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Evolving concepts in the management of the bone gap in the upper limb. Long and small defects

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Summary Vascularised bone graft is a well accepted technique when dealing with long defects. Its role in refractory nonunion, in small defects and in the growing patient is rarely discussed. In this paper the authors review the different alternatives to deal with bone defects in the upper extremity. The indications of vascularised corticoperiosteal graft for solving small defects harbouring refractory nonunion, and the use of vascularised bone phalanx and metatarsal for complex – but small – defects in the fingers is presented. The ability of the bone to grow and remodel when a living epiphysis is included, and to maintain the cartilage viability when a composite osteochondral graft is transferred are also discussed.

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Vascularised bone graft was introduced in the living by Taylor et al. in 1976¹ as a one-stage procedure to overcome large defects in long bones. The advantages of the technique: fast healing, rapid hypertrophy, resistance to infection, and ability to solve defects in the most unfavourable scenarios (scarred or irradiated beds) have been recognised and accepted by the reconstructive community. Vascularised bone graft became rapidly popular, to the point that nearly every bone of the human body has been transplanted, and it is used on an everyday basis.

Things have evolved since Taylor's first inception of the technique, and this article's purpose is to update the state

of the art of vascularised bone transfer in the upper limb. Refinements in management of long bone defects, the issue of refractory nonunion associated to small defects, and the inclusion of specialised tissue, such as cartilage or growing epiphysis will be presented. Beyond the scope of this article would be the issue of metaphyseal bone transfer to carpal nonunions, currently under quarantine in the hand literature.^{2,3}

Refinements in long bone-large defects reconstructions

Vascularised Fibula Graft (VFG)

Large bone defects in the upper limb may be managed using different surgical techniques. Conventional options include

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corticocancellous bone graft from the iliac crest, autologous non-vascularised fibula graft, allograft, and bone transportation techniques. Non-vascularised autografts⁴⁻⁶ maintain a role in small defects but have unpredictable results in the case of long bony gaps and are not indicated in infected, scarred and poorly vascularised beds. Allograft reconstruction is reserved to tumour cases^{7,8} and healing by creeping substitution is limited to the junction between allograft and host bone. For this reason, a very stable osteosynthesis is mandatory and prolonged immobilisation recommended. Even when consolidation is achieved, the large majority of the allogenic bone remains totally avascular and prone to stress fractures which are not likely to heal. Finally, bone transportation techniques^{9,10} have very few indications in the upper limb since they are uncomfortable for the patient, difficult to apply and potentially dangerous in such a complex anatomical district. In addition, the treatment must be prolonged for many months with increased risk of infection and soft tissue damage.

The clinical application of vascularised fibula graft goes back to the end of the 1970s¹ and since then the procedure has become more and more popular in the reconstruction of long bones.¹¹⁻¹⁶ This option takes advantage of the tubular structure of the fibula which meets all the biomechanical requirements of the recipient bone. The size of the fibula fits perfectly in forearm bone reconstruction, and may also be used in diaphyseal reconstruction of the humerus in spite of being much smaller. However, as it is a vascularised bone, the increased functional demands will cause the cortex to hypertrophy eventually reaching the same size as the host bone (Fig. 1).

The typical indication for vascularised fibula transfer in upper limb skeletal reconstruction is bridging a gap longer than 6 cm. The harvesting technique originally described by Taylor^{1,11} has been progressively refined to a lateral approach in the intermuscular plane between peroneus brevis and gastrocnemius muscles. The diaphyseal segment is harvested based on the peroneal vessels which provide both endosteal and periosteal blood supply. The periosteum and a thin muscular cuff should be carefully preserved in order to improve the vascularity of the bone. In addition, it is advisable to save a redundant portion of periosteum at the level of osteotomies (Fig. 2) which should overlap the junctions with the recipient bone improving the healing ability of the transferred fibula. In the case of simultaneous reconstruction of radius and ulna, the technique of Santanelli et al.¹⁷ should be adopted. They divide the fibula into two segments preserving the periosteum and the vascular pedicle intact in the gap, allowing both defects to be repaired. According to our experience a few technical details may be listed as follows:

1. Resect the recipient bone up to non-infected, healthy and well vascularised tissue. The length of the graft is not a variable influencing the outcome.
2. Step cut osteotomy are more demanding and with greater risk of malrotation. We do however prefer this technique in forearm skeletal reconstruction to improve bone contact. Furthermore, instead of simple screws at each end, we prefer plates to achieve a more reliable fixation. A simple plate bypassing the

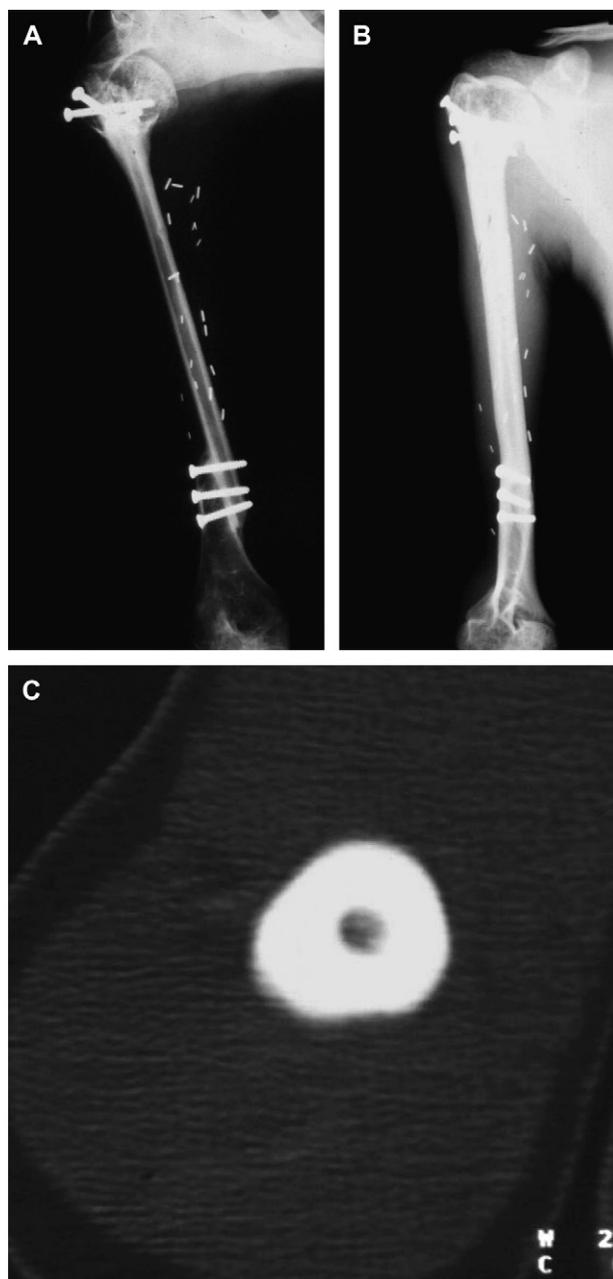


Figure 1 A: Diaphyseal reconstruction of the humerus after intercalary resection for bone sarcoma. At 6 months from surgery bone healing has been achieved at both sides but the diameter of the fibula still has not changed. B: Five years later, significant remodelling and hypertrophy occurred. C: Hypertrophy is concentrated on the cortex.

defect is ideal for the smaller defect. When the graft exceeds 12 cm long, however, we are forced to use two shorter plates, as there are not in the market plates to bridge such a long defects (Fig. 3).

3. In the case of simultaneous total wrist fusion, the specific plate designed by Weiss and Hastings¹⁸ is preferred for distal bone fixation.
4. In humeral reconstruction, discrepancy in diameter with the graft must be taken into account. After

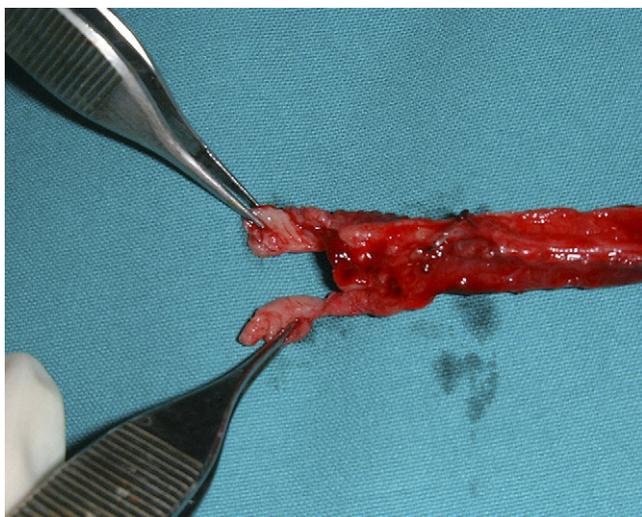


Figure 2 Inclusion of a redundant periosteal flap is recommended during harvesting. It should overlap the junction with the recipient bone, thus improving the ability to heal.

reaming the proximal humeral segment, it is usually possible to insert the fibula into the medullary canal. Distally, a step cut osteotomy of the humerus is recommended. This provides a very stable fixation, but can be improved by bridging with an LCP plate to further deal



Figure 3 A: A bridging plate is the preferred osteosynthesis method of the authors. However, since it is difficult to find an implant longer than 12 cm, in case of longer grafts two plates should be used in order to provide enough stability (B).

with the torsional stresses at the fibula, preventing possible fractures (Fig. 4).

5. Microvascular anastomosis may be performed using the deep humeral artery in the humerus and the anterior interosseous or the radial artery in the forearm.

