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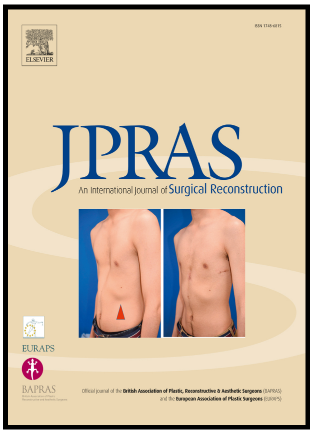

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In search of the ideal periosteal flap for bone non-union: The chimeric fibula-periosteal flap

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Short running head: Free chimeric fibula-periosteal flap in non-union

Abstract

Vascularized periosteal flaps may increase union rates in recalcitrant long bone non-union. The fibula-periosteal chimeric flap utilizes periosteum raised on an independent periosteal vessel. This allows the periosteum to be inset freely around the osteotomy site, thereby facilitating bone consolidation.

Patients and Methods

10 patients underwent fibula-periosteal chimeric flaps (2016 – 2022) at Canniesburn Plastic Surgery Unit, UK. Preceding non-union 18.6 months, with bone gap 7.5cm. Patients underwent pre-operative CT angiography to identify periosteal branches. A case-control approach was used. Patients acted as their own controls with one osteotomy covered by the chimeric periosteal flap

and one without, although in two patients both osteotomies were covered by a long periosteal flap.

Results

A chimeric periosteal flap was used in 12 of 20 osteotomy sites. Periosteal flap osteotomies had a primary union rate of 100% (11/11) versus those without 28.6% (2/7) (p=0.0025). Union occurred in the chimeric periosteal flaps at 8.5 months versus 16.75 in the control group (p=0.023). 1 case excluded from primary analysis due to recurrent mycetoma. Number needed to treat = 2, indicating that 2 patients would require a chimeric periosteal flap to avoid one non-union. Survival curves with hazards ratio 4.1, equating to 4 times higher chance of union with periosteal flaps (log rank p=0.0016).

Conclusions

The chimeric fibula-periosteal flap may increase consolidation rates in difficult cases of recalcitrant non-union. This elegant modification of the fibula flap uses periosteum that is normally discarded, and adds to accumulating data supporting the use of vascularised periosteal flaps in non-union.

Keywords

Periosteum; Fibula; Fractures, ununited; Free tissue flaps; Computed Tomography Angiography; Non-union

Introduction

History of Microvascular options in Long Bone Non-union

The incidence of long bone non-union is 5-10%, with bone grafting and revision of fixation failing to resolve in 31% [1]. Even after multiple revisions, recalcitrant non-union ultimately affects 3% of these cases. These recalcitrant cases - in particular poorly vascularised atrophic non-unions and post-radiotherapy non-unions [2] - are significantly more challenging to resolve, with secondary non-vascularised bone grafts resulting in poor outcomes [3]. Here, a vascularised transfer may be required to facilitate successful union [4]. The concept of microvascular transfers to aid in non-union, has been utilized since the 1970s, initially with vascularized fibula transfers and other osseus flaps [5]. This gradually evolved with the advent of vascularized periosteal flaps in the 1980s, secondary to Masquelet's seminal work involving experimental validation of the osteogenic potential of periosteal flaps [6 7 8]. However, reports on the use of periosteal flaps in long bone non-union were relatively sparse, until Kaminski et al. 2008 discussed the use of free vascularized corticoperiosteal flaps in the treatment of non-union of long bones, lamenting a potential ignored opportunity [9]. Interest has increased in the last decade and systematic reviews now support the use of periosteal flaps in recalcitrant non-union with pooled data indicating a 99% union rate [10].

Limitations of the Medial Femoral Condyle Periosteal Flap in non-union

There are a number of technical limitations related to the medial femoral condyle periosteal flap that are not clearly elaborated in previous studies. Firstly, medial femoral conydle flaps are too small to cover many defects in long bone non-union, particularly larger bones like the femur. Although flaps as large as 8 x 6cm have been described this should not be considered routine, as biomechanical studies suggest an upper limit of 7cm to prevent iatrogenic stress fracture [9 11]. Other periosteal flaps (anterior tibial periosteum, fibula periosteum without cortical bone) have been described with larger surface areas but their use in non-union is less established, with data limited to non-comparative case series [12 13]. Secondly, non-union defects that include bone gaps (eg septic or radiotherapy related non-union where bone excision is required) require cortical bone, which is limited with the medial femoral condyle flap. Intuitively, many of these defects appear to be more suitable to a vascularized fibula transfer rather than periosteal flaps, which raises the question of why not simply resort to a standard vascularized fibula?

