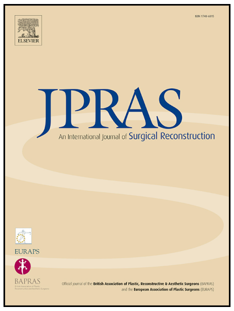

Vascularised bone transfer: history, blood supply and contemporary problems

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Title Page

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Vascularised bone transfer: history, blood supply and contemporary problems

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ABSTRACT

Background: Since the description of the free fibula flap by Taylor in 1975, many flaps composed of bone have been described. This review documents the history of vascularised bone transfer and reflects on the current understanding of blood supply in an effort to define all clinically described osseous flaps.

Methods: A structured review of MEDLINE and Google Scholar was performed to identify all clinically described bone flaps in humans. Data regarding patterns of vascularity were collected where available from the anatomical literature.

Results: Vascularised bone transfer has evolved stepwise in concert with advances in reconstructive surgery techniques. This began with local flaps of the craniofacial skeleton in the late 19th century, followed by regional flaps such as the fibula flap for tibial reconstruction in the early 20th century. Prelaminated and pedicled myo-osseous flaps predominated until the advent of microsurgery and free tissue transfer in the 1960s and 1970s. Fifty-two different bone flaps were identified from 27 different bones. These flaps can be broadly classified into three types to reflect the pedicle: nutrient vessel (NV), penetrating periosteal vessel (PPV) and non-penetrating periosteal vessel (NPPV). NPPVs can be further classified according to the anatomical structure that serves as a conduit for the pedicle which may be direct-periosteal, musculoperiosteal or fascioperiosteal.

Discussion: The blood supply to bone is well described and is important to the reconstructive surgeon in the design of reliable vascularised bone suitable for transfer into defects requiring osseous replacement. Further study in this field could be directed at the implications of the pattern of bone flap vascularity on reconstructive outcomes, the changes in bone vascularity after osteotomy and the existence of “true” and “choke” anastomoses in cortical bone.

INTRODUCTION

Bone grafts have been the mainstay of reconstruction of bone defects for more than a century[1]. When a critical but as yet undefined defect size is reached, the outcomes of non-vascularised bone grafting become unpredictable[1]. The work of Ostrup[2,3], Frederikson[2], Weiland[4], Berggren[5], Taylor[6,7], and Wood[8] highlight the advantages of vascularised bone. When compared with non-vascularised bone graft for the reconstruction of critical sized bone defects, vascularised bone shows earlier union and more robust biomechanical integrity[2,4], as well as resistance to progressive resorption and the devitalizing effects of defect site-related sepsis[8] and irradiation[3]. This can be inferred from the current understanding of osteogenesis, fracture healing and tissue perfusion.

Since the description of the free fibula flap by Taylor in 1975[6], a large number of osseous flaps have been described. Yet, in contrast to soft tissue reconstruction, it appears the anatomical patterns of vascularity in bone are not typically applied to the selection or manipulation of the osseous component of a flap. This is particularly the case in reconstructions where the soft tissue defect is the surgical focus. It is a basic tenant of composite reconstructions elsewhere, such as the nose, that the supporting structures are at least as important as the overlying soft tissue coverage. Indeed the failure of the former produces poor outcomes, such as contracture, that can be very hard to correct secondarily.

We are indebted to the efforts of Brookes[9], Trueta[10], Crock[11], Rhinelander[12] and others[13-17], whose anatomical studies have facilitated an understanding of the patterns of osseous vascularity. The design of reliably vascularised bone suitable for transfer into defects requiring osseous replacement is critical, and yet can often be overlooked at the detriment to the intended reconstruction. This review aims to define and classify the pattern of blood supply for all clinically described vascularised bone transfers as well as to identify and define questions relevant for contemporary research.

METHODS

A structured literature review was performed to determine all clinically described bone flaps. The search terms included "*vascularised bone transfer*" or *"bone flap"*. Further terms were used for each bone in the body as relevant (ie. *parietal bone, temporal bone* etc.). Articles were included only if it was the original clinical description for that particular bone transfer. This was performed with reference to any clinical description: case reports, case series and other higher quality studies. Articles without a clinical case or clinical description component (ie. theoretical papers and cadaveric-only studies) were excluded. Furthermore, vascularised transfers of the whole toe, finger or joints were not included. Databases used included MEDLINE (via PubMed) and Google scholar, and articles were limited to human studies and English language. A review of citations within the identified articles was also performed to identify any further records of relevance. Once all clinically described bone flap papers were identified, patterns of blood supply were defined with reference to the original clinical references of these bone flaps as well as relevant studies found through an additional scoping review of the anatomical literature and key references[17-19].

RESULTS

Described bone flaps

The results of our literature search as represented by a flow chart can be found in Figure 1. In total, 52 different bone flaps were identified from 27 different bones. Clinically described flaps incorporating a vascularised bony component are presented in Table 1, Table 2 and Table 3 for the axial skeleton, upper limb girdle and lower limb girdle respectively. Patterns of blood supply presented for each flap should be considered a guide, and were based on the anatomical and clinical literature where it was available.

History

Clopton Havers contributed to our early understanding of bone blood supply, publishing his "Osteologia Nova" which he communicated to the Royal Society in 1691[20]. After the early work of Antoni van Leeuwenhoek, Havers formally described the Haversian canal and surmised at its role in providing nutrients to the surrounding lamellae. Bernhard Albinus, a master of dissection in the 18th century, built on the work of Havers and was the first to fully appreciate the finer vasculature within bone[21]. With microscopy, he went on to describe the dual pattern of blood supply to bone from both a periosteal and a medullary origin. These findings would stand unchallenged for more than two centuries.