In a recent revision of a series of 12 cases of forearm reconstruction¹⁹ we found that the consolidation of the VFG proximally and distally required an average of 4.8 months (range, 2.5–8 months), a time frame comparable to other clinical series.^{12,15,20} According to our experience, rigid and stable osteosynthesis is a key point to the success of the procedure. This fact should be stressed, since, as reported above, the consolidation time of a vascularised graft is much longer than the equivalent bifocal fracture. A

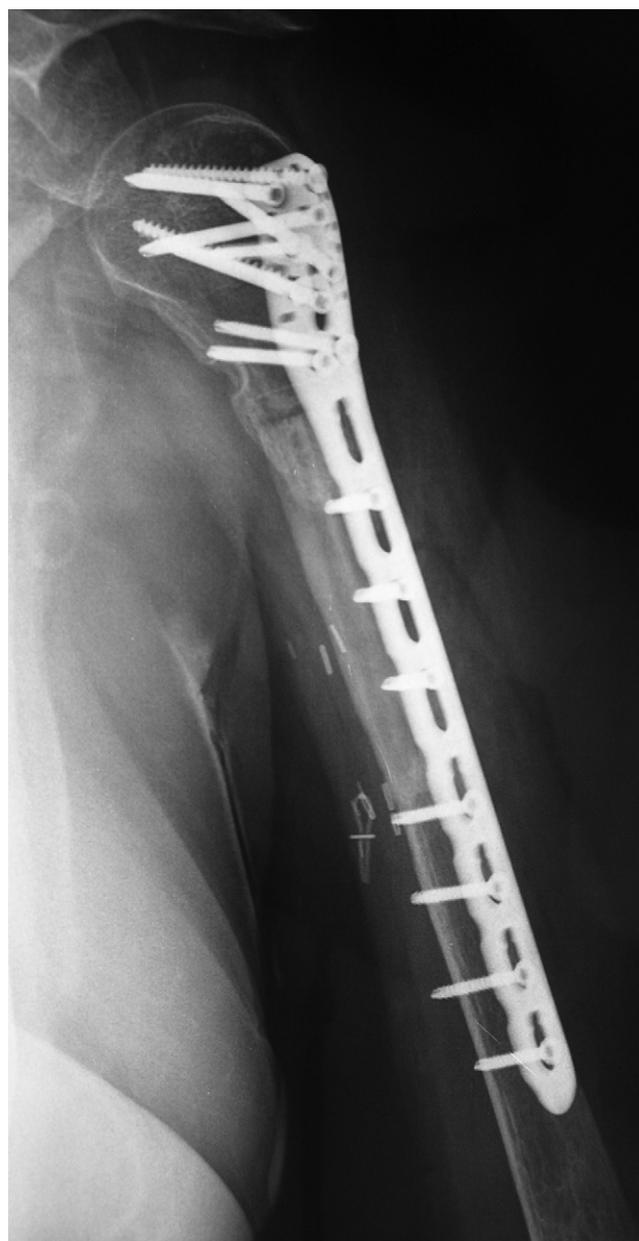


Figure 4 The use of a long plate which bypasses the graft is particularly important in the arm where significant torsion stresses are likely to occur.

reliable bone fixation is therefore mandatory in order to start an early rehabilitation programme and to improve the functional outcome. No secondary fractures were observed in our series, thus confirming that this complication may be prevented avoiding the use of osteosynthesis 'a minima'. In one case of humeral reconstruction, a failure of the implant at the distal junction occurred due to the use of a too short plate. After changing the implant with a longer one, fast healing occurred, confirming the role of stable bone fixation in the outcome (Fig. 5).

Remodelling of the vascularised fibula is a major issue in the paediatric age where some problems related to inadequate osteosynthesis may be overcome thanks to the biological potential of the immature bone. The healing time is usually much shorter and hypertrophy and axial remodelling lead to impressive results in a reasonable period of time (Fig. 6).

Vascularised Fibula Graft (VFG) plus Allograft

Because of its size, fibula may be mechanically inadequate to reconstruct bone defects in weight bearing segments. In lower extremity reconstruction, a slow hypertrophy of the fibular graft may be expected together with possible complications such as stress fractures. In order to provide a more stable solution shortly after surgery, an original technique was developed in the late eighties based on the combined use of allograft and VFG. This procedure turned out to be particularly useful in the reconstruction of femur and tibia after intercalary resection of bone tumours.^{21,22} An allograft matching in size the resected segment is reamed

and an autologous VFG is inserted into the medullary canal. The vascularised fibula must be longer than the allograft in order to provide adequate contact with the recipient bone. This procedure offers the attractive possibility to take advantage of the mechanical stability provided by the allograft at short term after surgery and of the biological potential of the VFG at medium and long term. In a series of more than 70 cases of bone reconstruction in lower extremity following this technique, we observed a high success rate, reduced complications, and a low incidence of secondary surgery.

Although this option is in the vast majority of cases applied to lower limb, it may be used in selected cases of upper limb reconstruction as well. In our experience the indication is limited to juxta-epiphyseal resection of the proximal humerus, thus salvaging the residual portion of the humeral head (Fig. 7). Owing to the well known high sensibility of allografts to infection, this option is not recommended in the case of open fractures and osteomyelitis. It can however, be safely adopted in bone defects resulting from tumour resection and recalcitrant nonunion of the proximal metaphysis of the humerus. The presence of the VFG inside the allograft enhances the bony union rate and prevents the possible long term complications related to the allograft such as resorption, fracture and mechanical failure.

The procedure can be summarised as follows:

1. Select a proximal humerus allograft of the appropriate size
2. Resect a portion of the epiphysis corresponding in size to the residual native epiphysis.
3. Open a slot in the medial diaphyseal portion of the allograft big enough to place the VFG and to allow the

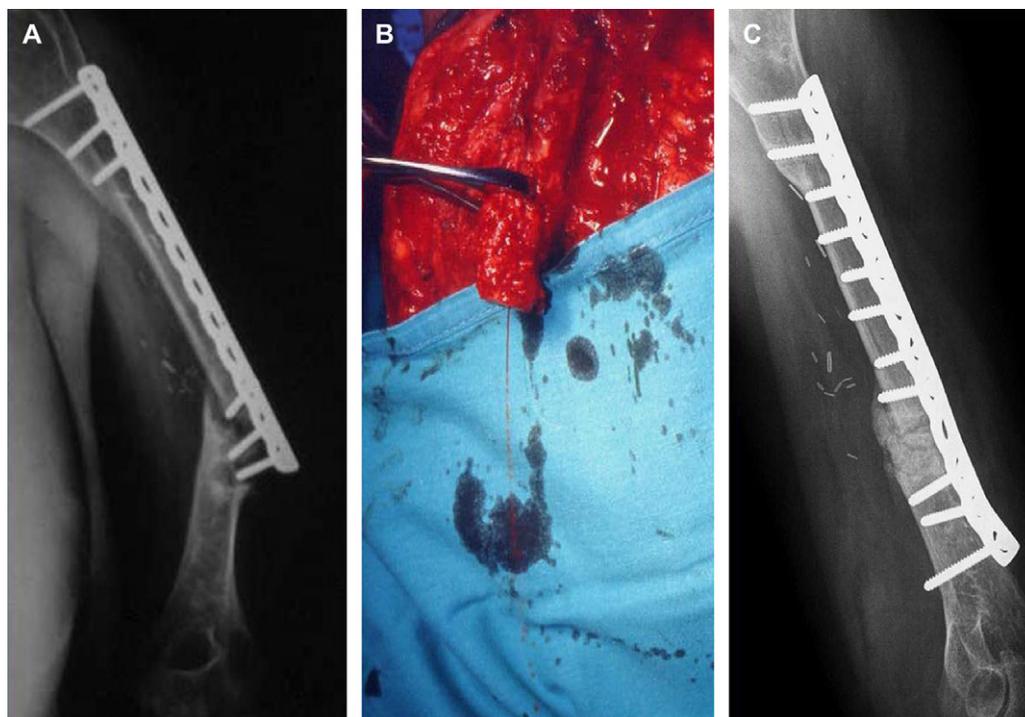


Figure 5 A: In this case of humeral reconstruction too few screws have been used at the distal junction and a fracture has occurred. B: At secondary surgery the fibula turned out to be optimally vascularised. C: Early union after changing to a longer implant.

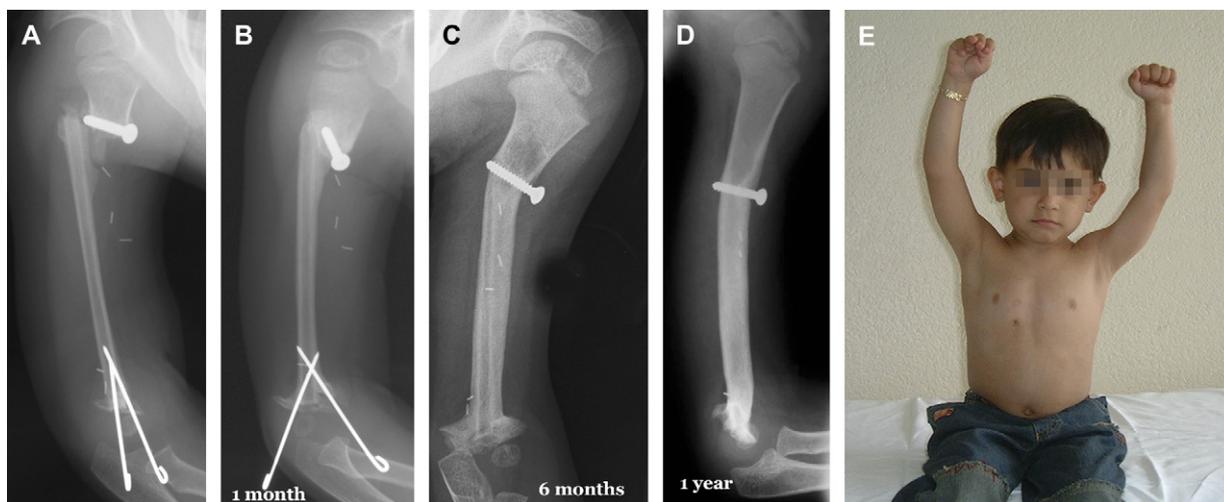


Figure 6 A: Due to poor bone fixation, a fracture occurred in this 5-year-old boy 2 months after reconstruction. B,C,D: After conservative treatment impressive axial remodelling and hypertrophy restored a nearly normal humerus. E: Functional outcome.

pedicle to reach the recipient vessels, which usually are the deep humeral artery and vein.

