The Role of Microsurgery in Pediatric War Injuries

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Reem A. Karami and Amir E. Ibrahim

12.1 Introduction

War is among the 10 leading causes of death in children around the world. More than 6 million children have been injured or permanently disabled by war over the past decade [1]. Children are particularly a high-risk population for injury due to inherent physical and physiologic vulnerability [2]. It is unfortunate that these injuries are not only civilian injuries but sometimes military injuries. Children are often recruited for military duty due to their helplessness and emotional immaturity [3].

Like adults, children are prone to penetrating vascular injuries, head and neck injuries, and injuries to the thorax and abdomen. Injury to the extremities remains to be a very common form of injury in war [4]. Limb injury has implications for a growing child increasing the need for revision surgery compared to adults. Battlefield trauma and war injuries are significantly different than civilian trauma. These injuries usually cause extensive soft tissue defects, bone fractures, and injury to nerves, tendons, and vessels that pose an overwhelming reconstructive challenge. The surgeon needs to account for wound contamination and large zones of injury with extensive microvascular compromise [5].

Over the past decade, there has been a paradigm shift in trauma care. With better damage control to stabilize critically injured patients, more wounded patients are being evaluated for reconstruction. This improved survival rate, in the setting of increasing severity of injuries, has contributed to an increase in the complexity of the wounds. This translated to an increase in the complexity of treatment modalities in war injured patients [6]. The reconstructive surgeons are often faced with extensive wounds and significant soft tissue and bone loss which drives them to consider procedures that were previously concerning. The aim of treatment no longer focuses

R. A. Karami · A. E. Ibrahim (✉)
Department of Surgery – Division of Plastic and Reconstructive Surgery, American University of Beirut Medical Center, Beirut, Lebanon
e-mail: ai12@aub.edu.lb

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solely on life, but a functional reconstruction is becoming a more feasible and realistic endpoint [7].

With advances in microsurgical practice, the role of free tissue transfer in ballistic trauma is rising. This reconstructive option is able to cover large defects with well-vascularized tissue in a single procedure. With microsurgical procedures, open fractures can be covered, enabling a faster recovery and preserving future limb function. A major advantage is that it allows for the transfer of unharmed tissue distant from the zone of injury [8]. The problem is that in a war scenario, it may be difficult to access a surgical service and equipment to perform these procedures. But even in a low-resource setting, a skilled surgeon should be able to perform these procedures; this is where experience becomes extremely relevant [9].

While free tissue transfer is established in the adult age group, its application in the pediatric age group is somehow recent. Anxiety over the feasibility of microsurgery in children remains. There is concern about small vessel size and vasospasm making the anastomosis more difficult and increasing flap failure rates. Limited donor site and donor site morbidity and growth implications should also be considered [10]. Ballistic trauma and subsequent injury to the microvasculature further add to this anxiety. Nevertheless, over the past decade, pediatric microsurgery has proven to have high success rates, making it a reliable reconstructive option [11].

12.2 Location of the Defect

Understanding the injury pattern and characteristics of the ballistic trauma will help guide the clinical decision in the form of reconstruction to be used. It is understood that head and neck trauma is an extremely common war injury in the pediatric age group. This is followed by extremity trauma, and thoracic and abdominal injuries [4].

12.2.1 Upper Extremity

The most common form of injury that might necessitate microsurgical reconstruction is extremity injuries. Compared to adults, children have a higher rate of upper extremity injuries. These vary from simple fractures to more complex traumatic amputations [12]. Mangled upper extremities are particularly challenging. Mutilation of the extremity with high-impact trauma, blast, and crush is associated not only with bony fractures but also with extensive soft tissue loss. Due to the severity of these injuries, microsurgical tissue transfer is often required not only for coverage but also to ensure a good functional outcome. Limb salvage is not the only concern here. Attempts at a functional limb restoration should be fully exhausted [13]. Prior to the era of microsurgery, preservation of mangled upper extremities

