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EXPERT'S OPINION • LOWER LIMB - PAEDIATRIC

Microvascular reconstruction of pediatric lower extremity trauma using free tissue transfer

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Abstract
While free tissue transfer has long been established as a reliable microsurgical technique in the adult population, its application in pediatric reconstruction is a relatively recent phenomenon. Despite initial concerns regarding minute vessel diameters, increased propensity for vasospasm, and limited tissue availability, pediatric free tissue transfer is now a widely used technique that has demonstrated an acceptable level of donor and recipient site morbidity in children. Five flaps commonly used in the reconstruction of lower extremity trauma are discussed in this paper: the latissimus dorsi, rectus abdominis, anterolateral thigh, gracilis, and the subscapular and parascapular flaps. The indications, blood supply, advantages, and disadvantages of each are detailed. Incredible progress has been made in the application of microsurgical techniques to the pediatric population over the last several decades. With a healthy understanding of the anatomy and functionality of the donor site, the reconstructive surgeon can repair a variety of complex injuries with an acceptable morbidity and mortality rate.

Keywords Pediatrics · Free flap · Trauma · Lower extremity · Microsurgery

Introduction

While free tissue transfer has long been established as a reliable microsurgical technique in the adult population, its application in pediatric reconstruction is a relatively recent phenomenon. Surgeons were initially hesitant to utilize pediatric free flaps due to the minute vessel diameters, perceived vessel spasticity, and limited tissue availability seen in this population. Moreover, donor site morbidity and potential implications for the child's future growth must be thoughtfully considered when planning the reconstructive options in this patient population [1, 2]. Despite initial doubts, pediatric free tissue transfer (PFTT) is now considered to be a viable reconstructive option with a high success rate [1–3].

The most common indication for PFTT to the lower extremity is for extensive soft tissue damage secondary to trauma [1, 3]. The use of PFTT allows for restoration of meaningful function and preservation of cosmesis, both of which are of utmost importance in the pediatric population as the lack of either may have lasting physical and psychological implications in children.

Despite great advances in microsurgery within the adult population, relatively little has been published regarding free tissue transfer in the pediatric population. This paper aims to detail several dependable flaps for use in lower extremity microsurgical reconstruction and to discuss challenges encountered when operating on pediatric patients.

The evolution of pediatric microsurgery

The first successful application of microsurgical technique in the pediatric population was for two cases of arm replantation, reported in 1964 by Malt and McKhann [4]. However, the first successful case of PFTT was a free groin flap performed by two Japanese surgeons, Harii and Ohmori, in 1975 [5]. In 1977, Ohmori reported a successful free groin flap in a 3-month-old infant, making the notion of a "minimum age" for successful free tissue transfer obsolete [6].

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Despite these early initial successes, doubts remained, as most early publications primarily consisted of scattered case reports and a few case series [5, 7, 8]. Finally, the 1989 publication of a 106 case series by Canales with an 88% success rate and a complication rate comparable to the adult population put the vast majority of debate regarding PFTT to rest, indicating that the use of free tissue transfer in the pediatric population was here to stay [9]. PFTT, like many other challenging topics in surgery, has had its success guaranteed by a thorough review of its failures and is now considered to be a key component in the arsenal of every microsurgeon.

Preoperative planning

Patient requirements

Virtually, all pediatric patients are eligible for reconstruction using free tissue transfer. Although it was previously believed successful anastomosis required vessel diameters of a minimum size, there has been no evidence of this, as successful anastomosis has occurred in vessels as small as 0.3 mm [2]. Similarly, there is no minimum age for PFTT, as successful transfer has been performed on infants [6]. Special consideration should be taken in flap selection as the area undergoing repair will likely undergo rapid growth as the child physically matures and the aesthetic result of the free flap may be subsequently compromised.

Wound condition

Extensive preoperative analysis of the injury site is necessary prior to microvascular reconstruction as the defect may involve vital structures. Damage to bone, tendon, vessels, and nerves should be assessed using appropriate imaging modalities. Flap choice is dependent upon defect extent and size, structures involved, and surgeon preference. Bony defects are unique in that they may warrant the use of osteocutaneous flaps for repair.