4. Fix the allograft and the inner fibula by means of a compression plate providing the best contact with the humerus at both sides.
5. Select the deep brachial vascular bundle as the recipient vessels.
6. Apply broad spectrum antibiotics therapy for one month after surgery

Epiphyseal transfer

Current indications for vascularised epiphyseal transfer include trauma, tumour and congenital disorders involving the growth plate of a long bone in children. The proximal humerus and the distal radius may be optimally reconstructed according to such a procedure (Figs. 8 and 9). Nevertheless, the procedure has occasionally been used in cases of custom made reconstruction of lower limb joints such as the hip and the knee. The aim of the procedure is to reconstruct the bone loss and simultaneously restore the growth potential, in order to effectively prevent future limb length discrepancy. Three donor sites have been suggested so as to reconstruct epiphyseal defects in children: the iliac crest, the inferior portion of the scapula and the proximal fibular epiphysis. All the above mentioned segments can be harvested with minimal morbidity in the donor area and all contain active growth plates. However, the iliac crest and the scapula are anatomically classified as apophysis and do not have the features of a true epiphysis.²³ In particular, they fail to provide a true articular surface when growth finishes, casting a shadow on the long term result. By contrast, the proximal fibular epiphysis meets all the biological and biomechanical requirements in case of replacement of the epiphyseal portion of a long bone, making it the best option for reconstructing the distal radius and the proximal humerus in the paediatric age.

The blood supply of the fibula has been extensively studied.^{24,25} The anterior tibial artery provides a constant recurrent branch to the proximal fibular physis and may

therefore be used as the vascular pedicle for a distant transfer. Since the diaphyseal and the epiphyseal vascular networks are not connected to each other until the skeletal maturity is reached,²⁶ in order to guarantee sufficient blood supply both to the epiphysis and to the diaphysis it has been suggested to provide the graft of two independent pedicles.^{27,28} This option needs multiple anastomoses, an extensive surgical approach, a very long operative time. This long ischaemia time, may put at risk the viability of the germinative cells of the growth plate. Taylor's anatomical investigations²⁹ confirmed the role of the anterior tibial artery in the vascularity of the fibular growth plate. They also demonstrated that sufficient blood supply can be provided to the proximal diaphysis by small musculoperiosteal branches. Thus, the anterior tibial artery is able to supply the graft, provided that both the epiphyseal vessels and the diaphyseal periosteal vascular network are preserved during the dissection.

The harvesting technique of the proximal fibula based on the anterior tibial artery vascular network has been recently refined.^{30,31} We modified the original technique described by Taylor et al. in 1988,²⁹ introducing a reverse flow model which provides a very long distal vascular pedicle and avoids the use of vein grafts. An anterolateral approach in the space between tibialis anterior and extensor digitorum longus muscles, prolonged proximally and laterally up to the biceps femoris tendon, is chosen in order to expose the fibula and the vascular pedicle. Great care must be taken in dissecting the peroneal nerve from the anterior tibial vascular vessels and in preserving the musculoperiosteal branches to the diaphysis of the fibula. Direct dissection of the epiphyseal recurrent branch is not recommended because of the high risk of injury. This small vessel must be protected by a muscular cuff including the portion of the extensor digitorum longus and peroneus longus muscles which are proximal to the intersection of the peroneal nerve. A strip of biceps femoris tendon is included in the graft and used for soft tissue repair in the recipient site.

Distal radius reconstruction is facilitated by the perfect correspondence in size with the host bone. Bone fixation is

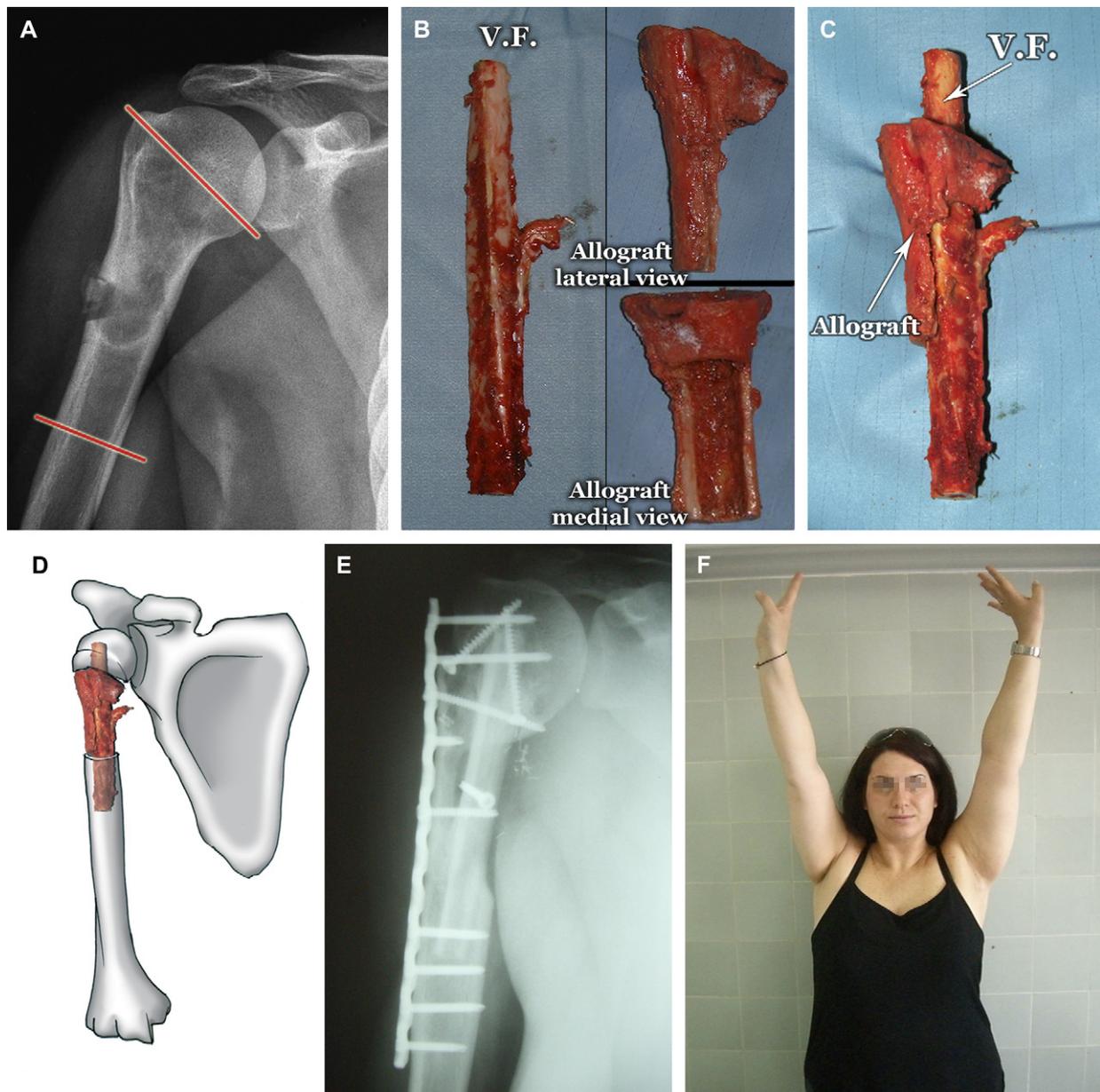


Figure 7 A: The oncological margins required for clearing this bone sarcoma needed to be very wide. The residual portion of the humeral epiphysis is too small to provide a stable osteosynthesis with the V.F.G. B, C and D: This problem may be tackled assembling a V.F.G. inside a humeral allograft of appropriate size. E: A bridging LC plate was used for fixation. F: Early union and optimal functional recovery were achieved thanks to a stable osteosynthesis.

usually achieved by plates and screws. The vessels are anastomosed end to end either to anterior interosseous or radial arteries, and the cephalic vein. Bleeding from the muscular cuff which surrounds the epiphysis after microvascular repair, indicates the restoration of the flow to the growth plate. The radiocarpal joint is stabilised using the biceps femoris tendon strip which is woven into the residual distal capsule.

The diameter of the humerus is approximately double, if compared to the fibula, and this anatomical mismatch is dealt with by an intramedullar insertion of the fibula shaft. In order to provide an elastic implant, the subsequent osteosynthesis should be achieved by a long locking compression plate with unicortical screws. The preferred

recipient vessels are the deep humeral artery and vein. The gleno-humeral capsule and rotator cuff are gently sutured around the fibular epiphysis to stabilise the joint.