Local bone flaps, such as the “osteoplastic” calvarial flap designed by Wagner in 1889[22] were designed to address issues of surgical access. Regional bone flaps[23] soon followed and were applied in the late nineteenth and throughout the twentieth century to segmental bone defects. Before and during World War I, Blair[24] reconstructed a range of bony defects in the craniofacial skeleton with the use of an approach not dissimilar to bone graft pre-lamination. In this way, he transferred a rib autograft into a random pattern neck skin flap for extended mandible reconstruction in 1915. The advent of microsurgery did not neglect bony tissues and Taylor appears to have provided the first clinical description of a free vascularised bone flap performed in 1974[6].

Modern orthopaedic and microvascular techniques drove the desire for a more complete understanding of the patterns of bone vascularity. Brookes[9], Trueta[10] and Crock[11] extended our understanding of bony blood supply in the modern era. They further helped to define the interplay between both the endosteal and periosteal vascular networks. This work and that of Ostrup[2,3], Weiland[4] and Berggren[5] provided the scientific basis for a number of osseous flap transfers including the fibula[6] and the deep circumflex iliac artery flaps[7], which now serve as workhorse flaps in modern reconstructive applications (Figure 2).

Blood supply to bone

The *ideal* bone flap should possess:

1. Similar morphology, whether cancellous, cortical or both and in the case of the latter, the number of cortices.
2. An uninterrupted blood supply following any form of manipulation e.g osteotomy, corticotomy, decortication or a combination of these.
3. Sufficient bone volume and a structural configuration that meets the biomechanical demands of the recipient site.
4. Minimal donor site morbidity

The functional organization of blood supply to bone is composed of an afferent arterial system, a capillary bed and an efferent venous system[9-12,25]. The *afferent* arterial system distributes oxygen and nutrients to the "*functional vascular lattice*" of cortical and medullary sinusoidal networks. These sinusoidal networks are comparable to capillaries in other tissues. The *efferent* venous system is a pathway of drainage through the cortex, to periosteal venules or through large medullary venous sinuses/nutrient veins to reach the extra-osseous venous system. Blood flow is considered to be centrifugal in direction from endosteum to the periosteum. The pressure gradient from within the marrow cavity (45-60mmHg) to the periosteal capillary network favours outward flow. This is further facilitated by the muscular pump mechanism and impact forces associated with locomotion[10]. A full discussion of bone venous drainage is beyond the scope of this article and we refer the reader to recent key references[9,25].

Perfusion of the bones in the appendicular skeleton is by three systems of vessels[9,10,18]: These are the endosteal nutrient vessels (NV), penetrating periosteal vessels (PPV) typical of the metaphysis and epiphysis, and non-penetrating periosteal vessels (NPPV) typical of the diaphysis (Figure 3). Intracortical connections between periosteal and endosteal supply are through a complex lamellar system of vessels that bridge obliquely to the longitudinal Haversian canals. The zone between periosteal supply and the endosteal supply is disputed[9-11], although it is suggested by some experimental studies that the inner two-thirds of cortical bone is supplied by the endosteal system whilst the outer one-third is supplied by the periosteal system, particularly at sites of dense fascial attachment[12] It is also suggested that the watershed or choke zone is dynamic, such that the endosteal supply dominates perfusion to cortical bone in youth whereas in advanced age, a greater thickness of the cortex may be supplied by periosteum[9]. Connection between these two systems occurs in the form of a passive intermediate capillary network where the endosteal source of flow is typically dominant[9,12,25].

Nutrient vessel (NV)

The NV has a periosteal and endosteal contribution to the pattern of long bone vascularisation, with both longitudinal and centripetal supply along the endosteal surface[9](Figure 3). The endosteal supply, composed of ascending and descending medullary vessels, extends to and supplies the metaphyseal cancellous bone[12]. Vascular supply thus extends across the entire endosteal bone surface and perfuses the inner 50% or more of the cortex. In vascularised bone transfer, this may permit reliable survival of an en-bloc segment of long bone based on a NV such as a segment of the fibula[6] or a rib based posteriorly on the posterior intercostal artery[26]. Of those flaps described, four different bone flaps appear to align with the NV pattern of blood supply (Tables 1 and 3).

Penetrating periosteal vessels (PPV)

In the adult, the metaphyseal and epiphyseal PPV provide a predictable end-artery extension to the endosteum [27](Figure 3). However, the PPV endosteal supply is less dominant than the NV, and generally only permits a unicorticate/corticocancellous osseous flap to be harvested when based on a metaphyseal PPV. The PPV pattern of supply appears to correspond with ten different described bone flaps (Tables 1, 2 and 3). The iliac crest flap based on the deep circumflex iliac artery is one example of this type of flap with multiple PPV arising from the pedicle[7], as is the medial femoral condyle (MFC) flap with a more discrete perfusion pattern[28](Figure 4).