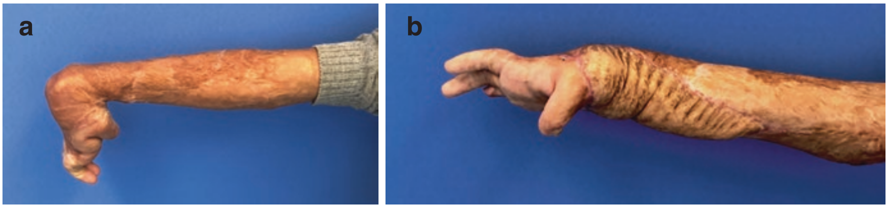

Fig. 12.1 (**a**) A 13-year-old boy with severe wrist contracture. (**b**) After release, wrist fusion, and reconstruction

was not a possibility. With the refinement of surgical technique, a more sophisticated reconstruction is possible (Fig. 12.1). Free flaps can be designed to include multiple types of tissue. Functional muscle transfer has a definite role in the restoration of upper extremity function, especially for recovering finger, wrist, elbow, and shoulder flexion and extension. This can be achieved by the transfer of innervated gracilis of latissimus dorsi flaps [14, 15].

12.2.2 Lower Extremity

Lower extremity injuries are less common than in adults and are mostly seen in landmine strikes [4]. As a general concept, the lower leg has a paucity of soft tissue and so tolerates trauma poorly. Trauma to this area inadvertently leads to soft tissue loss often needing free tissue coverage. The need for free tissue transfer becomes more imminent in cases of Gustilo type IIIB and IIIC open fractures. Conversely, the thigh has a good amount of muscle and soft tissue which allows for local flap coverage as opposed to free tissue transfer [16]. The foot and ankle also need special consideration as they are not amendable to reconstruction with grafts, especially in young children because of the need for weight bearing and free movement of joints and tendons. Local flaps in the foot are small in size rendering them inadequate for coverage of larger defects [17].

Another important issue with the lower extremities is bony growth. Injury to the growth plate is often problematic creating various degrees of growth disturbances. Limb length inequality and angular deformity are sequelae in the future. This issue is further ameliorated in younger children rather than adolescents because of more years of continued growth. Therefore, preservation of the growth plate becomes essential. Microsurgical physeal transfer, even though difficult to achieve, is necessary to allow for longitudinal growth [18].

Complex lower extremity reconstruction requires proper preoperative planning. Even though a single-staged reconstruction is ideal, it may not be practical depending on the situation.

Finally, in the setting of traumatic amputation, free tissue transfers are used to cover the amputation stump. In a growing child, skin grafts and local flaps for stump closure are less optimal choices, as they frequently require revisions. Reliable and durable coverage is the epitome to help improve the quality of life of the patient and decrease ulcerations and complications of the stump [19].

12.2.3 Head and Neck

The vast majority of microsurgical reconstruction of head and neck defects occur after the oncologic resection of neoplasms. There is a limited role of free tissue transfer in traumatic head and neck reconstruction [20].

Most large traumatic head and neck defects in a war setting are actually the result of major burns. Although skin grafts, local flaps, and pedicled flaps are the mainstay of burn reconstruction, they have their limitations in certain anatomic areas [10]. This is readily apparent in anterior neck defects. Anterior neck burns can be covered by skin grafts or by skin substitutes. But often in children, normal skin grows faster than these grafts increasing the risk of contracture and subsequent failure of the reconstruction. Free tissue transfer allows versatile and pliable tissue to be introduced into a heavily burned area. The aim of the reconstruction here is not only to restore esthetic appearance but to also maintain function and range of motion [21].

Even though the majority of free flap reconstruction of burns is used in the delayed setting, for contracture release, its use in the acute setting is also doable. In cases of exposed vital structures such as nerves, vessels, bone, and cartilage, free tissue transfer becomes essential. In addition, early coverage will decrease morbidity, and hospitalization time and will allow for earlier rehabilitation and an eventual better functional recovery [22].

The downside of microsurgical tissue transfer in head and neck reconstruction is the inability to bring in thin tissue with similar thickness to the native facial skin (Fig. 12.2). Prelamination and prefabrication of flaps have been proposed to deal with this issue, but unfortunately, this is not possible in the setting of acute war injuries.

12.2.4 Thorax and Abdomen

The role of microsurgery in the reconstruction of chest and abdominal defects in the acute setting is limited. Due to the abundance of local tissue and muscles, the majority of defects can be closed by pedicled myocutaneous flaps with or without synthetic mesh. Free tissue transfer is infrequent and reserved for situations where no local options are available or in cases of local flap failure [23]. It may also be used in areas where pedicled flaps reach with difficulties, such as the lower thorax and upper epigastric areas. The paucity of local tissue and the ribcage rigidity make local flap mobilization difficult [24]. In general, free tissue transfer is mostly done as a delayed form of reconstruction and is rarely used in the acute war setting.