In our experience the growth rate to be expected after the transplant, ranges between 0.7 and 1.4 cm. per year.^{32,33} The factors which might interfere with the growth of the graft can be summarised as follows:

- The age of the patient: the growth potential is a function of the age and it can change as long as skeletal maturity is not reached
- The recipient anatomic district: the new heterotopic location influences the growth by means of mechanical and humoral factors

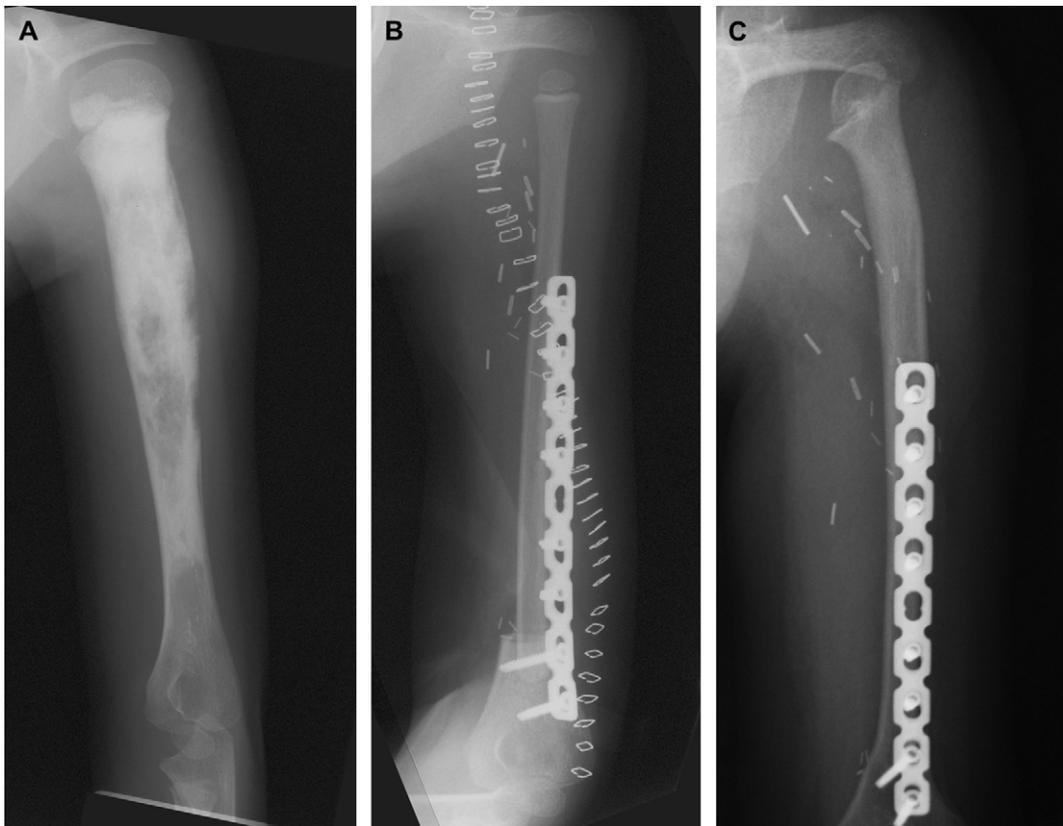


Figure 8 A: Extensive osteogenic sarcoma located in the proximal humerus required a subtotal resection of the humerus in a 7-year-old boy. B: Reconstruction has been achieved by means of an auto-transplant of proximal fibula on the anterior tibial vascular network. C: Longitudinal growth and remodelling at three years from surgery.

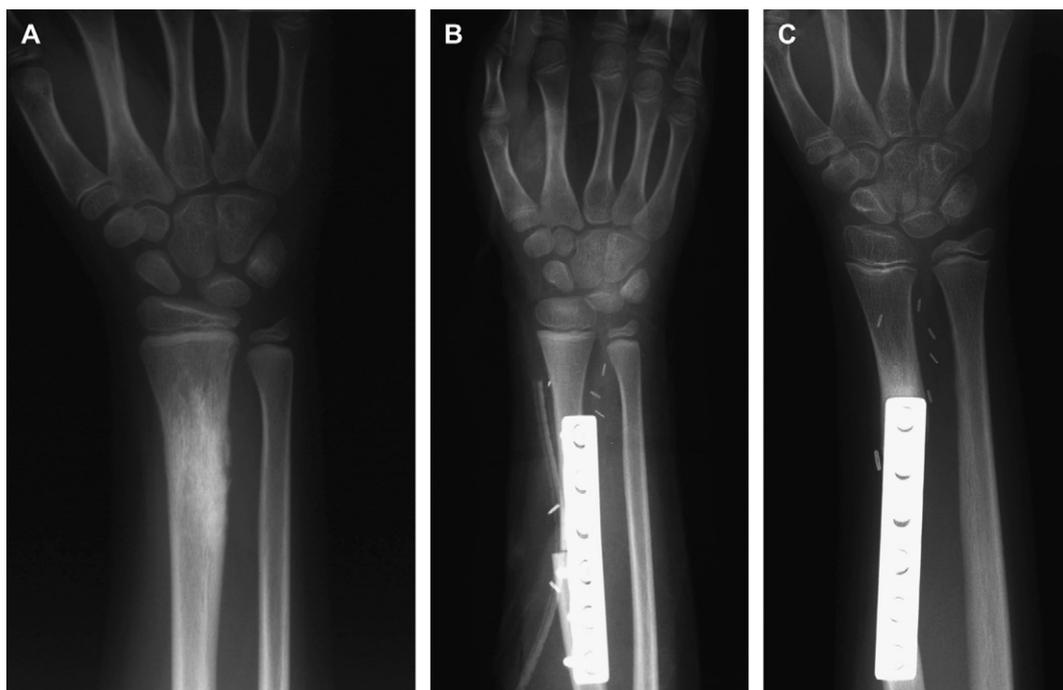


Figure 9 A: Osteogenic sarcoma. B and C: Following reconstruction by proximal fibula vascularised graft.

- The blood supply: the quality and the quantity of blood supply and their variations have inevitable repercussion on growth
- Adjuvant chemotherapy: it is routinely administered preoperatively and postoperatively in case of bone sarcomas. An inhibition of the skeletal growth is reported as one of the side effects.

From a functional standpoint, excellent results are usually achieved in distal radius reconstruction (Fig. 10). In our series, all patients recovered a nearly normal range of motion on all planes and the wrist turned out to be pain free and stable. Neither axial deviation nor subluxation of caput ulnae has been observed. The articular surface underwent significant remodelling, governed by the loading stresses present in the new location, developing

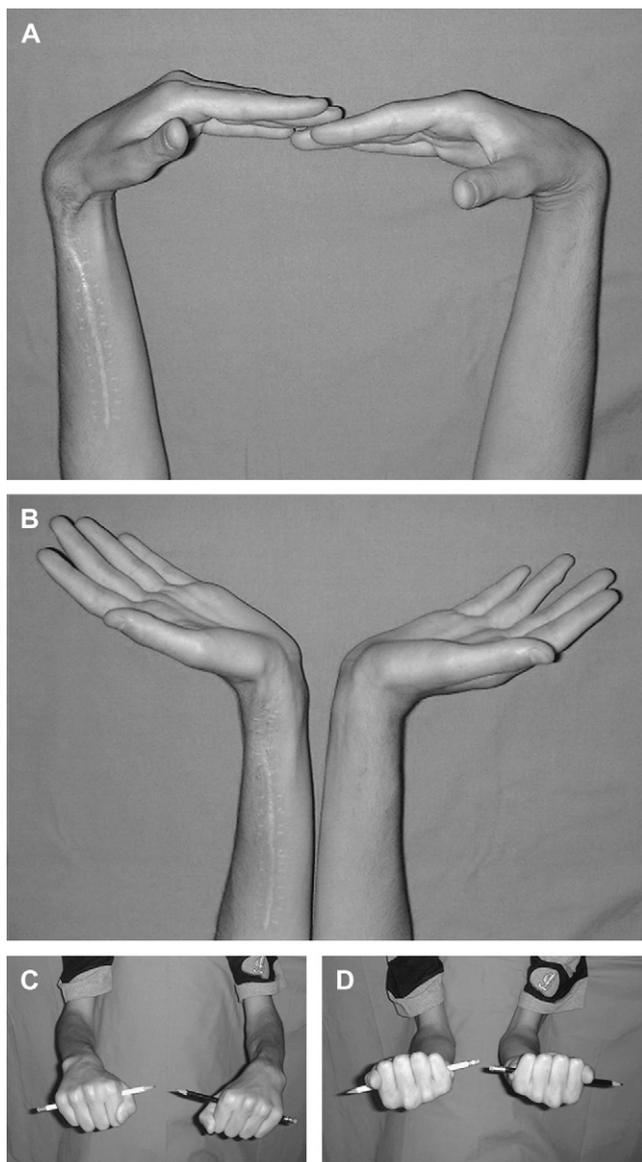


Figure 10 Excellent functional results may be expected in distal radius reconstruction. A: Flexion and (B) extension of the wrist are as much as 80% of the contralateral side. C, D: Prono-supination is nearly normal.

a concave surface which improved stability and range of motion.

Proximal humerus reconstruction provides less exciting results due to anatomic mismatching between fibular head and glenoid. In addition, all the tumour cases are complicated by the ablation of a variable amount of the muscles with negative consequences in active motion. However, acceptable range of motion for daily activities can be expected in all cases (Fig. 11), and epiphyseal transplant maintains its supremacy over conventional techniques also in this anatomic district.

The procedure may be summarised as follows:

1. Use an anterolateral approach to the fibula
2. Carefully dissect the peroneal nerve from the anterior tibial vascular bundle. Take into account the possibility of damaging some motor branches which must be repaired with microsurgical technique
3. Harvest a strip of biceps femoris tendon together with the bone
4. Harvest a long distal pedicle for reverse flow anastomosis
5. Perform stable bone fixation with the recipient bone with plates. In case of total resection of the radius, a radio-ulnar surgical synostosis is recommended.

Although the procedure is technically demanding because of the difficult dissection of the vascular pedicle and not complication free, this reconstructive option is now sufficiently refined and reliable to be applied in a multitude of pathologic conditions including trauma, tumour and congenital disorders. The major complication in a personal series of 27 cases consisted of a temporary palsy of the peroneal nerve which, in the vast majority of patients, recovered within 8 months from surgery.

Long bone-small defects: corticoperiosteal flaps

Most nonunions of the long bones can be successfully treated by rigid fixation and non-vascularised bone grafting.^{34–38} However, some will repeatedly fail to unite in spite of a well executed operation.