Non-penetrating periosteal vessels (NPPV)

The NPPV do not appear to have a contribution to the endosteum, and the periosteal contribution to the cortical bone is generally limited to areas of the outer one-third where fascial and periosteal attachments are dense[12](Figure 2). It would appear, periosteum with a thin layer of cortical bone is all that can be reliably harvested on the NPPV system, and much experimental work supports this concept[10,13,14,16]. In the setting of ablative surgery, trauma or the placement of an intramedullary nail where flow from the NV is interrupted, the periosteal blood supply to the corticocancellous bone becomes important[12]. The pattern of vascularisation in cutaneous flaps can be manipulated in accordance with the angiosome concept espoused by Taylor[29]. It is not known whether the same applies to bone such that by fate or design, a more substantial volume of bone can be brought to rely on an anatomically minor source of perfusion. Fifty osseous flaps conform to the NPPV pattern of supply (Tables 1, 2 and 3).

The NPPVs can be further sub-classified on the basis of anatomical studies performed by Simpson[17](Figure 3). In addition to direct periosteal branches from source arteries, there are connections between arterial networks in muscle or fascia attached directly to bone. Direct periosteal (DP) vessels pass directly from a named truncal or compartmental artery without traversing a bridge of muscle or fascia to reach the periosteum. An example of this type of flap would be the 2nd metacarpal flap[30]. Another sub-type of NPPV is the musculoperiosteal pattern (MP), where branches to the periosteum arise from vessels that course within and a muscle that has an origin or insertion on the bone. An example of this would be the sternum[31] or ribs[32,33] via their respective muscle attachments to pectoralis major, latissimus dorsi and serratus anterior. The third branching pattern is the fascioperiosteal (FP), whereby vessels to the periosteum pass from sources arteries that course between layers of folded deep fascia connected to bone. The radial forearm osteocutaneous flap[34] is an excellent example of the latter, with direct FP vessels of the NPPV-type that permits harvest of a cortical flap in conjunction with fasciocutaneous tissue.

Epiphyseal blood supply

In youth, the presence of growth plates complicates arterial supply further. Experimental and clinical studies suggest that the epiphyseal surface of the growth plate is supplied from epiphyseal vessels, often derived from direct epiphyseal arteries that enter between the articular cartilage and the physeal growth plate[35]. This is responsible for vascularity to the resting, germinal, proliferating, and upper hypertrophic cell layers of the growth plate by a process of diffusion[10]. The metaphyseal surface of the growth plate derives its blood supply from the nutrient artery, which is considered to be the dominant supply to the metaphysis[27]. This is the primary source for the osteoprogenitor cells that produce the osteoid required for endochondral bone formation. In addition to the epiphyseo-metaphyseal supply there is also a periosteal supply from local perichondrial vessels that integrate and link with the local epiphyseal and metaphyseal supply. The fibular epiphysis is a good example where knowledge surrounding the vascular supply to the growth plate can be manipulated to facilitate transfer of a growth plate with sustained long bone growth[35]. Irregular type bones, such as the carpal and tarsal bones, are predominantly covered in articular cartilage or have ligamentous connections, and as such, carry a blood supply akin to the epiphyseal pattern, where multiple epiphyseal vessels contribute to arterial supply and venous drainage[9].

DISCUSSION

Patterns of blood supply and implications for bone healing

It seems logical that successful reconstruction of critical sized bone defects should demand appropriately vascularised and morphologically similar bone, though the precise dimensions of a defect that is critical is not known and may vary from one circumstance to another. The evolving role of select vascularised bone transfers in achieving union and carpal stability in chronic recalcitrant scaphoid non-union where non-vascularised and pedicled vascularised bone transfers have failed is testament to this[36,37]. An understanding of the patterns of osseous vascularisation may help to explain this. Recent reports on the use of pedicled transfers for scaphoid nonunion suggest variable union rates between 27% and 100%, depending on the choice of flap[30,36,38,39]. The pattern of blood supply for these pedicled bone flaps generally corresponds to the NPPV configuration[30,38,39]. This pattern of blood supply may not be sufficient to vascularise the entire bone segment raised – especially if there is a cancellous component included. For pedicled grafts in scaphoid nonunion, there are exceptions. Mathoulin and Haerle[36] described a pedicled bone graft of the distal radius based on the radial palmar carpal arch artery (rPCA), an artery that routinely penetrates the cancellous bone of the distal radius and thus represents an epiphyseal-type PPV pattern of blood supply[40]. In a series of 17 patients where this flap was used to treat scaphoid nonunion[36], all obtained union in an average of 60 days. Jones et al.[37] compared a free medial femoral condyle flap and a pedicled vascularised distal radius bone flap, based on the 1,2 intercompartmental supra-retinacular artery (1,2-ICSRA) pedicle, for scaphoid non-union. They found a higher rate of union ($P=0.005$) and shorter time to healing ($P<0.001$) for the MFC flap. As described earlier, the pattern of blood supply to the MFC flap is best categorized as a PPV (Figure 3) configuration with the ability to harvest a vascularised corticocancellous portion (Figure 3D). The 1,2-ICSRA best resembles a NPPV direct periosteal blood supply, with only 6% of vessels entering the cancellous component of the graft on cadaveric studies[40]. It must be recognized that many factors may be at play in the study by Jones et al., including the potential for sampling error (n = 22) and selection bias with a retrospective series including multiple operating surgeons. However, reliable vascularity to the entire corticocancellous graft may yet play a role in the success of the rPCA[36] and the MFC flap[37] in scaphoid nonunion. Further comparative studies across common bone reconstructions may help to correlate perfusion type and bone flap success but clearly, an understanding of the vascularisation of bone units used for reconstruction is critical.