Fig. 12.2 (**a**) A 10-year-old boy with severe neck contracture. The patient had undergone multiple previous release and skin grafting, intralesional steroid injections, and CO_2 laser resurfacing. (**b**) Inhibited full neck extension. American University of Beirut Medical Center, (**c**) After release and reconstruction with a free fasciocutaneous ALT flap. (**d**) Full extension achieved

12.3 Timing of Reconstruction

The timing of reconstruction has long been a controversial topic. The controversy is even more when considering pediatric patients. Godina's landmark paper in 1986 suggested that early flap coverage, within 72 hours, improved outcomes. Coverage in the subacute period, 72 hours to 90 days, had the highest complication and flap failure rates [25]. Three decades after Godinas work, with advances in wound management and microsurgical technique, it seems that reconstructions in the subacute period have an improved success rate. Many studies show that the initial acute period can be extended to 10 days [26]. This is especially important in a war setting since it is not always possible to operate early on. It takes time to transfer patients from the combat zone to a well-equipped trauma center. While the patients await transfer, temporizing interventions such as negative pressure wound therapy can be installed. This influential tool in reconstructive surgery has significantly improved since the time of Godina and has aided in the care of traumatic wounds [27]. If the setting allows, early emergent free flaps can also be an option. This approach will decrease hospital stay, the future need for revision surgeries, and most importantly shortens the period of immobilization [28].

All of these studies were done on adults. The data can be extrapolated to the pediatric age group. The rate of flap loss and flap-related complications in pediatric patients was also lower if the reconstruction was performed within the first 7 days of injury [29]. The basic principle is the same. It is universally accepted that aggressive early debridement, external fixation, early soft tissue coverage with well-vascularized tissue then delayed bone reconstruction are the gold standard. Selecting the proper time for coverage depends on interdependent local and general factors. Surgeon experience and surgical team preparation also play a role.

Delaying reconstruction in the lower extremity is tolerated much better than in the upper extremities. In the upper extremity, prolonged immobilization will probably result in joint stiffness and tendon adhesions. This is why earlier reconstruction is recommended in upper extremity reconstruction [30]. In any case of delay, extensive physical therapy and mobilization should be done to maintain joint motion.

12.4 Choice of Flap

12.4.1 Myocutaneous Flaps

Myocutaneous flaps are ideal when you are reconstructing a large three-dimensional defect. Muscle is able to provide bulk to obliterate dead space. It is also extremely well vascularized and is indicated in heavily contaminated wounds where they provide better antibiotic delivery and better control of bacterial inoculation [31].

The most commonly used free muscle flap in children is the latissimus dorsi (LD) [32]. The LD is a reliable muscle with a reliable blood supply and little anatomic variation. The thoracodorsal artery is of good caliber even in smaller children. The pedicle is also long providing some flexibility in surgery and most importantly allowing the anastomosis to be performed outside the zone of injury without the need for vein grafts [33].

An important thing to be taken into consideration is donor site morbidity. Even though many report no donor site morbidity with the LD, others opt for partial muscle harvesting. Complete removal of the latissimus dorsi muscle may impact chest and shoulder development causing shoulder imbalance. This is why partial preservation of the muscle might be somewhat beneficial [34].

The second most commonly used muscle flap in pediatrics is the rectus abdominus muscle. Again, reasons for its use include consistent and familiar anatomy. The downside is donor site morbidity [35].

The musculocutaneous anterolateral thigh flap, including the vastus lateralis muscle, is also a workhorse flap. The main advantage is easy harvesting and low donor site morbidity. Harvesting can be done in the supine position, limiting the need for repositioning and subsequently operative time. It has a long pedicle with large-sized vessels [36]. Most importantly it can be used as a flow-through flap, which can be useful in cases of ischemic limbs with significant soft tissue loss. The flap can be used to re-establish distal flow and provide coverage at the same time [37].