Timing

In pediatric trauma cases necessitating free tissue transfer, timing of defect repair is a controversial topic. A landmark paper by Godina in 1986 suggested that coverage of soft tissue wounds within 72 h—an “early” free flap –improved operative outcomes [10]. With the development of temporizing interventions such as wound VACs and Alloderm, the necessity of such early surgical intervention has been challenged [11]. Research since Godina supports that FTT within 1 week of injury has significantly fewer complication rates than repair occurring greater than 7 days after initial injury [12], potentially suggesting that technological advancements have increased the ideal time frame in which to repair the defect. Exposure of vital structures warrants immediate defect coverage.

Use of angiography

The use of preoperative angiography for preoperative analysis of the donor site’s vascular anatomy is another topic of debate that has not been analyzed extensively in the pediatric population. In 1999, Lutz published a prospective study of 120 adult free fibular cases and determined that angiography was not necessary, with two caveats: (1) cases with abnormal pedal pulses preoperatively and (2) significant previous lower leg trauma [13]. Surgeons who do not advocate for preoperative angiography argue that any vascular malformations encountered can be successfully assessed intraoperatively [13]. In contrast, several authors strongly advocate routine preoperative vascular anatomy assessment and argue that other assessment modalities do not suffice [14, 15]. Rosson and Singh performed cost analysis of preoperative imaging modalities and argue that MRI angiography is a cost-effective and noninvasive option that should be utilized in all donor limbs. At their institution, unrecognized peronea arteria magna added an average of $140,000 to their patients’ hospital bills. They argue that traditional angiography should only be utilized if MRA is equivocal [16]. Needless to say, the use of angiography varies widely by surgeon and institution.

Flap selection

Trauma to the lower extremity is particularly difficult to repair given its propensity to expose vital structures the paucity of soft tissue found in this region [17]. The microsurgeon has a plethora of flap choices in his or her armamentarium; however, the selection of the correct flap for reconstruction takes an excellent understanding of surgical anatomy as well as considerable amount of judgement regarding the type of flap needed. Factors to be considered when selecting a flap include: defect size and extent, recipient vessel availability and length, and the need for neurotization. The use of higher magnification, fine sutures and instruments, atraumatic dissection, and local vasodilation underlie are paramount in raising all of the following flaps [18].

Latissimus dorsi flap (LDF)

Frequently called the “workhorse” flap, the LDF is one of most commonly used flaps in reconstructive surgery. The latissimus is a sizeable, fan-shaped muscle that is considered to be the largest of the posterior trunk muscles. It is often chosen in lower extremity reconstruction due to its size and consistent vascular supply, as well as having a vascular pedicle of sufficient caliber, even in very young children [12].

The LDF is considered to be a type V muscle per Mathes and Nahai classification [19]. The thoracodorsal artery is the dominant pedicle of the latissimus; however, it receives a segmental secondary blood supply from perforators originating from both the posterior intercostal and lumbar arteries. The thoracodorsal artery arises from the subscapular artery and predominantly supplies the proximal and lateral two-thirds of the muscle, with perforators supplying the remainder. The latissimus has a vast network of secondary arterial branches which form anastomoses throughout the muscle, permitting the muscle to be thinned or raised segmentally [20].

In lower extremity reconstruction, the LDF is primarily indicated in defects that are too large to be repaired via local, pedicled flaps. Due to the high durability and bulk of this flap, it is of great use in lower extremity reconstruction as it may be used to repair the weight-bearing, plantar surface of the foot. The act of walking requires protective sensation and the latissimus may be neurotized for this purpose [21]. While the LDF confers a great advantage in its bulk, it may also be thinned and used to repair defects of the lower extremity which require a thinner flap, such as the dorsal surface of the foot.

The LDF is optimally harvested with the patient positioned in either the lateral decubitus or prone position. While the harvest of the latissimus is relatively straightforward with clearly delineated anatomic boundaries, it may be difficult to differentiate the border of the latissimus and the subscapularis muscle. Intraoperative manipulation of the upper extremity allows for the activation and relaxation the latissimus, allowing the surgeon to confidently identify the muscle edge [22].