Limitations of Fibula Flaps

Standard vascularized bone flaps without additional periosteum have relatively high primary non-union rates. A primary non-union rate of 39% was noted in a review of 160 cases [14], and 19% in a multicenter study on sarcoma [15]. Methods to increase union rate have included the fibula "sleeve" technique, whereby periosteum is left redundant at both the proximal and distal ends of the fibula bone. This technique was initially described by Hung Chi Chen in reconstruction of mandibular defects, with CT indicating higher rates of union in comparison to a standard fibula flap [16]. Although we have used this technique successfully in non-union of small bones such as the clavicle, there are technical problems that limit its use. The most significant relates to insetting of periosteal 'sleeve', as there is often a size discrepancy with the diameter of host bone (eg femur), meaning that the 'sleeve' is too small to wrap circumferentially around osteotomies in larger long bones. This is particularly relevant when the fibula is placed as a construct within a larger diameter bone such as the tibia, or proximal diaphyseal flare of the humerus. Secondly, as the distal portion of the fibula is used to reconstruct bony defects, the length of a distal periosteal sleeve is naturally often limited.

A novel approach to address non-union: the chimeric Fibula-periosteal Flap

These shortcomings of medial femoral condyle periosteal flaps (too small to cover larger osteotomies), standard fibula (high primary non-union rate), and the fibula periosteal ‘sleeve’ technique (problems with insetting of periosteum around osteotomies), have been addressed with a modification of the fibula flap. The split chimeric fibula-periosteal flap involves dividing the fibula flap into two separate segments – an osseus segment and a periosteal flap segment - supplied by independent pedicles from the peroneal vessels. This affords greater flexibility in insetting the periosteal flap around the osteotomy sites, as it no longer attached directly to the fibula cortex, and can therefore be wrapped transversely around larger diameter bones or positioned longitudinally to cover proximal and distal osteotomies. This study explores the impact of the chimeric fibula-periosteal flap on long bone non-union.

Methods

Caldicott Guardian approvals from Information Governance, NHS Greater Glasgow and Clyde, and study approvals through Governance department of Canniesburn Plastic Surgery Unit for retrospective case review. Additional ethics approvals not required following discussion with West of Scotland

Research Ethics service. STROBE guidelines followed for reporting case-control studies.

Non-union definition

Non-union is defined by the FDA (1986) as *'a fracture that has not healed for 9 months and has not shown radiographic progress for 3 months'*, or pragmatically as *'a fracture that has no potential to heal without further intervention'* [17]. However, given that all cases in this series are previous complicated non-union cases and not primary fractures, the FDA definition is not applicable. Here we use a non-union definition of healing at 14 months without further operative intervention, the mean time to union in one of the largest series of fibula flaps [18].

Outcome measures

This study employed a case-control approach. With each fibula having 2 osteotomy sites, the intervention group was the osteotomy site with periosteal flap and the control group was the standard osteotomy interface. Patients therefore acted as their own controls, except in two cases where the periosteal flap covered both osteotomies **(Figure 1).** Matching was therefore not required as controls were derived from the same intervention group. Primary outcome measure was primary union, based on review by both a radiologist and orthopaedic consultant. The null hypothesis was that there was no difference in union rates between periosteal and non-periosteal osteotomy sites. Patient reported outcomes (PROMs) included DASH score as part of routine patient care. Inclusion criteria included all patients who underwent a fibula-periosteal chimeric flap for long bone non-union or for prophylaxis of avascular bone scaffolds (extracorporeal irradiated bone or allograft), with a minimum of 14 months follow up (unless primary union occurred at both osteotomy sites prior to the 14 month cut-off). Exclusion criteria included patients with inadequate follow up period. Data collected by an independent researcher not involved in the surgical procedures. Statistical analysis with GraphPad Prism (version 9.5.0 MacOS, GraphPad Software, San Diego, California USA), significance level p=0.05.