12.4.2 Fasciocutaneous Flaps

As microsurgical practice is progressing, there has been a shift from concerns about flap survival to concerns about donor site morbidity. When the conditions allow, the use of fasciocutaneous flaps and perforator flaps is advocated. Fasciocutaneous flaps are used for coverage of superficial wounds where no bulk is needed. They are also useful in contour resurfacing. They can be tailored to the defect size. Most importantly they provide an excellent surface for gliding tendons and joints. This is especially important when staged reconstruction is planned; they are easily reelevated to allow tendon transfers and bone grafting [38]. In children, the most commonly used fasciocutaneous flaps were the radial forearm, the groin flap, and the scapular and parascapular flaps [32].

In pediatric patients, fasciocutaneous flaps are associated with a higher rate of debulking surgeries, especially when used to reconstruct foot and ankle defects [17]. Ultimately the reconstructive surgeon must be capable of performing both musculocutaneous and fasciocutaneous flaps depending on the indication.

12.4.3 Perforator Flaps

Microsurgical procedures in children are difficult as is without including the tedious perforator dissection. Many surgeons shy away from perforator flaps in pediatrics. Recent studies show that perforator dissection does not add substantially to the difficulty of the case or duration. Therefore, if one takes into account the decreased donor site morbidity perforator flap becomes a reasonable option [39]. Therefore, the question is no longer whether or not microsurgical procedures can be performed in children, but rather which donor site is the least morbid yet is still able to fulfill the needs of the wound and the patient [40].

Perforator flaps have plenty of advantages including having a sizable source vessel (Fig. 12.3). Proper dissection also provides long pedicle length allowing the

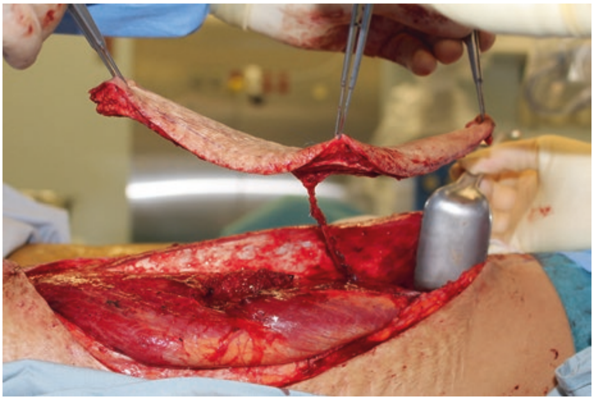

Fig. 12.3 Fasciocutaneous ALT flap based on one perforator

anastomosis to be performed outside of the zone of injury. As in adults, these are very reliable flaps that are often the primary choice in soft tissue reconstruction. The anterolateral thigh flap, the thoracodorsal artery perforator flap, and the deep inferior epigastric artery perforator flap were among the most commonly used flaps [32].

12.4.4 Bone Flaps and Physeal Transfer

In a war zone, the main initial concern is wound coverage rather than bony reconstruction. Management of bone loss in mangled extremities continues to challenge the reconstructive surgeon. Different practices have been described to manage these severe open fractures. Most commonly, early aggressive debridement, skeletal stabilization with an external fixator, and early wound coverage with a flap followed by staged bony reconstruction is performed [8]. Another less popular alternative is a single-staged reconstruction. This has the advantage of a single surgery proving structural stability and promoting a faster bony union. Because the procedure is done early, vessel scaring and inflammation is prevented. With better quality vessels the microanastomosis should become easier [41].

The ideal bone should be vascularized providing osteoinductive, osteoconductive, and osteoprogenitor elements. The vascularized fibula is the most commonly used bone. It can be used to reconstruct long bones and head and neck defects. The resorption rate is relatively low, it provides good strength and should resist infection [42].

Special consideration in pediatric patients is growth. In case of any injury to the growth plate lack of symmetric growth will lead to limb length discrepancy and progressive functional impairment. Vascularized physeal and epiphyseal transfer is possible and allows the potential for future longitudinal growth [43].

The need for flap debulking in general has decreased with the use of thin perforator flaps. Nevertheless, in areas where the native skin is thin such as the hand, foot, anterior leg, and the head and neck area flap debulking becomes essential. The two most common methods for that is direct excision and liposuction, both of which if performed properly and at the correct timing, could be safe procedures [44].