The major advantage of the LDF is its versatility. Its ability to be thinned and large tissue availability allow this flap to be tailored to the exact needs of almost any defect (Fig. 1a–e). Furthermore, it is easily harvested due to the consistent and clear anatomy of this region. The size of the latissimus is a double-edged sword, as the main disadvantage of this flap is its bulk. When used to repair the distal lower extremity, the bulkiness of this flap may impair both aesthetic outcomes and quality of life, as it may limit the footwear options available to the patient [23].

Rectus abdominis flap (RAF)

The RAF is another commonly used workhorse flap in pediatric reconstructive surgery. This is largely due to its reliable blood supply, relatively straightforward harvest, and the large size of the flap obtained [24]. The RAF has a Mathes and Nahai type III blood supply [19], as it is supplied by two dominant pedicles: the deep inferior epigastric artery and the superior epigastric arteries. At the arcuate line, the deep inferior epigastric artery enters the muscle and eventually creates an anastomotic network with the superior epigastric artery approximately halfway between the xiphoid and the umbilicus. The superior aspect of the muscle has a greater abundance of skin perforators as compared to the inferior portion, thus the area superior to the umbilicus is the most reliable skin paddle [25].

The RAF joins the LDF as one of the two most commonly used flaps in pediatric lower extremity reconstruction and is indicated in the coverage of extensive, large surface area defects [26]. This is largely in part due to its axial type III blood supply, and long, large caliber pedicle [27]. It should be noted that unlike the latissimus, the RAF and its vascular pedicle may be very small in young patients, potentially limiting its pediatric application [12]. The rectus flap may be split distally with two axial tails, which is of great benefit when repairing the defects that encompass both the lateral and medial malleolus [28].

In the pediatric population, it is recommended to harvest this flap using a Pfannenstiel incision to optimize cosmesis [12]. Several variations of this flap exist, commonly being raised as either a vertical rectus abdominus musculocutaneous (VRAM) flap or a transverse rectus abdominus musculocutaneous flap (TRAM), based upon the dermal component of the flap. When raising the RAF, a lateral or medial band of tissue is typically left in order to anchor the remaining muscle and preserve its functionality [29].

Like the latissimus, the RAF allows for the coverage of extensive defects. While several other free flaps used in lower extremity reconstruction also offer large surface areas and consistent blood supplies, the RAF confers distinct advantages in is lack of donor site deformity, easily hidden scar, and lack of need to reposition the patient while harvesting the flap. Furthermore, the length of the RAF pedicle allows for anastomosis outside the zone of injury [29]. While postoperative sequelae including abdominal wall insufficiency are well documented in the adult population [30], the incidence of hernias in the pediatric population remains unclear. Nevertheless, the harvest of this flap requires repair of the anterior rectus sheath, particularly inferior to the umbilicus. Similar to the latissimus, the bulk of the RAF may preclude its use in certain defects of the foot and ankle, but some atrophy may be expected with time [31].

Gracilis flap (GF)

The gracilis muscle is a thigh adductor that can be found medially, lying between the adductor longus and sartorius muscles anteriorly and semimembranosus posteriorly.

The gracilis is a Mathes and Nahai type II flap [19]. It derives the majority of its blood supply from a branch of

Fig. 1 A 15-year-old Caucasian male who had a trailer fall on his right foot. He sustained an open fracture of his right first through third metatarsals and significant soft tissue injury. The patient had undergone amputation of several of his digits on his right foot and had exposed metatarsals. A serial debridement had performed with the application of cadaver skin allograft and wound VAC. The dimensions of soft tissue defect were 14 × 14.5 cm. Due to exposed hardware and the dimensions of the wound a decision was made for a free latissimous dorsi muscle flap transfer for coverage of the patient's right dorsum foot defect. A left left-sided latissimus dorsi muscle flap was dissected out for harvest. The right foot and ankle were dissected for the anterior tibial artery and vein. Arterial anastomosis was performed in an end-to-end fashion between the anterior tibial artery and the thoracodorsal artery using 9-0 nylon. The anterior tibial vein was anastomozed with the thoracodorsal vein in an end-to-end fashion using a 2-mm coupler. The postoperative course of the patient was uneventful. Before discharge, a split-thickness skin graft was applied to the flap. **a** The right foot dorsum defect following serial debridements and application of cadaver skin allograft. **b** A left latissimous dorsi muscle flap was raised for covering the defect which its pedicle is pointed with a plastic vascular clump. **c** The immediate postoperative outcome with the free latissimous dorsi muscle flap in place after vascular anastomosis was performed. **d** A long-term outcome (3 years), anteroposterior view. **e** A long-term outcome (3 years), lateral view

the medial femoral circumflex artery in addition to one or two minor pedicles which arise from the superficial femoral artery. Of note, the majority of the perforators to the skin are located proximally, which should be considered when elevating a myocutaneous gracilis flap [32].