González del Pino et al.³⁹ defined as 'recalcitrant non-union' one that has had three or more previous treatment attempts; conventional methods would most probably fail in this setting. Furthermore, the presence of some comorbid factors such as previous infection, initially open fracture, aggressive internal hardware, or the need of a flap at any stage, will markedly worsen the prognosis due to local bone devascularisation and scarring. The non-union rate in this situation may be so high that a vascularised bone graft may be justified primarily.³⁹

The dilemma we face when using conventional donor sites (fibula, iliac crest) for this problem, is that most nonunions on long bones of the upper extremity have a small bone defect (1–2 cm), and it is very difficult to guarantee the nutrition of a small bone segment. Furthermore, most cases are located in distal areas, around tendons, and there, large volume increments are poorly tolerated. For this scenario the periosteum, rather than

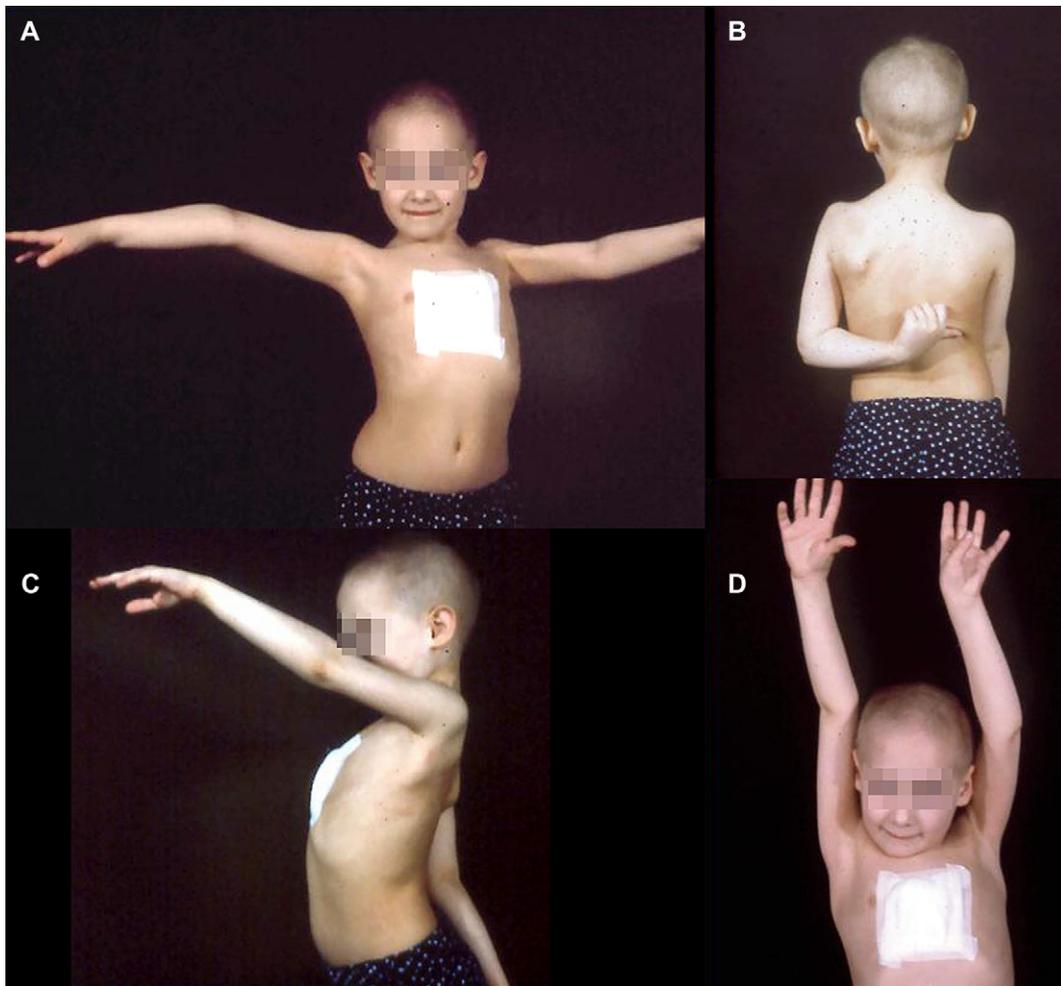


Figure 11 In humeral reconstruction some limitation in motion secondary to anatomical mismatching and muscular ablation for oncological reasons are to be expected. (A,B,C,D) However, the overall range of motion is usually sufficient for everyday activities.

the bone, would be ideal, as it is thin, pliable, well vascularised, and has intrinsic bone forming potential.

The first attempts to transfer the periosteum in the extremities were only partly successful.^{40–42} Doi and Sakai^{43,44} realised that when the periosteum was elevated from the bone, the deeper periosteal layer which has the highest bone forming potential (known as cambium layer) was damaged. They modified the harvesting procedure by including a thin stratum of cortex on the depth of the flap keeping the 'cambium layer' intact.⁴⁵

Sakai and Doi's flap is harvested from the medial femoral condyle. It can include, at times, a skin paddle (the saphenous flap) and we have some experience including muscle (a portion of the vastus medialis). The main problem of this flap comes from the fact that the medial condyle is vascularised competitively by the articular branch of the descending genicular artery and the superior medial genicular artery. In the first case a long pedicle (8–10 cm) will be available, but in the second only 3–4 cm of pedicle will be obtainable after a painstaking dissection.

The medial femoral condyle is approached, under tourniquet, through a longitudinal incision in the medial aspect of the distal thigh. The vastus medialis is dissected from the medial intermuscular septum, and reflected

anteriorly. The blood supply to the periosteum would then be assessed and a decision made as to which vessel to base the flap on (Figs. 12 and 13). The original authors recommend harvesting the periosteum with a thin layer of cortex with a chisel so as to make the graft pliable. We prefer to include a layer of spongiosa on the depth of the graft, in this way transferring a larger amount of vascularised bone. With the help of an oscillating saw the cortex can be cut allowing bending of the flap (Fig. 14).⁴⁶

On the recipient side, the nonunion is cleared of fibrous and scarred tissue. The bone ends are stabilised with a plate, and the gap is filled with cancellous bone graft taken from the medial femoral condyle. The periosteal flap is then wrapped around the nonunion on the side opposite the plate and stabilised there with sutures. The flap is revascularised to local vessels end to side.

Our experience with corticoperiosteal graft in the upper limb is limited to six cases and has been recently reported.⁴⁶ In five cases we dealt with long bone nonunions: two humerus, two ulna and one radius, and in one the flap was used to achieve fixation on a difficult arthrodesis. All nonunions have had multisurgery (from 3–7 procedures) prior to the 'salvage' operation. In every case the bone was debrided and rigid fixation was obtained by using

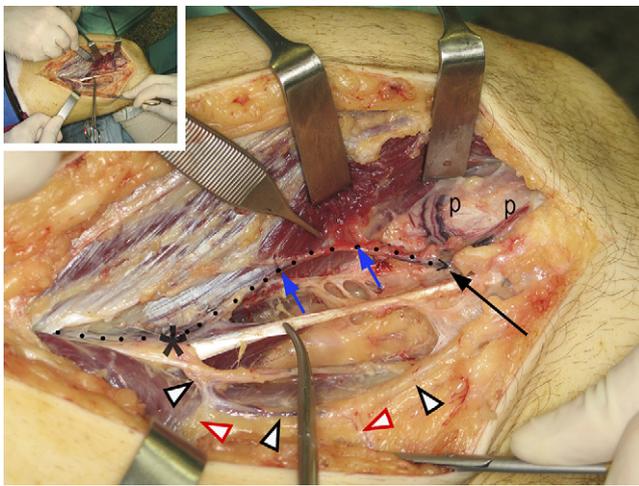


Figure 12 Intraoperative view during harvesting of a medial condyle corticoperiosteal flap showing the vascular anatomy. The descending genicular artery has been marked with dots. An asterisk highlights the division of saphenous (cutaneous) branch and the articular (periosteal) branches. Before it ends on the periosteum (p: periosteal branches) it gives off several muscular branches to the vastus medialis (blue arrows). The superior medial genicular artery has been ligated (long black arrow). The course of the saphenous vessels has been highlighted by hollow arrows and two perforating branches to the skin with hollow red arrows. (Inset: corresponding panoramic view).

LC-DCP or LCP reconstruction plates. Cortical gaps were frequently asymmetrical, varying at its minimum aspect from 0 to 3 cm, and at its maximum side from 2 to 3.5 cm. The defect was filled with cancellous bone chips taken from the femoral condyle and the periosteal graft was placed opposite to the plate embracing the nonunion. In most cases it was stabilised by suturing to the plate. Range of motion was started immediately after the operation. All achieved radiographic union in less than 2.5

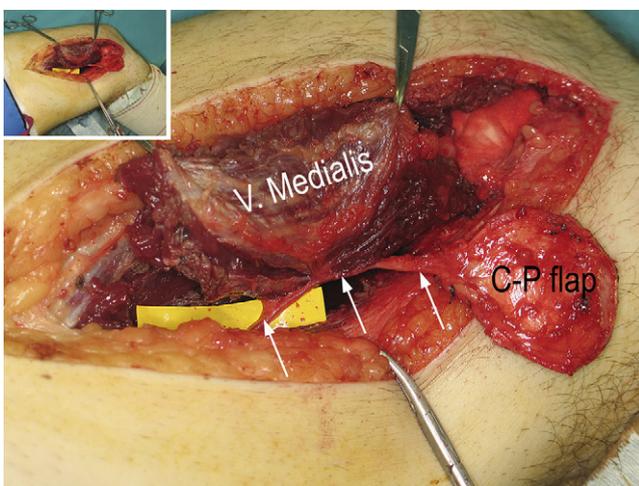


Figure 13 The combined muscular (vastus medialis) and corticoperiosteal (cp) flap has been elevated to solve a compound bone-soft tissue loss. The course of the descending genicular artery and vein are highlighted by arrows. (same patient as Figure 12).

months (Fig. 15). All returned to their previous work, or level of sports activity, except one patient who had concomitant injuries. No complaints from the donor site were referred after 2 months.