Osteotomy design to preserve blood supply

Issues concerning the viability of the free vascularised osseous transfer have been raised recently and may highlight the role of osteotomies in the reconstructive design process[41]. Jacobsen et al.[41] studied free fibula flaps used to reconstruct the mandible in 10 patients. Biopsies at the time of dental implant insertion (mean 19 months post-op) were taken. All bone biopsies showed evidence of either complete cortical necrosis or patchy bony necrosis, despite description by the authors as having a bleeding periosteal layer overlying intact cortex at the time of biopsy. Although most patients had undergone radiotherapy to the region, this is still a curious observation. The fibula flap is a tubular corticocancellous strut that typically relies on the NV for bone viability in microvascular transfer. In keeping with the current understanding of bone blood supply, it is conceivable that interruption of the endosteal supply and subsequent reliance on the NPPV circulation may devitalise portions of the flap distal to the segment in direct continuity with the NV. It is necessary to osteotomise the fibula up to six times to ensure an adequate contour of the bone flap for implant placement and restoration of facial contour. This in turn may lead to decreased or arrested perfusion to osteotomised segments, leading to varying rates of resorption and patchy necrosis of the transferred bone. This could have major consequences such as loosening of hardware intended for osteosynthesis and the inability to osseointegrate prosthetic implants. It is possible that clinical outcomes are moderated by the dynamic and age-dependant nature of the watershed outlined earlier. Alternatively, the iliac crest, with its distinctive natural curve, may be transferred without osteotomies for central or hemi-mandibular defects, which thereby serves to preserve the PPV-type blood supply for this flap. Osteotomy-related devascularisation may help to account for the higher incidence of implant loss with vascularised fibula for mandible reconstruction when compared with iliac crest, as demonstrated by a recent meta-analysis[42]. Moreover, in the emerging era of tailored oncological care, head and neck cancer patients can expect much improved survival rates, and so, longevity of a functioning reconstruction becomes increasingly important.

"True" and "choke" anastomoses in cortical bone

A further consideration of importance to bone flap harvest and osteotomy design are the zones of blood supply within the bone cortex and along its periosteal surface (Figure 3). Gur et al.[43] showed that an osteotomy distal and proximal to the nutrient artery in a live porcine model does not change viability of the fibula bone if the periosteal envelope is preserved. In this study eight pigs underwent unilateral osteotomy at several different sites along the fibula and after 21 days there was no clear difference in bone histological viability between the segments, despite a reduction in bone blood flow to these segments [43]. This raises the possibility that the centrifugal flow of blood, driven by the endosteal pressure gradient, is reversed in certain areas with flow therein shunting from the periosteal system to the endosteum – perhaps mirroring the presence of "true" anastomoses[44] between the periosteal and endosteal circulation at these sites. As flow through this system is attenuated, viability to the remaining flap may be partly preserved based on this periosteal supply alone[14].

Further understanding can be derived from the work of Huggins and Weige[13], who were able to show medium to large areas of medullary infarction in rabbit femurs during the immediate 2 weeks following nutrient artery ablation. From a histological perspective, those bones reviewed after this two week period (up to 88 days post intervention) showed minimal change compared with normal bone tissue. Following a period of avascularity and reduced intramedullary pressure, the periosteal circulation may re-assert itself as the principal source of perfusion to the corticocancellous bone. This mechanism may not be dissimilar to the concept of "choke" anastomoses in the integument[44] and vascular changes as seen with the delay phenomenon[19].

Another concept is the change in periosteal blood supply during age[9], and the effects this may have on the cortical bone choke zone. In particular, Trueta[10] and Crock[11] both reported a pronounced periosteal blood supply to cortical bone in human cadavers of the seventh decade and older. Brookes evaluated this concept further, and compared the dominance of the periosteal supply to the femoral diaphysis in a limited number of limbs attained from subjects between 21 and 88 years of age at the time of death[9]. He found that before the age of 35, the diaphyseal cortex was predominantly vascularised by the endosteal circulation and that in older age (70 years and older) the periosteum was more dominant. When extrapolating this concept to vascularised bone transfer, it may be that the perfusion to the iliac crest based on the DCIA PPV-type circulation is more reliably preserved in the younger demographic. In contrast, for the elderly patient, the osteotomised fibula (with its distal segments sustained only by the NPPV type circulation) may be a more appropriate choice to ensure sufficient bone vascularity. The clinical significance of the age-related changes in cortical bone blood supply, as it relates to vascularised bone transfer, appears unclear to date and both anatomical and clinical studies are required to further define the impact of this concept.

In addition to the anastomotic zones in the cortex, there is also a dense vascular network along the periosteal surface. For the fibula, the outer cortical bone distal to the NV foramen relies on the NPPV pattern of supply, which is particularly dense at sites of muscle attachment[17] and is the basis for the peroneus brevis osteomuscular flap[45]. Harvesting muscle attached to the longitudinal axis is typically employed to protect the peroneal artery pedicle but may also help to augment overall blood supply to the bone flap by making use of the MP NPPV pattern of supply[17]. In terms of venous drainage, adjacent muscle harvested with the flap may also assist venous outflow and thereby reduce the intrinsic resistance of the vascular circuit within the bone transfer, as muscle can augment venous drainage in long bones[10]. Ultimately, this may have implications for improved anastomotic patency in the bone flap. Further work using modern histological and imaging techniques is required to validate the process of ongoing perfusion to segments of bone sustained only by the periosteal circulation, age-related changes to the periosteal blood supply as well as the possible existence of "true" and "choke" vessel phenomenon in cortical bone.