The GF is indicated for small to medium sized lower extremity defects and is often used in injuries requiring functional muscle transfer. Due to its functional potential, it is commonly associated with facial reanimation in the pediatric population, but remains a dependable choice for lower extremity reconstruction. The denervated GF atrophies with time and is ideal for use in injuries of the foot and ankle, as it contours well to the defect site [33].

The harvest of the gracilis is performed with the patient placed in a supine position with the donor thigh abducted. Care should be taken to place the incision line on the most medial aspect of the thigh, following an axis from the pubic tubercle to the medial knee joint, in order to improve long-term aesthetic outcomes. While raising the flap, the cutaneous branch of the obturator nerve should be identified and preserved [34].

The GF has reliable vascular and nervous pedicles, making it another dependable flap for the reconstruction of lower extremity trauma. Its harvest results in minimal donor site morbidity and preserves the musculature required to ambulate with crutches—making this flap choice ideal in pediatric patients who will need to use mobility aids postoperatively. Unlike other neurotized muscle flaps, the gracilis will atrophy with time, displaying improved contour and cosmesis over its innervated counterparts. This process often prevents the need for secondary debulking operations [33]. While the gracilis confers many advantages, it is limited by its relatively small size and unsightly scar.

Anterolateral thigh flap (ALTF)

The anterolateral thigh (ALT) flap is a relatively new free flap that has shown promising results in pediatric reconstruction [35]. It provides a large amount of tissue in addition to a lengthy and large caliber vascular pedicle, which is based on the descending branch of the lateral circumflex femoral artery. This flap can be harvested to provide a wide array of tissue subtypes and typically provides a large amount of skin [36]. The lateral cutaneous nerve of the thigh provides innervation to the flap.

According to the Mathes and Nahai classification system, the ALTF is considered to be type B or C, as all of the perforating arterial branches are either septocutaneous or myocutanous [37]. The perforators can be found near the mid-thigh and are derived from the descending branch of the lateral circumflex femoral artery [25]. In the vast majority of flaps, the skin vessels are predominantly musculocutaneous [36, 38]. Flap harvest is not affected by perforator composition, although musculocutaneous perforators do add some difficulty to the procedure [36].

Preoperatively, the cutaneous perforators should be identified using bedside Doppler ultrasound. The ALTF is harvested with the patient in a supine position, allowing for a two-team approach as the patient does not require repositioning. The ALT may be raised as a cutaneous, fasicocutaneous, musculocutaneous, chimeric, or a flow-through flap, depending on the needs of the defect [36].

Some authors argue the ALTF is versatile enough that can be used in place of most other soft tissue free flaps [36]. It is an inherently a thin and pliable flap that is useful in the repair of the foot and ankle. It can be raised as a sensate flap in order to repair defects of the plantar surface of the foot and can be raised as a composite flap with the fascia lata in order to strengthen the Achilles tendon [35]. Furthermore, it is an ideal option for a patient requiring the use of postoperative crutches seeing as that it will not affect the musculature of the upper extremity or torso.

The ALTF is a highly versatile flap that has a relatively long pedicle, provides a myriad of tissue types, and has the ability to be sensitized or thinned (Fig. 2a–g). Like other fasciocutaneous flaps, the ALTF confers its strongest advantage in its lack of donor site morbidity. It is rare for a donor site to provide such ample amounts of sensate tissue while lacking long-term functional deficits [36]. Despite the ALT's strengths, it has many disadvantages which have limited its widespread use. The high variability of musculocutaneous and septocutaneous skin perforators from flap to flap and the added difficulty of dissecting musculocutaneous perforators has led to its lack of popularity [38]. While several authors have reported consistent vascular pedicles [39, 40], others have reported extensive variations in the pedicle branching patterns [38]. Several authors have also reported rare incidents in which the perforating vessels were entirely absent [38, 41]—a risk that many surgeons are unwilling to take.