Power

For retrospective studies, sample size calculations are not indicated. Post-hoc power analyses indicated 95.5% study power (dichotomous endpoint, two independent sample study).

Participants and Setting

11 patients underwent split fibula-periosteal chimeric flaps from 2016 to 2022 at Canniesburn Plastic Surgery Unit, Glasgow, UK, under the care of a single surgeon (SL) **(Table 1).** 1 patient excluded due to insufficient follow up period **(Flowchart 1).** Of the remaining 10 cases, indications were 6 infected non-unions, 2 atrophic, 1 radiotherapy related, and 1 prophylaxis of avascular bone scaffold in sarcoma. Duration of preceding non-union was mean 18.6 months, with bone gap mean 7.5cm. A chimeric periosteal flap was used in 12 of 20 osteotomy sites. Mean flap size 19.55cm^2. All operations documented with intra-operative photography. Flap positions recorded in operation notes corroborated with photographic records (discrepancy noted in 1 case).

Surgical Technique

All patients underwent planning with CT angiography prior to surgery, to delineate periosteal flap branches **(Figure 2; Supplementary Figures 1, 2).** The periosteal flap component was prepared on a back table. The osseus component was templated from the defect, and designed on the distal fibula. Prior to fibula osteotomy the periosteal branches to periosteum proximal to the osteotomy were identified **(Figures 3, 4; Supplementary Figure 3, 4).** These are relatively abundant and therefore one was chosen to allow conformation of the flap to the osteotomy sites. The periosteum was stripped from the un-used proximal bone segment using a periosteal elevator. When the periosteal flap was larger than the distal osseus segment, it was placed longitudinally and was able to cover both proximal and distal osteotomies **(Figure 5).** Otherwise the periosteal flap was wrapped transversely around a single osteotomy site **(Figure 6, 7).** Periosteal flaps were secured with suture fixation only. To confirm vascularisation of the periosteal flaps, the periosteal branch was assessed with doppler after anastamoses completed and flap edges checked for bleeding. In our initial cases we examined raising a 1-2cm distal periosteal sleeve in combination with the chimeric periosteal flap, but found that these could not be adequately inset around the osteotomy due to diameter discrepancy with the host bone **(Figure 8).**

Results

Union rates

Osteotomy sites employing chimeric periosteal flaps had a primary union rate 100% (11/11 osteotomies), and without 28.6% (2/7) at 14 months (Fisher's exact test p=0.0025) **(Supplementary Table 1, Supplementary Graph 1).** Of cases that did not unite primarily, two underwent further operative intervention. The first required two further bone grafts and revision fixation, uniting at 24 months. The second united after a secondary medial femoral condyle periosteal flap (at 26 months). Both of these delayed unions occurred at the osteotomy site without a chimeric periosteal flap. 1 case excluded from primary data analysis due to recurrent fungal mycetoma necessitating entire fibula segment removal prior to the 14 month cut-off period (at 12 months post surgery). Intra-operative tissue samples had been fungal free prior to fibula, and infectious diseases department concluded that this was due to abdominal translocation from alcoholic excess.

Time to union and Survival Analyses

Union occurred in chimeric periosteal flap osteotomies at 8.5 months [95% CI, 6.55, 10.36]. Union time in osteotomies without periosteal flaps (including the two cases requiring secondary surgery to facilitate union) was 16.75 months [0.45, 33.05]. Difference in mean union time was 8.3 months [1.34, 15.25] (unpaired t test p=0.023). A cumulative frequency curve indicated significantly different union rates over time (Log rank p=0.0016) **(Graph 1).** Hazards ratio 4.10 (95% CI 0.55, 82.78; Cox proportional hazards regression), indicating approximately 4 times higher chance of union at any time point with a periosteal flap.

Number needed to treat

2 patients would need treated with a chimeric periosteal flap to avoid one non-union. Odds ratios could not be calculated as adverse outcome incidence was 0% in periosteal group.