CONCLUSION

Vascularised bone is an excellent reconstructive option for bone defects, particularly in the setting of critical-sized defects. An important part of defect analysis is the osseous defect and consideration should be given to its functional requirements because in this regard, not all bone flaps are the same. Further study will be needed to define the implications of the pattern of bone flap vascularity on reconstructive outcomes, whether osteotomy in certain flaps handicaps the intended reconstruction, and whether "true" and "choke" anastomoses exist in cortical bone.

FIGURE LEGENDS

Figure 1. Flow diagram depicting the literature review process and results. *Search terms for this component of the strategy included each bone in the human body (parietal bone, temporal bone etc.). ^The pattern of blood supply was assessed based on the description in the article along with a scoping review of the anatomical literature and in accordance with work by Panje and Cutting[18], Cormack and Lamberty[19] and Simpson[17].

Figure 2. Traumatic segmental defect of the right radius (A, B) reconstructed with a free vascularised fibula transfer (C) with clinical union and an optimal functional outcome (D). White arrow with whole stem indicates defect site. White arrow with interrupted stem indicates defect with fibula reconstruction.

Figure 3. A system for bone flap classification based on the current understanding of blood supply patterns to bone. NV, nutrient vessel; PPV, penetrating peiosteal vessel; NPPV, non-penetrating periosteal vessel; Asc., ascending; Desc., descending.

Figure 4. The chimeric medial femoral condyle flap, harvested from the medial aspect of the knee (A, B). The blood supply, via the osteoarticular branch of the descending genicular artery (C, arrow), is the most common source vessel for bone harvest (D, arrow). Based on this vessel axis, variations of skin and muscle (D, arrowhead), cartilage and tendinous tissue can be harvested alongside bone.

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Table 1. Clinically described vascularised bone transfers of the *axial* skeleton with source vessels and proposed patterns of blood supply. NV, nutrient vessel; PPV, penetrating peiosteal vessel; NPPV, non-penetrating periosteal vessel; DP, direct periosteal; MP, musculoperiosteal; FP, fascioperiosteal; Ref., reference for original flap description; STA, superficial temporal artery; OccA, occipital artery; SmA, submental artery; SpThyr, superior thyroid artery; TAA, thoraco-acromial axis; IMA, internal mammary artery; TDA, thoracodorsal artery; PIntercostA, posterior intercostal artery.

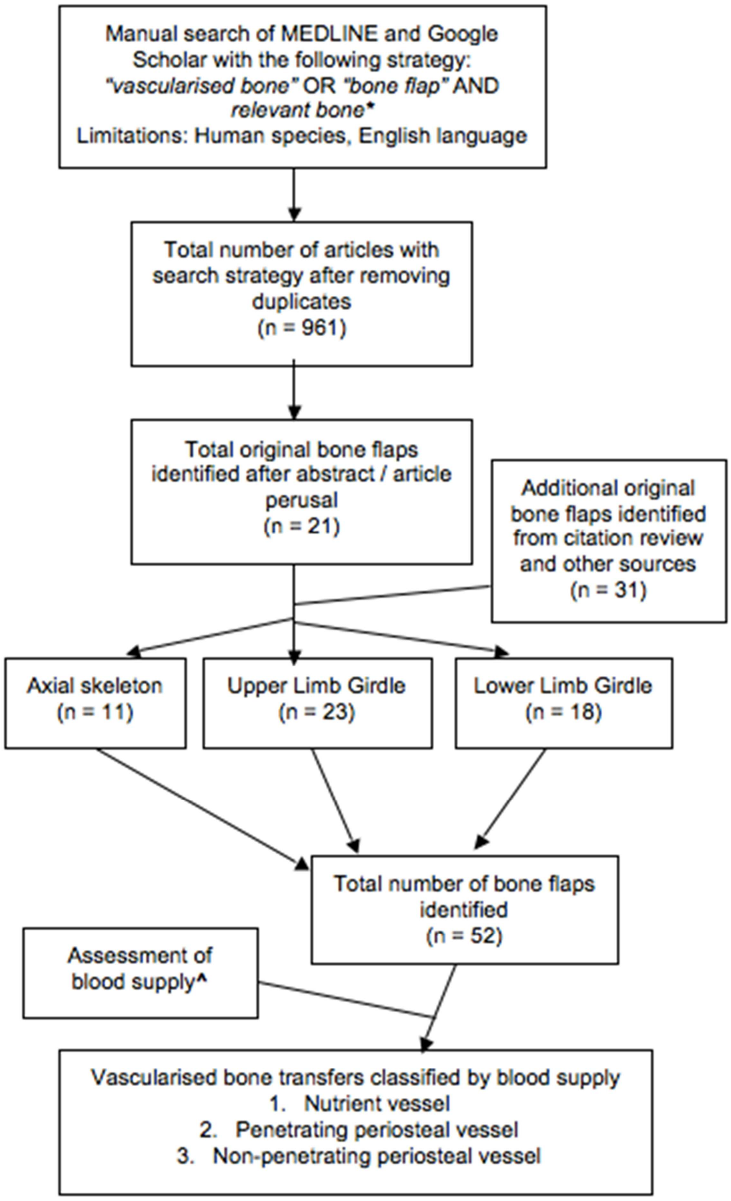
Bone flap (source vessel)	**Ref.**	**Blood supply**
Temporal/parietal bones (STA)	46	NPPV (FP/MP)
Occipital bone (OccA)	47	NPPV (FP/MP)
Mandible, coronoid process (STA)	48	NPPV (MP)
Mandible, body (SmA)	49	NPPV (MP)
Hyoid with sternohyoid (SpThyr)	50	NPPV (MP/DP)
Sternum, anterolateral (TAA)	31	NPPV (MP)
Rib, anterior (TAA)	51	NPPV (MP)
Rib, anterior (IMA)	52	NPPV (DP/MP)
Rib, laterally with serratus anterior (TDA)	32	NPPV (MP)
Rib, laterally with latissimus dorsi (TDA)	33	NPPV (DP/MP)
Rib, posterolateral (PIntercostA)	26	NV & NPPV (DP)