Scapular and parascapular flap (SF, PSF)

The fasciocutaneous SF and PSF of the shoulder are favored due to their ease of harvest, consistently long and large diameter vascular pedicles, general hairlessness, and large amount of donor tissue provided [42].

THE SF and PSF receive their blood supplies from branches of the circumflex scapular artery [43]. After the circumflex scapular artery passes through the triangular space, it divides into the transverse branch, which supplies the scapular flap, and the descending branch, which supplies the parascapular flap.

In lower extremity trauma the SF and PSF are indicated in large lower extremity defects that do not require neurotization. They are frequently used in the resurfacing of large anterior leg wounds or whole ankle skin resurfacing. For composite bone and skin defects, an osteocutaneous or osteomyocutaneous chimeric SF/PSF free flap can be utilized [44].

The scapular and parascapular flaps must be raised with the patient in the lateral decubitus position, with the upper extremity either abducted or adducted [42, 45]. The patient will need to undergo repositioning during the operation. The

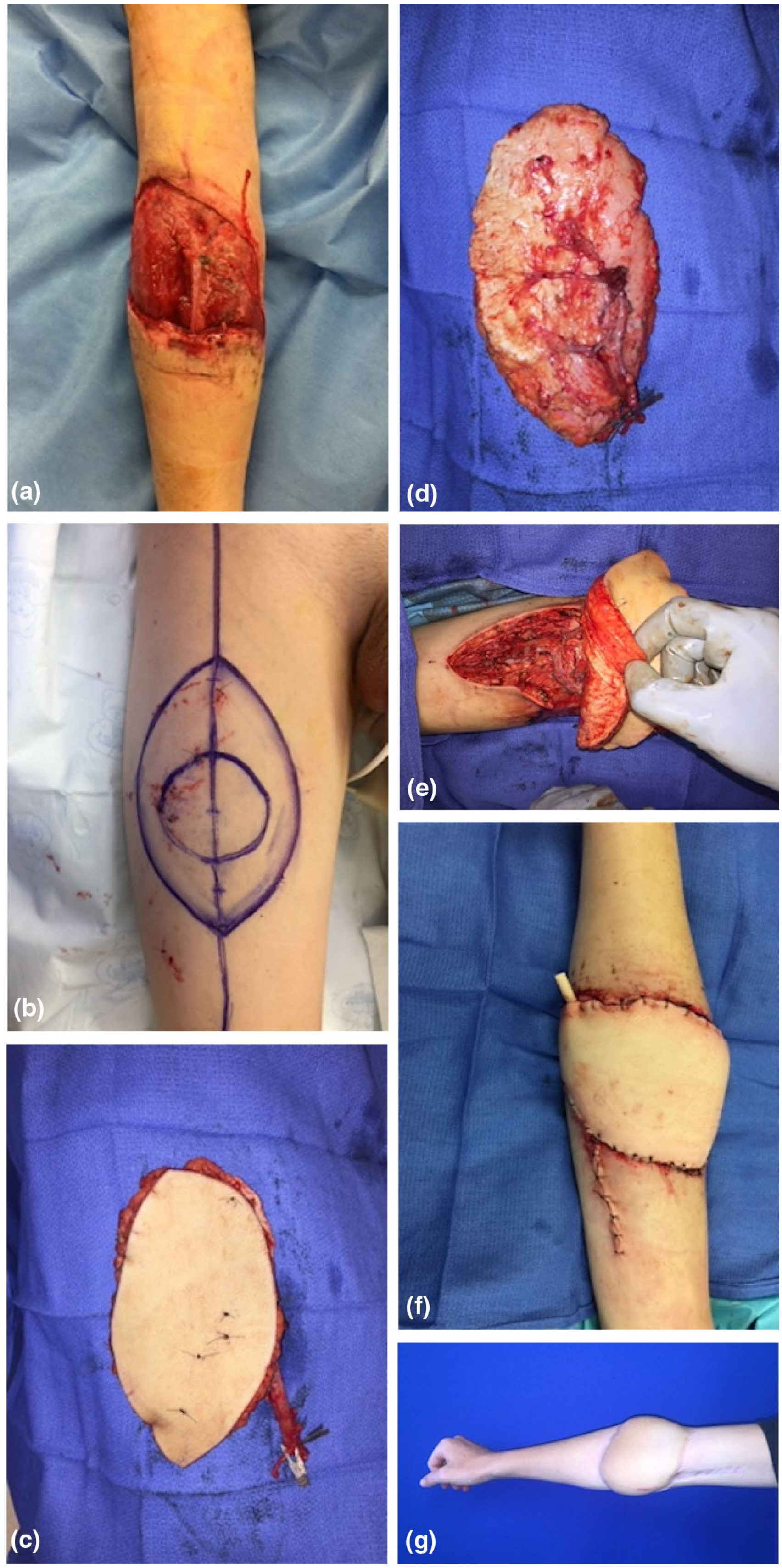

Fig. 2 A 13-year-old Caucasian male patient with an ATV accident resulting in an open 14 × 10 cm wound on the right antecubital fossa. Initial debridement and irrigation of the right antecubital fossa, including skin, subcutaneous tissue, and fascia was performed. Additional interventions included exploration of the right median nerve at the proximal forearm, nerve wrap to median nerve, and wound vacuum-assisted closure application. The second stage of reconstruction included a free fasciocutaneous perforator anterolateral thigh (ALT) flap from the right thigh for coverage of the defect of the right antecubital fossa. The artery of the flap was anastomosed end-to-side to the right brachial artery, one of the venous commitantes was anastomosed end-to-side to the brachial vein, and the other vein end-to-end to the right basilic vein. The postoperative course of the patient was uneventful, without complications. The elbow range of motion was within normal limits. The patient was seen at the office 2 years after the initial surgery. There was tissue redundancy but the patient and his family were not interested in improving cosmesis. **a** The defect over the right antecubital fossa. **b** Flap markings on the right thigh: the inner circle corresponds to the midpoint between the lateral upper edge of the patella and the anterior superior iliac spine, where usually a perforator is commonly located. **c** A posterior view of the ALT flap with the pedicle and its two perforators. **d** An anterior view of the anterolateral thigh (ALT) flap. **e** The ALT flap post vascular anastomosis. **f** The immediate postoperative outcome. **g** Long-term follow up