Surprisingly this flap has not become very popular, and apart from the original authors' investigations^{43,44,47} only three clinical papers have been published in the English literature.^{46,48,49} This lack of widespread usage may come from the fact that the anatomical variations might make the 'occasional' microsurgeon feel very uncomfortable. This is a shame, because it is an excellent tool for minor defects in long bones, and we have been impressed by its performance. Once the anatomy is mastered and understood, the flap is very straightforward to elevate and can be harvested in less than one hour. There are many flaps in modern microsurgery, that do not have a classic picturebook anatomy, but the surgeon has to raise it 'free style':⁵⁰ this flap deserves a second opportunity. The reader is referred to the original papers of Sakai and Doi for further details.^{43,44} If combinations with the saphenous flap are considered then the original Acland's et al. paper should be consulted.⁵¹

Small bone-small defects

Intercalated defects at the fingers or metacarpals can be reconstructed most times with non-vascularised bone grafts and, if needed, some type of local or free flap.⁵²⁻⁵⁶ However, as stated above when the defect is long, or because of the poor local conditions, non-vascularised bone grafts are likely to fail^{14,37,39,57}, making vascularised bone graft a reasonable alternative.

The difficulty at the fingers is the lack of a safe vascularised bone graft donor site. Classic donor sites such as the fibula or the scapula were impractical, and small bone graft donor sites, such as the medial condyle,⁵⁸ the modified iliac crest,⁵⁹ or even the radial metaphysis,⁶⁰ are unable to carry a skin flap that matches a soft tissue defect in a finger.

The metatarsals have been used as an alternative since the early days of microsurgery,⁶¹ but they are too big for the digits. Both MacFadden⁶² and Isenberg⁶³ presented case reports in which a hemimetatarsal was transferred successfully for reconstructing intercalated defects of the fingers, making up for the size problem. We have had some experience with both techniques, but were not totally satisfied. At times, if the segment needed is too small, the bone block may end up being minimally vascularised. This is due to the fact that most metatarsal have dominant nutrient arteries and hence less developed periosteal branches.^{64,65}

Conversely, the blood supply to the toe phalanges have been studied and is rarely dependent on a single nutrient artery⁶⁶ but on tiny periosteal and capsular branches coming from the digital arteries.^{65,67} Two constant arcades encircle the neck of the proximal phalanx and the base of the middle phalanx.^{65,67} At the base of the proximal phalanx, branches that derive from the plantar and dorsal digital arteries and lead to the bone have been identified.^{65,67}

When faced with a small bony defect in a finger that requires a vascularised graft, our preferred donor site is a composite middle toe phalanx or a part of a proximal phalanx (Fig. 16). The surgical procedure is similar to

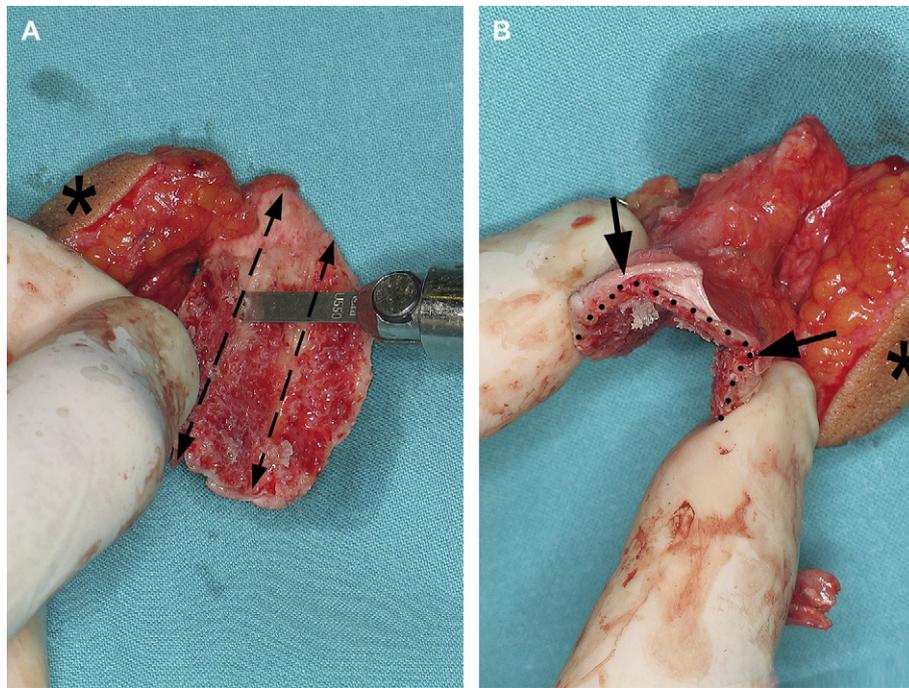


Figure 14 Bony tailoring of the corticoperiosteal part. A: The deep (spongiosa) surface of the flap is being carefully cut with an oscillating saw to the periosteum. Black striped lines mark the osteotomies. B: After the two osteotomies, 90° rotation of the 'wings' of the bony paddles is possible. The flap would be placed opposite the plate. In this case the flap was raised with a skin island (asterisk).

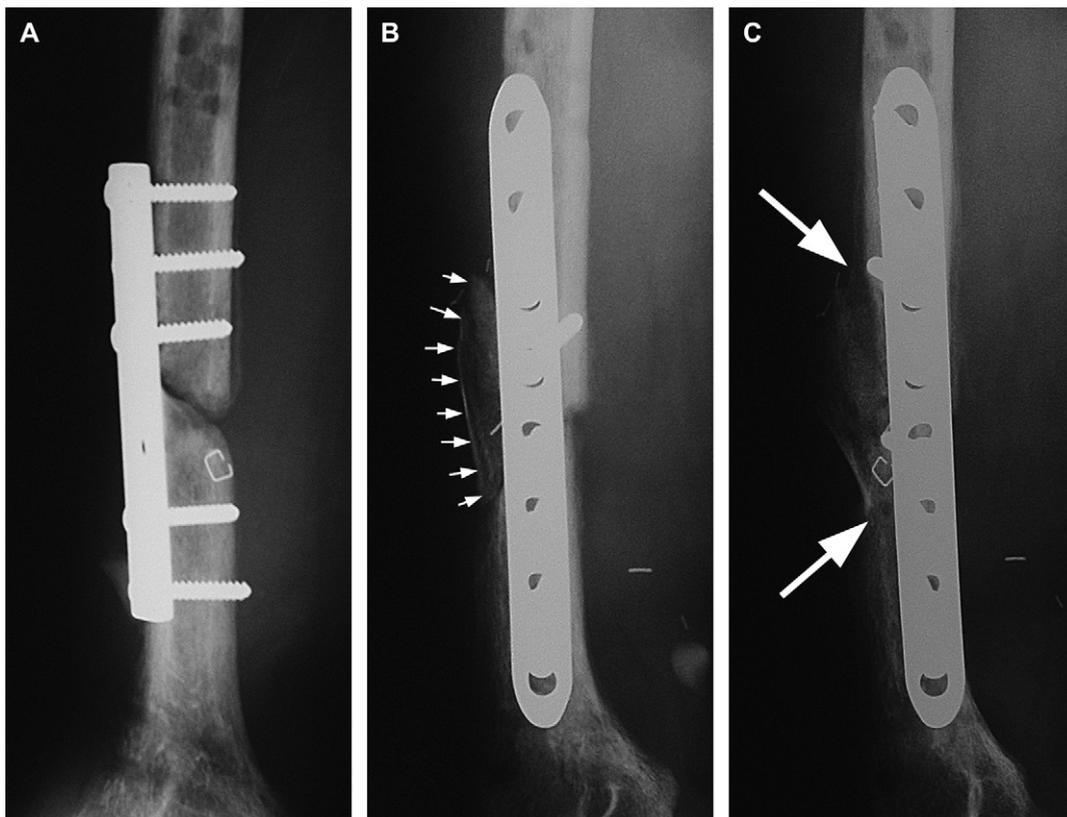


Figure 15 Atrophic humeral nonunion. A: Status after an open humeral fracture treated elsewhere with a pedicled latissimus dorsi and two previous attempts for achieving union. B: Small arrows point to the corticoperiosteal flap lying on the humerus two weeks after surgery. C: Bony union 2.5 months after surgery (arrows).

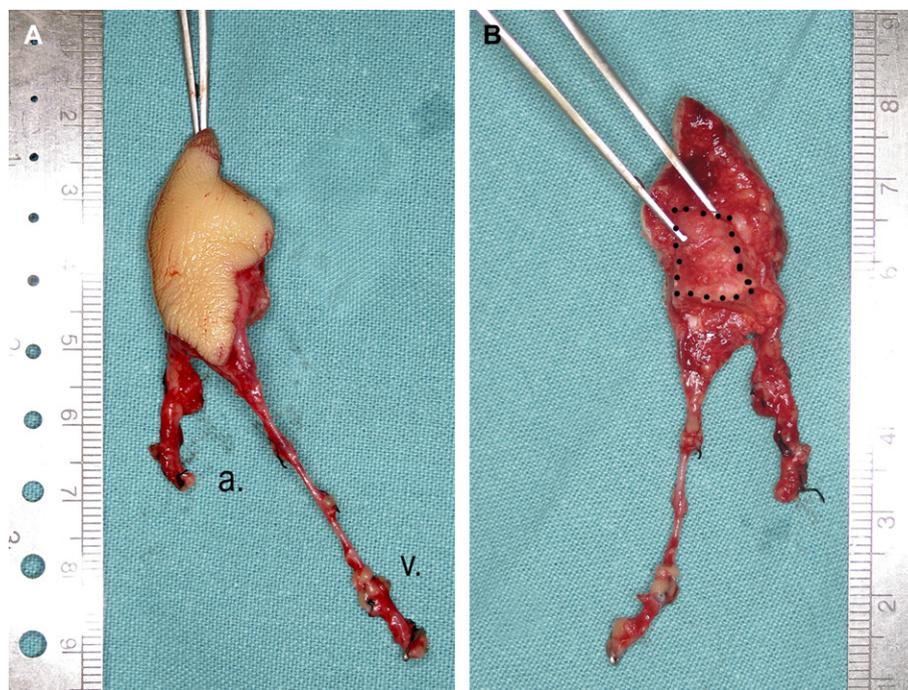


Figure 16 The second toe phalanx vascularised flap. A: Medial aspect of the flap. (a: tibial digital artery; v: subcutaneous vein). B: Deep aspect of the flap showing the middle phalanx (dots).