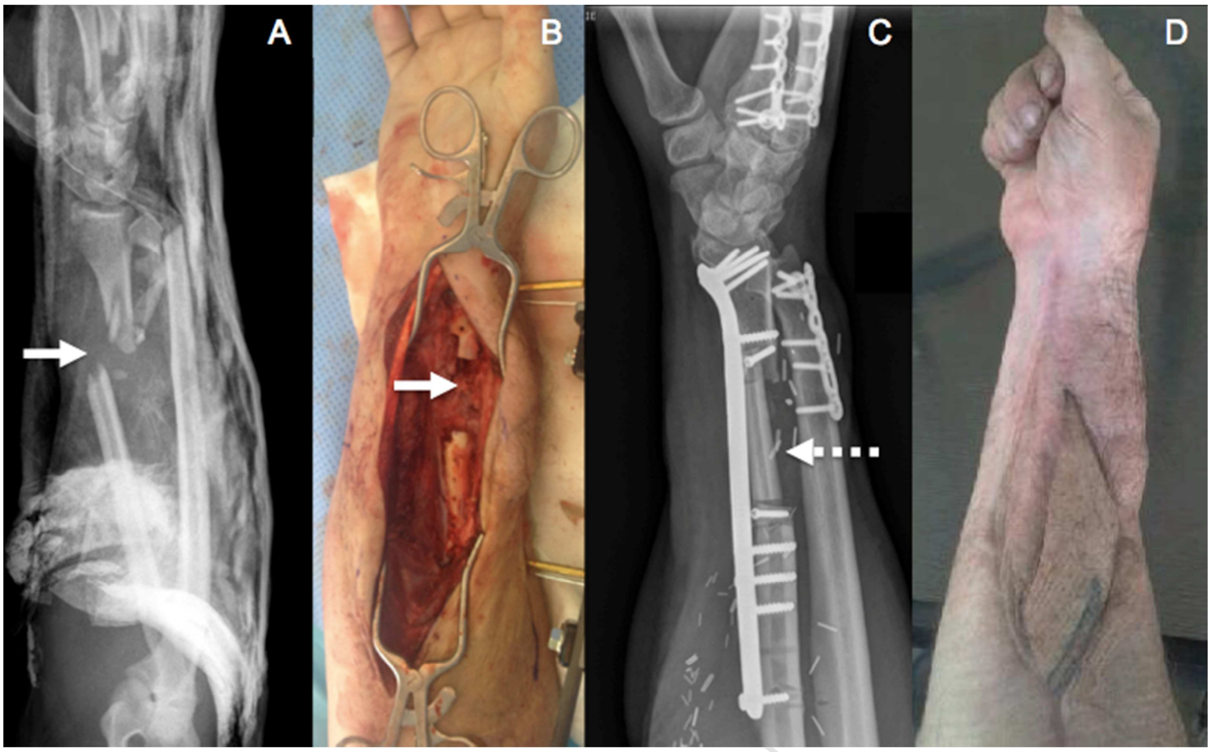
Table 2. Clinically described vascularised bone transfers of the *upper limb girdle* with source vessels and proposed patterns of blood supply. NV, nutrient vessel; PPV, penetrating peiosteal vessel; NPPV, non-penetrating periosteal vessel; DP, direct periosteal; MP, musculoperiosteal; FP, fascioperiosteal; Ref., reference for original flap description; SCMbr, sternocleidomastoid branch of superior thyroid artery; TCA, transverse cervical artery; TDA, thoracodorsal artery; CSA, circumflex scapular artery; DSA, dorsal scapular artery; PBA, profunda brachii artery; UA, ulnar artery; PinterosA, posterior interosseous artery; RA, radial artery; AIA, anterior interosseous artery; rPCA, right palmar carpal arch artery; 1,2-IC SRA, 1st/2nd-intercomparmental supra-retinacular artery; 4th/5th- extensor compartment artery; DB of UA, deep branch of ulnar artery; SPB of RA, superficial palmar branch of radial artery; 1-DMA, 1st dorsal metacarpal artery; 4-DMA, 4th dorsal metacarpal artery; PPDA, proper palmar digital artery; *can be harvested with latissimus dorsi or serratus anterior.