scapular flap incision should be made in an elliptical fashion, for ease of closure, and contain the triangular space within the lateral end of the ellipse. The medial end of the ellipse may extend to the midline if necessary [45]. The parascapular flap incision should follow a similar form, with the triangular space located in the lateral aspect of the pedicle. Instead of extending horizontally like the scapular flap, the axis of the parascapular ellipse should be oriented in a plane which follows the lateral edge of the scapula.

The scapular and parascapular free flaps confer several advantages. Their shared pedicle is typically constant in location, length, and size. These flaps are easily combined with others to create chimeric flaps, specifically tailored to the needs of the defect [42]. The scapular and parascapular flaps have relatively low donor site morbidities and do not disrupt the patient's musculature [42, 45]. Unfortunately, both flaps lack cutaneous innervation and the donor site scar has a tendency to spread [43]. Additionally, the patient must be repositioned during the harvest of both flaps.

Postoperative care

Proper postoperative care following PFTT is paramount to achieving excellent outcomes. Patients should be admitted to the ICU postoperatively for highly regulated flap monitoring [46].

Flap monitoring

For at least the first 24-h postoperatively, flap viability should be assessed on an hourly basis [26, 47]. Monitoring is frequently performed by using Doppler ultrasound at the bedside. Momeni et al. reported routinely monitoring their flaps every 4 h after the initial 24 h period until discharge [26].

Elevation

The affected extremity should be elevated according to surgeon preference. Some recommend keeping the extremity at the level of the heart or higher to reduce the amount of venous congestion within the flap [43]. Others implement a postoperative dangling protocol which consists of strict extremity elevation for approximately 2 weeks, which is then followed by a slow increase in the duration extremity dangling during postoperative weeks 3 and 4 [47]. To aid in immobility, plaster splinting can be used [47].