Surgical factors influencing non-union

A number of surgical factors may influence consolidation, including mechanical stability, insufficient debridement, and osteotomy position. No mechanical instability was noted in cases of non-union seen after fibula-periosteal flap, as these were all atrophic/oligotrophic non-unions and no instability was noted in cases requiring re-operation. With instability, a tendency to hypertrophic non-union with associated loosening of components would be more apparent. Debridement of both osteotomy ends to healthy, bleeding bone was done by the same senior orthopaedic surgeon blinded to the position of the periosteal flaps at time of debridement. Osteotomy position may have some effect on likelihood of consolidation, and therefore confounding by flap position was assessed [19]. Periosteal flap position at proximal osteotomy (n=6) or distal (n=5), and controls (proximal =3, distal =4) was not significantly different, p>0.99 (Fisher's exact test).

PROMs

Post-operative DASH score mean 42.08 [95% CI 18.91, 65.26].

Ancillary analyses

Mycetoma failure included

Data re-analysed with the single infective failure (mycetoma) case included, with both osteotomy sites imputed as worst outcome (non-union). Results remained significant (p=0.0044).

Using FDA definition

The FDA definition is **not** applicable for secondary non-union cases as previously explained. Nonetheless re-analysing data using this definition, results remained significant (periosteal group union = 8, non-union = 3; control group union 1, non-union 6; Fisher's exact test p=0.0498)

Comparison of Final Union rates irrespective of secondary surgery

Final union rates were 100% in chimeric periosteal osteotomies (11/11), compared to 57.1% in control osteotomies (4/7). This is a **confounded** analysis due to 29% secondary surgery rate in control versus 0% in periosteal group. Nonetheless results remained significant (Fisher's exact test, p=0.049).

Multiple Logistic regression of Non-union risk factors

Non-union risk factors such as age, smoking and radiotherapy [20] were not significant for FDA definition of union **(Supplementary table 2).**

Discussion

In search of the ideal periosteal flap

The chimeric fibula-periosteal flap was inspired by the incidental observation that ossification of the fibula vascular pedicle is seen in 27% of mandible reconstructions, due to residual periosteal attachments around the peroneal vessels [21]. This led us to explore the possibility of raising an independent periosteal flap from the proximal portion of the fibula, a section that is normally discarded or left attached to the peroneal vessels. Anatomical studies indicate a relatively high incidence of periosteal branches in the fibula, with a mean of 12.8 branches, an intersegmental distance of 1.36cm, and a 94% chance that a 2cm segment of periosteum will contain a periosteal branch [22]. Pre-operative CT angiography was used to aid identification of a separate proximal periosteal vessel from the peroneal pedicle [23].

The chimeric fibula-periosteal flap has a number of key advantages over a standard fibula. The key advantage is that incorporation of a periosteal flap may significantly improve union rates. Furthermore it makes use of redundant tissue that is normally discarded, and therefore creates no additional donor site morbidity. It also allows insetting around large osteotomy sites with larger host diameter discrepancies, which is not possible with the fibula “sleeve” technique. The chimeric fibula-periosteal flap also has benefits over the medial femoral condyle periosteal flap, namely that it allows a larger periosteal flap size and inclusion of a large segment of cortical bone.

Alogrithm for reconstruction of non-union defects

There are broadly four indications for periosteal flaps in bone non-union, including:

1. Atrophic or Oligotrophic Non-union
2. Septic non-union
3. Radiotherapy related non-union
4. Prophylaxis of high risk non-union in avascular bone scaffolds

Our approach for reconstruction is illustrated in **Flowchart 2**, and the supporting rationale for this algorithm is discussed below.

1) Atrophic non-unions without bone gaps

There are numerous classifications for non-union but broadly speaking, *hypertrophic* non-unions do not require any form of microvascular intervention. These are well vascularized and show radiographic evidence of attempts at callous formation, suggestive of a normal osteogenic response, and usually only require bone stablization with revision fixation. Instead it is the *atrophic* and *oligotrophic* non-unions, which are logically more suited to microvascular techniques. For these the choice of flap depends on the size of bone. For smaller defects without bone gaps, a medial femoral condyle periosteal flap may suffice. In larger defects particularly around the lower limb, the iliac fossa periosteal flap is preferred, which we recently described [24].

2) Septic non-union

Standard orthopaedic approaches to septic non-union include the two stage induced membrane technique (Masquelet technique), although non-union rates are relatively high at 27.8% [25]. Standard fibula flaps also have high reported non-union rates in septic non-union of up to 23% [14].