Bone flap (source vessel)	**Ref.**	**Blood supply**
Clavicle, sub-total (SCMbr)	53	NPPV (MP/FP)
Clavicle, medial (SCMbr)	24	NPPV (MP/FP)
Clavicle, lateral	54	NPPV (FP)
Scapular spinous crest (TCA)	18	NPPV (MP)
Scapular inferior angle (Angular artery of TDA*)	55	PPV
Scapular lateral border (CSA)	56	NPPV (DP/FP/MP)
Scapular medial border (DSA)	57	NPPV (DP/FP/MP)
Humerus, lateral (PBA)	58	NPPV (FP/MP)
Ulna, olecranon (PBA)	59	NPPV (MP)
Ulna, volar shaft (UA)	60	NPPV (FP/DP)
Ulna, dorsal shaft (PInterosA)	61	NPPV (FP/MP)
Radius, lateral shaft (RA)	62	NPPV (FP)
Radius, volar shaft with pronator quadratus (AIA)	38	NPPV (MP)
Radius, volar/medial shaft (rPCA)	63	PPV > NPPV (DP)
Radius, dorsal metaphysis (1,2-IC SRA)	30	NPPV (DP)
Radius, dorsal metaphysis (4,5 ECA)	39	NPPV (DP) > PPV
Pisiform (DB of UA)	64	NPPV (DP)
Scaphoid tubercle with abductor pollicis brevis (SPB of RA)	65	NPPV (MP)
Hamate (DB of UA)	66	NPPV (DP)
1st metacarpal shaft (1-DMA)	67	NPPV (DP)
2nd metacarpal shaft (1-DMA)	68	NPPV (DP)
5th metacarpal shaft (4-DMA)	69	NPPV (DP/MP)
Middle phalanx (PPDA)	70	NPPV (DP/FP) & PPV

Table 3. Clinically described vascularised bone transfers of the *lower limb girdle* with source vessels and proposed patterns of blood supply. NV, nutrient vessel; PPV, penetrating peiosteal vessel; NPPV, non-penetrating periosteal vessel; DP, direct periosteal; MP, musculoperiosteal; FP, fascioperiosteal; Ref., reference for original flap description; DCIA, deep circumflex iliac artery; SCIA, superficial circumflex femoral artery; LCFA, lateral circumflex femoral artery; SGA, superior gluteal artery; 4-LA, 4th lumbar artery; 4,5-LA, 4th/5th lumbar arteries; MCFA, medial circumflex femoral artery; DGA, descending genicular artery; LSA, lateral sural artery; ATA, anterior tibial artery; PTA, posterior tibial artery; PerA, peroneal artery; DPA, dorsalis pedis artery.

Bone flap (source vessel)	Ref.	Blood supply
Ilium, anterior crest (DCIA)	7	PPV & NPPV (DP/MP)
Ilium, anterior crest (SCIA)	7	NPPV (DP/MP)
Ilium, anterior with tensor fascia lata (LCFA)	71	NPPV (MP)
Ilium, anterior with sartorius (LCFA)	72	NPPV (MP)
Ilium, lateral (SGA)	73	NPPV (MP) & PPV
Ilium, posterior (4-LA)	74	PPV & NPPV (DP)
Ilium, posterior with erector spinae (4,5-LA)	75	NPPV (MP)
Femur, greater trochanter with quadratus femoris (MCFA)	76	NPPV (MP)
Femur, medial condyle (DGA)	28	PPV
Femur, adductor tubercle (DGA)	77	NPPV (MP)
Femur, distal anterior with vastus intermedius (LCFA)	78	NPPV (MP)
Femur, posterior with lateral head of gastrocnemius (LSA)	79	NPPV (MP)
Fibula, epiphysis (PerA & ATA)	35	NV & PPV
Fibula (PerA)	6	NV & NPPV (DP/MP)
Fibula, distal (PerA)	45	NPPV (DP/MP)
Calcaneus (PTA & tarsal branches)	80	NPPV (DP/MP) & PPV
1st metatarsal (DPA)	81	NPPV (DP)
2nd metatarsal (DPA)	82	NV & NPPV (DP)