Anticoagulation

The topic of anticoagulation in the pediatric population remains controversial, and no consensus exists regarding its use [1]. Some authors do not use anticoagulation at all, while others use it routinely, and still others modulate their pattern depending on the need for replantation or revascularization [1]. Others recommend the use of systemic anticoagulation only in very young patients, as their undeveloped vessels have been observed to be translucent and have a gelatinous consistency [23]. If heparin is used for anticoagulation, a dose of 100 IU/kg or 150 IU/kg/day is recommended [1, 18].

Vasospasm

Environmental factors such as room temperature and excessive stimulation by visitors should be controlled to reduce vasospasm [43]. Medications such as chlorpromazine can also be used to minimize vasospasm, with the added benefit of minimizing postoperative anxiety [18].

Overcoming the challenges of the pediatric free flap

Significant anatomic and physiologic challenges have been associated with PFTT. These challenges include smaller vessel size, perceived increased tendency toward vasospasm, prolonged anesthetic times, and limited tissue availability. Over the past four decades, great progress has been made in improving surgical technique and debunking many of the perceived limitations of PFTT, which has led to the widespread application of FTT in the pediatric trauma population.

Pediatric FTT creates a unique challenge for the reconstructive microsurgeon in that the he or she must anticipate the significant growth and development that will soon affect both the donor and recipient sites. The physiologically normal fluctuations in a child's body habitus may significantly affect flap contour. Additionally, myocutaneous flap harvest may result in long-term asymmetry and weakness [48]. Despite these challenges, assessment of both short- and long-term outcomes of PFTT has supported that free tissue transfer is not associated with significant morbidity at either the donor or recipient sites [48] nor with significant growth disturbances [9]. Long-term outcomes in quality of life are reported to be virtually identical in both the adult and pediatric populations [48].

As more research on PFTT enters the medical literature, perceived difficulties with vessel diameter and vasospasm have been reported to be much less significant than initially thought. Research has shown that relatively speaking, pediatric pedicle vessel diameters are larger than their adult pedicle counterparts, effectively negating the initial concerns expressed by microsurgeons regarding minute vessel diameters [49]. Upton and Guo argue that the vessel diameters encountered in PFTT are comparable to those encountered in hand surgery and should be more than adequate for the experienced surgeon [50]. Furthermore, the notion that pediatric vessels are more prone to vasospasm and thrombosis has been directly challenged by several series [50, 51]. Some argue that traumatic dissection and isolation of vessels within vascular pedicles account for increased failure rates and that the vasospasm seen in this population is grossly exaggerated [50]. Parry also challenged the pediatric vasculature's increased propensity for spasm and hypothesized that the underdeveloped muscularis layer of the arterial vasculature in children may support this observation [51].

Despite initial doubts on its feasibility, PFTT success rates have been reported to be comparable to and even higher than those seen in adult free tissue transfer [49, 51]. It has been hypothesized that high rate success rates of PFTT can be attributed at least in part to some of the physiologic characteristics of pediatric blood vessels. Pediatric vessels are often in much better condition than their adult counterparts, which have sustained years of abuse secondary to comorbid conditions and lifestyle factors including arteriosclerosis, diabetes, hypertension, and smoking [51]. Pediatric patients further harbor the "tremendous functional reserves" of youth, which serve to support them during the strenuous postoperative recovery period required in these extensive operations [50]. Finally, pediatric patients have been found to tolerate postoperative immobilization better than adults and therefore have more favorable rehabilitation results as they are quicker to learn new, positive habits when recuperating from operative intervention [46].

Conclusions

Since the initial application of microsurgical techniques to the pediatric population in the 1970s, there has been a gradual widespread acceptance of PFTT as a treatment modality for complex surgical problems. Advances in technology, technique, anatomic description, and perioperative care have allowed for the routine, safe, and efficient application of microsurgery to the pediatric population. Despite these advances, PFTT remains a highly complicated technique that requires use of higher magnification, fine sutures and instruments, and atraumatic dissection. Areas of debate such as the routine use of anticoagulation, and the ever-changing biomedical technologies provide ample fodder for ongoing research and development.

Compliance with ethical standards

Conflict of interest All of the authors declare that they have no conflict of interest.

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