3) Radiotherapy associated Non-union

Radiotherapy related non-union has an incidence of 2-10% after adjuvant radiotherapy in sarcoma. Revision fixation results in an unacceptable non-union rate of 82%, with many culminating in endoprosthetic replacement or amputation [26]. Radiotherapy results in a stronger biological effect than periosteal stripping [27], essentially causing a severe form of atrophic non-union with reduced vascularization, abnormal periosteum and abnormal bone mineral: matrix composition. This lends itself ideally to the concept of the chimeric fibula-periosteal flap, as both the bone and periosteum are abnormal.

4) Prophylaxis of Avascular bone scaffolds

Avacular bone scaffolds - such as long bone allografts and extracorporeal irradiated bone - are typically employed in sarcoma defect reconstruction. These are notorious for high rates of non-union, with extracorporeal irradiation at 26% to 30% [28] [29] and allograft at 25.5% [29]. The use of periosteal flaps in these situations may obviate or reduce the need for multiple revisions to obtain final union. This is particular salient in the oncology patient, where general anaesthesia and repeated surgery are associated with immunosuppression and theoretical risks of tumour release from dormancy [30, 31]. Of note, in avascular bone scaffolds such as allograft, the diaphyseal (shaft) osteotomy generally takes longer to unite at 16 months, than metaphyseal (neck) at 6.5 months. Strikingly, the reverse was observed in our case of Capanna with distal periosteal flap, with the distal osteotomy united on CT at 9 months whilst the proximal osteotomy remained unhealed at 14 months **(Supplementary Figures 5, 6).**

The burden of secondary surgery for final union

Final union was only achieved in the control osteotomy group by secondary surgery in 50% of cases. This is not to be underestimated. Additional surgical burden, prolongation of patient's suffering, time off work, and risks in the oncology patient all have significant impacts. Given that the chimeric periosteal flap can usually cover only one osteotomy site, how should we manage the remaining osteotomy? We attempted the 'sleeve' periosteal modification at the distal end of the fibula in conjunction with the chimeric periosteal flap, but this did not inset adequately around the host bone. Instead, consideration may be given to using a simultaneous medial femoral condyle periosteal flap at the remaining osteotomy site (as was used asynchronously in case 7). Given the high rates of non-union noted in this study at the control osteotomy, this is not an unreasonable proposal. None of the chimeric periosteal flaps in this series required further surgery, in line with data from systematic reviews indicating a 99% union rate with periosteal flaps in recalcitrant non-union [10]. These data add to the growing body of evidence that point towards a paradigm shift in the surgical approach to non-union. Periosteal flaps should be considered earlier in the management of non-unions, particularly in units with established Orthoplastic expertise.

Bias, Limitations and Generalisability

Any non-randomised trial is always subject to bias. Nonetheless, the osteotomy sites without periosteal flaps in this study act as a natural control group using a case-control approach. Moreover, no statistical difference was noted in location of periosteal flap at the distal or proximal osteotomy. The chimeric fibula-periosteal flap may have selection bias in favour of upper limb non-unions, as lower limb non-unions are usually treated in the West of Scotland orthoplastic sevice with bone transport techniques. These are less frequently used in the upper limb and have the highest complication rates of any technique in systematic reviews [32]. Lastly, standard definitions of non-union are not applicable in revision of recalcitrant cases – we would suggest both the use of the definition described here rather than the FDA definition, and employing a Hazards Ratio survival analysis. The data presented here are nonetheless robust - with repeated measures using FDA definition, imputation of data for the mycetoma case, and final non-union after secondary surgery – all still statistically significant despite these analyses being subject to confounding and non-validity. These findings are generalisable to other orthoplastic units with well integrated microsurgical and orthopaedic trauma expertise.

Summary

The chimeric fibula-periosteal flap is a novel and elegant modification of the fibula flap that employs periosteum that is routinely discarded, adding no additional donor site morbidity. The data presented here demonstrate a number of benefits over standard fibula or medial femoral condyle periosteal flaps, including:

1) Increased rates of union – in the most difficult recalcitrant non-union cases, chimeric periosteal flaps have a primary union rate of 100% versus 28.6% in standard osteotomies.

2) Versatility in periosteal flap insetting around osteotomy sites – particularly with larger bones that have cross-sectional discrepancy with the fibula bone

3) Use of redundant tissue – periosteal tissue that is normally discarded from the proximal fibula.