Manual search of MEDLINE and Google Scholar with the following strategy:
"vascularised bone" OR "bone flap" AND relevant bone*
Limitations: Human species, English language
Total number of articles with search strategy after removing duplicates (n = 961)
Total original bone flaps identified after abstract / article perusal (n = 21)
Additional original bone flaps identified from citation review and other sources (n = 31)
Axial skeleton (n = 11)
Upper Limb Girdle (n = 23)
Lower Limb Girdle (n = 18)
Total number of bone flaps identified (n = 52)
Assessment of blood supply^
Vascularised bone transfers classified by blood supply
1. Nutrient vessel
2. Penetrating periosteal vessel
3. Non-penetrating periosteal vessel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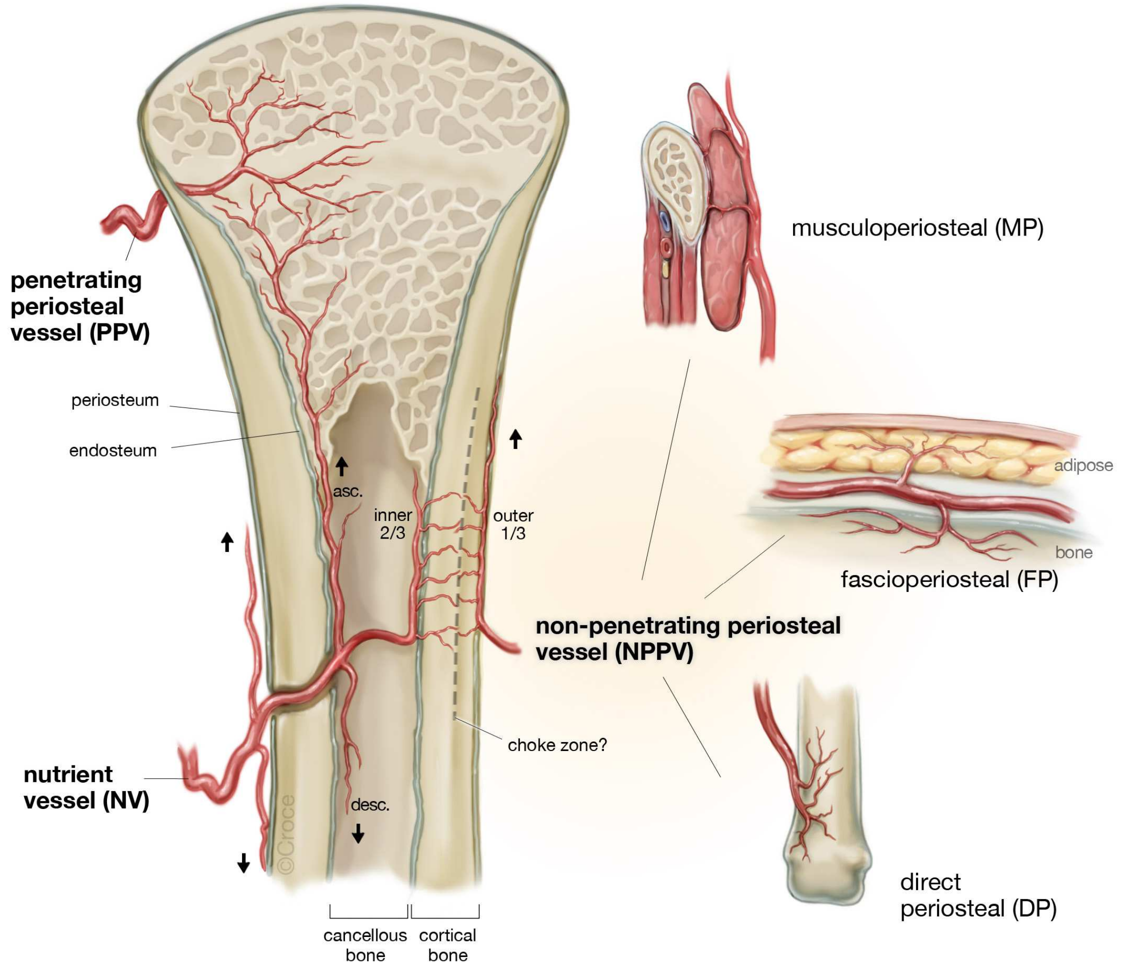
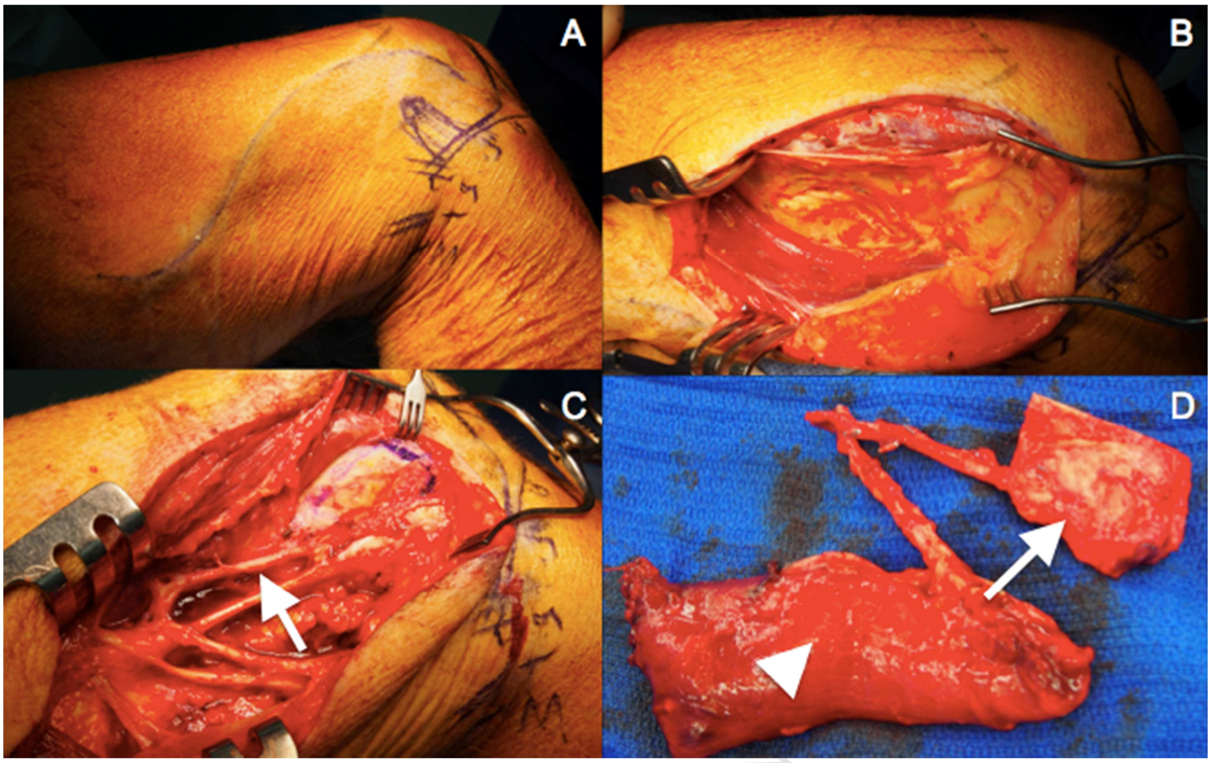

musculoperiosteal (MP)
penetrating periosteal vessel (PPV)
periosteum
endosteum
asc.
inner 2/3
outer 1/3
adipose
bone
fascioperiosteal (FP)
non-penetrating periosteal vessel (NPPV)
choke zone?
nutrient vessel (NV)
desc.
©Croce
direct periosteal (DP)
cancellous bone
cortical bone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