a standard toe harvesting with some particularities highlighted below. The skin flap is designed over the bone to be harvested. Through a dorsal zigzag incision a subcutaneous vein is first dissected. The skin flap is incised on the side of the pedicle and elevated plantarwards. It is essential to keep intact the connections between the digital artery, the donor bone, and the vein dorsally by including a small soft tissue cuff in the vicinity of the bone. The corresponding digital nerve is separated from the digital artery, reflected plantarly, and left on the toe. The digital artery is then dissected proximally and side branches are tied off with 5/0 silk, clips, or 9/0 nylon depending on their size. Traction on these tiny branches is to be avoided, as avulsion from the main digital artery may cause persistent spasm or even failure of the part to be revascularised. It is vital to isolate and ligate a couple of constant but tiny arterial branches of the digital artery that are located just proximal and distal to the toe's proximal interphalangeal joint. After a very short course from its origin these branches dive deep into the tendon sheath, and are equivalent to the proximal and middle transverse digital arteries of a finger.⁶⁸ These branches can be a source of bleeding and spasm if inadvertently cut or avulsed. The surgeon should specifically look for them, and dissect them for 2 to 3 mm so as to gain enough room to pass a ligature around them. At times this may require opening the tendon sheath.⁶⁹ The digital artery is then ligated distally to the bone to be harvested.

Once the dissection on the pedicle's side is terminated, the contralateral side is rapidly dissected out by incising the skin island and performing a subperiosteal dissection of the phalanx, preserving in place the neurovascular bundle. The segment of bone to be harvested is then cut, while still in place on the toe, as afterwards it is very difficult to manipulate the small block of bone. The flap is usually

pedicled on a digital artery and a subcutaneous vein. This makes the microsurgical part a bit more difficult but the dissection is very straightforward and less destructive for the foot.

The donor toe can be preserved in every case whenever a phalanx or part of a phalanx is harvested. The other pedicle maintains the blood supply to the toe, and the space is partially closed by axial collapse and by suturing the extensor to the flexor tendons in a similar way to that recommended for children when non-vascularised proximal phalanx is harvested.⁷⁰

We have reconstructed 11 cases of bony defects in the fingers. In all cases a skin paddle was included for covering and/or obliterating dead space. Two cases were metatarsal segments and the rest vascularised toe phalanx (or part of a phalanx). In nine cases the bone defect had a concomitant infection which was cleared by one-stage radical debridement and bone graft transfer (Fig. 17). With this protocol we were able to clear the infection primarily in all but one case.^{71,72} The rest had different forms of combined defects, including four where a piece of vascularised cartilage was included (see below).

Vascularised osteochondral grafts

Cartilage defects have been traditionally treated in the hand by perichondrial resurfacing,⁷³ or non-vascularised osteochondral grafts (fibula, rib or toe segments).^{74–76} Unfortunately, although the initial X-rays may look excellent, the mid term results have been variable: a physiological explanation may be behind the scenes. We have all been taught that the cartilage gets its nutrients from the synovial fluid, the blood flow playing a minimum role, if any.⁷⁷ However, there is experimental evidence that at least on the deep

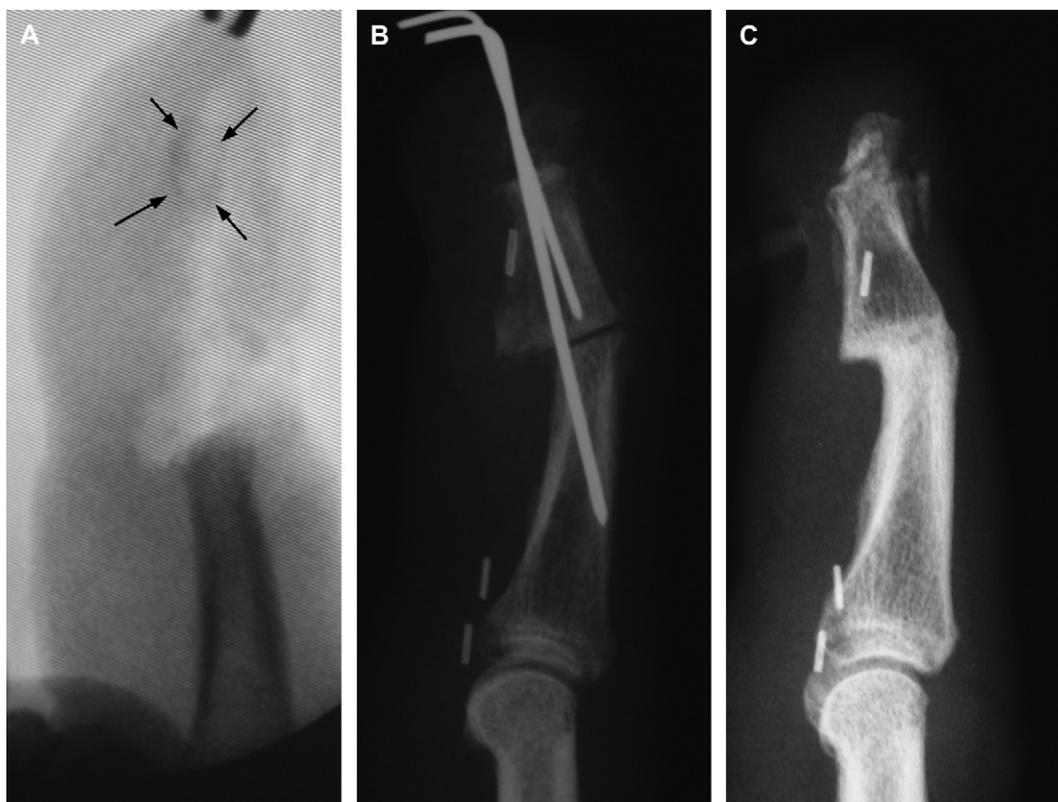


Figure 17 Fifty-seven-year-old patient with a chronic infection in the DIP joint-distal phalanx region after an open comminuted fracture-dislocation. A: Radical debridement of the infected bone left only a small chip of the tuft of the distal phalanx which could be preserved (limited by arrows). A concomitant soft tissue defect is evident. B: The vascularised middle toe phalanx interposed on the defect. C: Result at one year (the patient continues to be free of infection at the latest follow-up visit, 2 years after the operation).

layers the blood supply of the subchondral bone is important in cartilage metabolism.^{78,79} This is underscored by the fact that vascularised joints maintain the articular space in the long term,⁸⁰ while non-vascularised joints collapse.^{65,81} So, contrary to classic teaching, present evidence points to a major role of the blood supply in chondral biology (at least on the osteochondral interface).

Bearing in mind that bone has been transferred for years and that it maintains its biological and mechanical properties when its vascular nutrition is kept intact,^{1,11} we intuitively thought that osteochondral grafts, particularly large ones, should be transplanted with their blood supply intact too.

It is not uncommon that after fracture a large segment of the cartilage of the scaphoid or lunate fossae is found to be irreversibly damaged. When this occurs the only alternative is to perform some form of radiocarpal fusion: radio-lunate or radio-scapho-capitate fusion.^{82,83} Partial arthrodeses, however, limit the range of motion at the wrist and overload the neighbour mobile joints. Giachino et al., were the first to reconstruct these defects by using non-vascularised osteochondral blocks taken from the proximal tibio-fibular joint.^{84,85}

We searched for a donor site, which being vascularised was similar to the distal radius facet. We initially focussed our interest on the proximal fibular epiphysis. However, the anatomy of the tibial facet of the proximal fibula is

variable, the amount of transferable cartilage small, and morphologically quite different from the distal radius surface.^{86,87} Furthermore, although remodelling has been shown by Innocenti et al. in children,³³ in adults the dissimilarities are such, that degeneration by incongruity is to be expected,^{88,89} regardless of the fact that the cartilage is living. Hence, we disregarded this potential donor site, and we focussed our attention on the base of the third metatarsal, which has a size comparable to a scaphoid or to a lunate fossa.⁹⁰

The base of the third metatarsal has a dual blood supply, sometimes depending on the distal lateral tarsal artery, and others on the arcuate artery. Both arteries are direct branches of the dorsalis pedis axis. In our anatomical study we found that in some cases both were dominant whereas in others one of them was reduced to a minute twig (Fig. 18-A). Again as in the case of the corticoperiosteal flap, a 'free style' harvesting is necessary.⁵⁰

To reconstruct the distal radius facet we proceed as follows. The recipient site should be assessed first as to know the donor site requirements, and above all to know the conditions of the cartilage of the scaphoid, lunate, and the distal radius. If the cartilage of any of the carpal bones is damaged then we proceed to a limited arthrodesis.^{82,83} Conversely, if we think that the cartilage of the radius is not irreversibly damaged, but simply malunited, we proceed first to explore the joint with the arthroscope, as it