4) Combined osseus and periosteal components – beneficial in non-unions with concomitant bone gaps.

5) Prophylaxis in high risk non-union cases such as avascular bone scaffolds – may ameliorate primary non-union rates of up to 30%. Particularly important in patients with limited life-expectancy in order to expedite return to normal activities.

Funding

No funding was received for this study.

Ethical Approval

Caldicott Guardian approvals were obtained from Information Governance, NHS Greater Glasgow and Clyde and study approval through the Governance department of Canniesburn Plastic Surgery Unit for retrospective case review. Additional ethics approvals not required following discussion with the West of Scotland Research Ethics service.

Conflict of Interest

The authors have no disclosures.

Patient Consents

No patient identifiable material was used in this manuscript.

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Graph 1: Cumulative Frequency Graph for primary union. Right censored data are indicated by black points on the graph. This indicates that a patient had non-union at their most recent follow up date. 100% of chimeric periosteal flaps had united by 13 months. The difference between curves is significant (Log rank p= 0.0016).

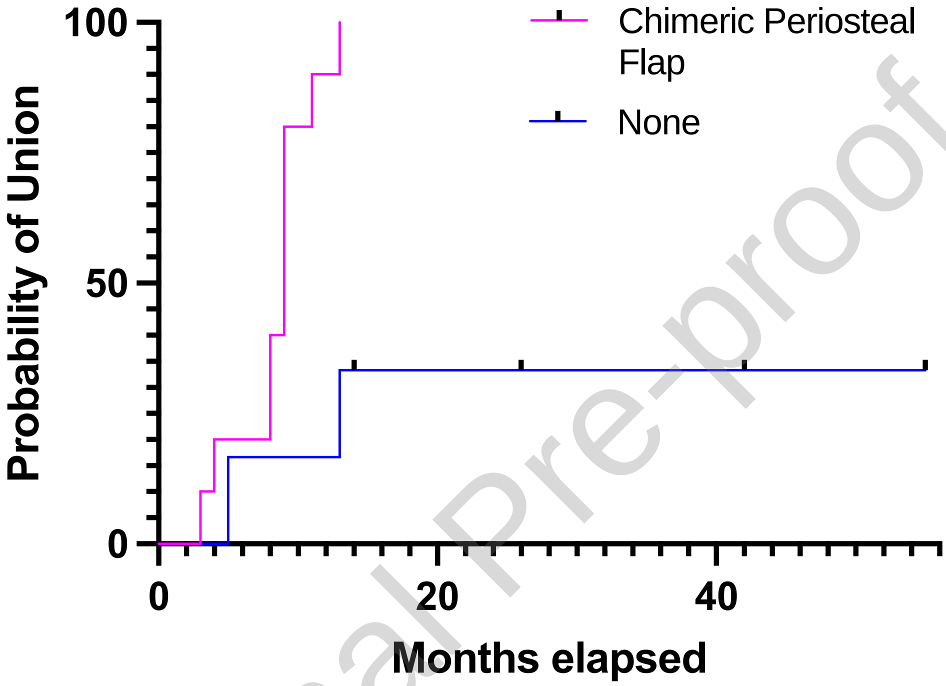


Figure Legends

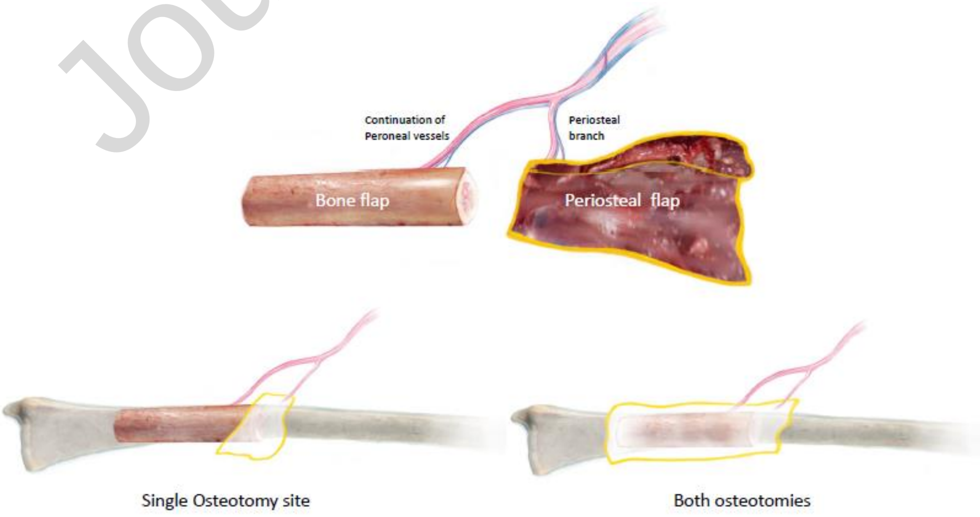