12.5 Radiographic Evaluation

With the extraordinary advances in the field of radiographic imaging, it has become part of the routine practice to obtain preoperative imaging assessment in reconstructive microsurgical cases. Particularly, computed tomography angiography (CTA) has been increasingly employed. Magnetic resonance angiography (MRA) is also another option, with less exposure to both intravenous contrast and radiation [45]. Other sound options are ultrasound and the handheld doppler [46]. In a conflict zone where resources are limited these two options may come in handy.

Generally speaking, preoperative imaging will help map perforators and subsequently shorten operative time and increase the efficacy of flap harvest. Specifically, for high-energy trauma patients, imaging becomes essential to assess not only perforators but recipient's vessels. Screening for arterial injury and aneurysmal pathologies is essential [47].

12.6 Vessel Size and Vasospasm

Surgeons were initially hesitant to perform free flaps on pediatric patients due to the minute vessel diameter and vessel spasticity. Initially, Gilbert suggested that the minimum diameter to perform a safe microanastomosis was 0.7 mm, stating that smaller vessels will create a technical limitation [48]. With skill improvement and the development of ultradelicate microinstruments, supermicrosurgery is being done on vessel sizes between 0.3 and 0.8 mm [49]. This means that surgical technique is not as challenging as it once was. The initial concerns of feasibility fade away. Another important thing is that the relative size of the pedicle vessels compared to the size of the body is larger in children than in adults [39]. This is why body mass index should be considered rather than just chronologic age [35]. Perhaps it is not only the vessel diameter that matters. Pediatric patients inherently have thinner vessel walls making anastomosis more demanding [50].

The true issue with pediatric microvasculature is spasms. Vasospasm is vasoconstriction of the vasculature that can be encountered anytime during the microanastomosis, which is resistant to mechanical dilatation and causes a significant reduction of blood flow [51]. Pediatric vessels are more prone to spasms and so vessel dissection should be kept as minimal as possible to avoid any vessel trauma [52]. Others suggested harvesting a cuff of muscle with the perforator during perforator dissection to minimize vasospasm [17].

It is also reasonable to use local vasodilators such as papaverine and lidocaine. It is really important to control body temperature and pain post-op to help decrease vasospasm [53]. An upside to pediatric vasculature is that since pediatric patients do not suffer from atherosclerosis, peripheral vascular disease, hypertension, diabetes, and smoking, their vessels are pristine and ideal for free tissue transfer [54].

The problem with traumatic war injuries is that often the vasculature is damaged because of the high-energy trauma. This is why it is recommended to perform the anastomosis outside of the zone of injury. There is an inflammatory response in the surrounding soft tissue beyond the margins of the wound that result in perivascular changes in the blood vessels. There is clear-cut margin for the zone of injury at it is difficult to define but it is generally recommended to do an extensive proximal dissection [55]. A tool that might help assess the quality of the vessels is a visual assessment of pulsatile flow [56]. If the pedicle is not long enough, vein grafts may be needed to help stay outside to zone of injury.

12.7 Anesthesia Time

Without question, microsurgical procedures have a long operative time. The time does differ substantially from adults. Because of the heterogeneity of the cases, it is difficult to give an average operative time. Simple fasciocutaneous flaps will take less time than cases that require bony reconstruction [54].

Children can tolerate anesthesia as well as adults. Even though some reports show that increased anesthesia time in pediatrics might have an effect on developmental and behavioral disorders, no conclusion could be drawn about causality [57]. Laryngospasm and airway complications are also something to consider in pediatric patients undergoing prolonged general anesthesia [58].

In the combat zone, where resources are limited, the use of regional anesthesia can be cost-effective. Regional anesthesia is safe and offers the benefit of intra- and postoperative pain control. Specifically, in cases of free tissue transfer, with regional block, there is an increase in circulatory blood flow, maintenance of normal body temperature, and a decrease in the systemic stress response [59]. All these factors improve inflow to the flap and could help decrease vasospasm.

A combination of general and regional anesthesia can be done. When the effect of general anesthesia is over and systemic neurogenous stimuli increase in the early postoperative period, it is wise to have regional anesthesia control to decrease pain and vasospasm [60].

12.8 Flap Outcomes

Reports about flap success rates in children in the literature range between 62 and 100%. The most common cause of flap failure is venous and arterial thrombosis, followed by kinking of the pedicle and vasospasm. Overall flap failure rate averages at 5.01% [61]. This is slightly higher than failure rates in adults which average at 3%. In cases of reexploration, flap salvage occurs on average in two out of three cases explored, which is comparable to the adult population [50].