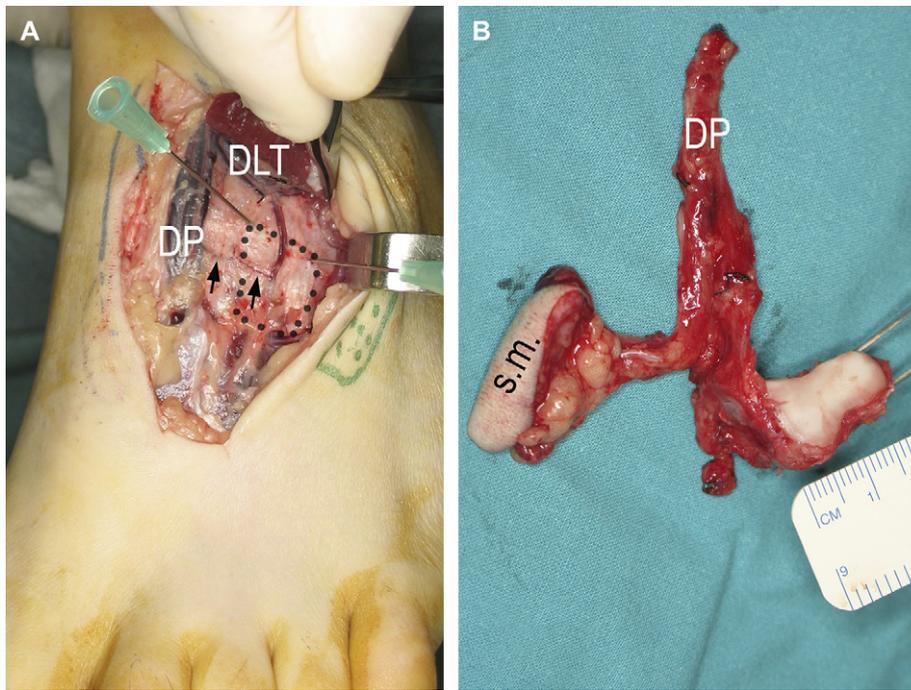


Figure 18 Intraoperative view during harvesting of the base of the third metatarsal. A: The vessels going to the base of the third metatarsal (limited by dots) are shown in this case in which the distal lateral tarsal artery is dominant. Conversely, the arcuate artery is small (highlighted by arrows). B: The harvested flap in this same case. (s.m.: skin monitor; DP: dorsalis pedis).

is possible to correct malunited fragments under arthroscopy.⁹¹ If the conditions for an osteochondral graft are set (i.e. damaged on the cartilage of the radius but preserved on the opposing carpal bones) we proceed to create a tridimensional defect on the distal radius so as to leave room to fit the graft.

The technique of raising the flap has been detailed previously.⁹⁰ Briefly, the foot is approached through a zigzag incision in the cleft between the extensor hallucis longus and the extensor digitorum longus. The extensor hallucis brevis is cut and retracted laterally together with the extensor digitorum longus, which will expose the blood supply

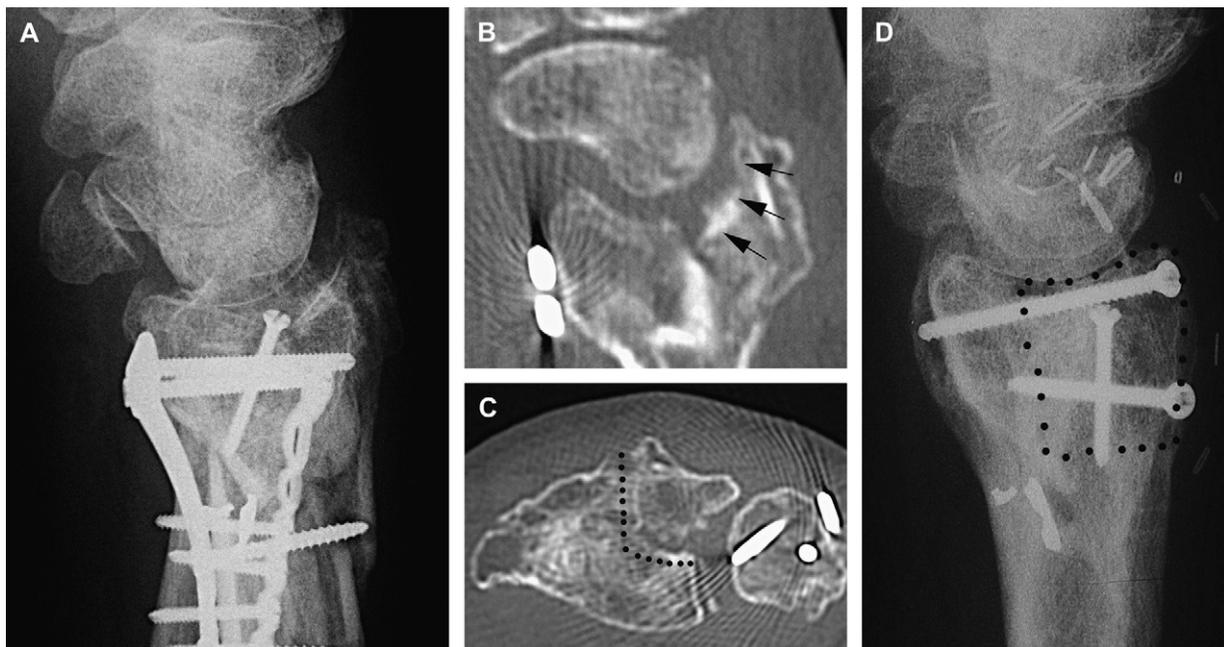


Figure 19 A: Preoperative X-rays of a patient with a malunited lunate facet of the distal radius. B: In the sagittal CT scan damage on the malrotated fragment is shown (arrows). C: The area to be excised has been marked with dots in this axial view. D: X-ray 18 months after the operation. The osteochondral fragment is delimited by black dots.

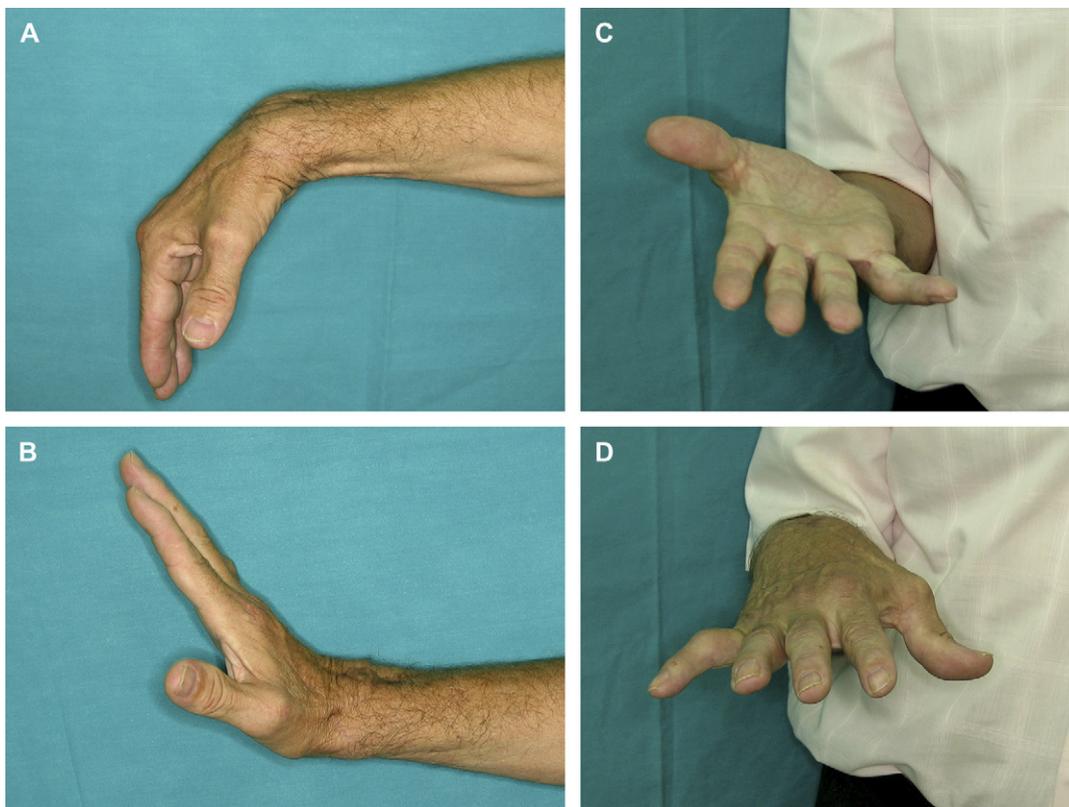


Figure 20 A–D: Functional result of the same patient.

to the dorsum of the foot (Fig. 18-A). Once the anatomy is clear the base of the metatarsal is cut and pedicled on the dorsalis pedis. A skin monitor is elevated in every case to control the transplant (Fig. 18-B). The osteochondral graft is tailored to fit into the defect and rigidly fixed there. Revascularisation is done end to side to the radial artery and to local veins.

The donor site is simply closed under an aspirative drainage. Protected deambulation on a rigid sole shoe is allowed after 3–5 days. On follow-up radiograms the metatarsal recedes slightly which seems to be the key of not having had any case of metatarsalgia to date.

We have a limited experience of three cases of distal radius facet reconstruction (two lunate fossa, one scaphoid fossa) with a follow up longer than one year (Figs. 19 and 20). Our results^{92,93} have been very satisfying with improvements in range of motion and above all in pain (Flexion-extension 91°; Grip 72% of the contralateral; Pain on a VAS 2). The main difficulty of the technique comes from the variability of the anatomy, however. On the other hand, the size of the parent dorsalis pedis vessels makes them quite accessible for the occasional microsurgeon.

We have also reconstructed small cartilage defects at the PIP and MCP joints by using vascularised bone grafts taken from the toe phalanges.⁷¹ The principle is similar to the above and the bone harvesting technique has already been presented in Section 3 of this article. Our experience is limited to four cases with a follow up longer than one year. The articular space has been maintained and range of motion improved from the preoperative situation.

The vascularised osteochondral graft concept can be exported to other fields of orthopaedic surgery, where focal

damage to the cartilage needs to be replaced by like tissue. New donor sites would need to be investigated in cadaver, so as to find tridimensional blocks that would fit into a given defect. This latter issue seems to be the main limitation when considering its application to large joints such as the knee or the shoulder. However, for the hand and wrist, donor site availability is not so much a problem and we foresee a wider application of this concept. We are at this moment investigating cartilage biology in osteochondral grafts in the experimental animal.

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