive care unit ideally should be reserved for early postoperative monitoring.

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