Without a doubt, microsurgical tissue transfer after blast injury has higher complications than straightforward flaps for all of the above-mentioned reasons. Controlling a number of factors can help improve flap outcomes. The pearls of a successful reconstruction are early aggressive debridement and staying away from the zone of injury. In general, the surgeon must be comfortable with performing flaps in trauma patients. Properly selecting a flap that the surgeons are comfortable with is also crucial.

12.9 Postoperative Anticoagulation

The routine use of anticoagulation postoperatively is controversial. Although over the past 30 years microsurgeons have been using anticoagulation the protocols vary widely. Even though numerous studies have attempted to come up with a protocol, no singular method has been proven to be effective [62]. The use of intraoperative heparin irrigation seems to have a positive effect on the flap with minimal risk to the patient. By consensus, thrombolytics are used in case flow is not immediately reestablished or in case of a difficult anastomosis where revision was needed. Postoperative treatment with aspirin or heparin remains to be controversial [63]. Some authors advocate the use of systemic prophylactic heparin, stating that it might have a role in decreasing postoperative thrombosis [64].

With the current data, an evidence-based decision cannot be made. It remains that surgical technique is the main factor that will affect the outcome. The use of anticoagulation to complement the anastomosis is a matter of personal choice and experience.

12.10 Complications

When considering at the success rate of free tissue transfer, it is not only flap survival that matters. It is important to look at the complications and assess the quality of life improvement. Complications in general can be divided into early and late in terms of timing. Another way to look at things is minor and major complications with respect to the overall outcome. In general, trauma patients have a higher rate of complications as compared to post-oncologic and congenital reconstructions [54].

12.10.1 Early Complications

Other than flap failure, early complications include partial flap loss, tip necrosis, hematomas, infection, and osteomyelitis. Partial flap loss and wound breakdown are often treated with debridement and local wound care. Wound infection is a common complication in this category of war trauma patients [65]. Whether soft tissue infection or osteomyelitis, early debridement, and coverage are critical for prevention. In case infection develops post-op, the initial treatment is aggressive antibiotic therapy [66]. Soft tissue reconstruction has a crucial role in the healing of the severely injured lower extremity. Even though initially it was thought that muscle flaps are more vascularized and so a wiser option for fighting infection, more recently it was shown that fasciocutaneous flaps have a similar efficacy [67].

12.10.2 Late Complications

Chronic osteomyelitis with sinus tract formation, bulky flaps, pressure ulcers, hypertrophic scarring, and limb length discrepancy are all late complications of free tissue transfer. In general flaps to the foot have a higher complication due to the inherent anatomic location [61]. The location of the foot puts it at increased pressure from both ambulation and weight bearing and from footwear, making it more prone to developing pressure ulcers [52].

Chronic osteomyelitis is a complex entity to treat. It happens to be common in post-traumatic injuries with reported rates between 4 and 64%. Even though a single-staged procedure is ideal, frequently multiple debridements, local and systemic antibiotic therapy, and dead space obliteration with vascularized tissue are the standard [68].

The need for flap debulking, in general, has decreased with the use of thin perforator flaps. Nevertheless, in areas where the native skin is thin such as the hand, foot, anterior leg, and the head and neck area flap debulking becomes essential. The two major methods for that are direct excision or liposuction, both of which if performed properly and at the correct timing, could be safe procedures [44].

Overall, late complications can be avoided with careful preoperative planning and attention to detail.

12.11 Special Consideration: Below the Age of 2 Years

Younger children below 2 years of age pose a special challenge. The decision to proceed to free tissue transfer in this population weighs heavily on both parents and surgeons. It is important before embarking on these procedures to speak to the parents and allow them to be part of the decision-making process because any failure of the flap will leave the child with a donor site defect that will be present for the rest of their lives.

There is a paucity of reports about free tissue transfer in children below the age of 2 years. In one series, it was reported that the vessels of these younger children are not more delicate than those of older children. The success rate was reported at 98% putting surgeons more at ease for performing these procedures [69]. Again, flap survival depends mostly on surgeon technique and skills rather than vessel size.

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