Figure 1: Illustration of Split Chimeric Fibula-Periosteal Flap. A periosteal branch is identified in the proximal half of the fibula, and the periosteal flap is raised from the bone on this separate vessel. The osteotomy is performed keeping the distal fibula bone segment vascularised on the continuation of the the peroneal vessels. The chimeric periosteal flap can be wrapped around a single osteotomy site. If the bone segment is short the periosteal flap can cover both distal and proximal osteotomies.

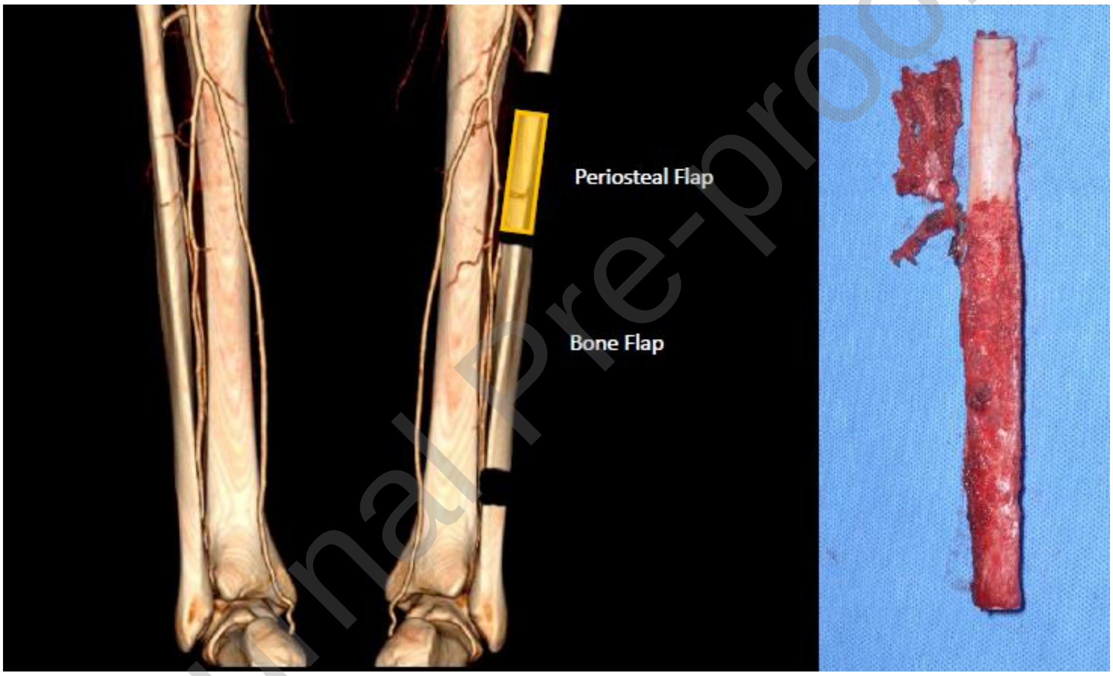


Figure 2: CT angiogram identification of periosteal branches. A 40 year old female patient with desmoid tumour of the right humerus had undergone multiple previous operations for local control, followed by radiotherapy. She subsequently suffered a fracture of her right humerus, which was initially treated conservatively and then internally fixed. This failed to make radiological or clinical progress over 17 months, and a decision was made to revise this with a fibula-periosteal flap. A CT angiogram was used to identify the periosteal branches in the proximal half of the fibula (also see Supplementary Figure 1 and 2).

Figure 3: Vascularised fibula prior to osteotomy. Multiple periosteal branches are seen in the proximal half of the fibula (white arrows). See Supplementary Figure 3 for close up of periosteal branches.

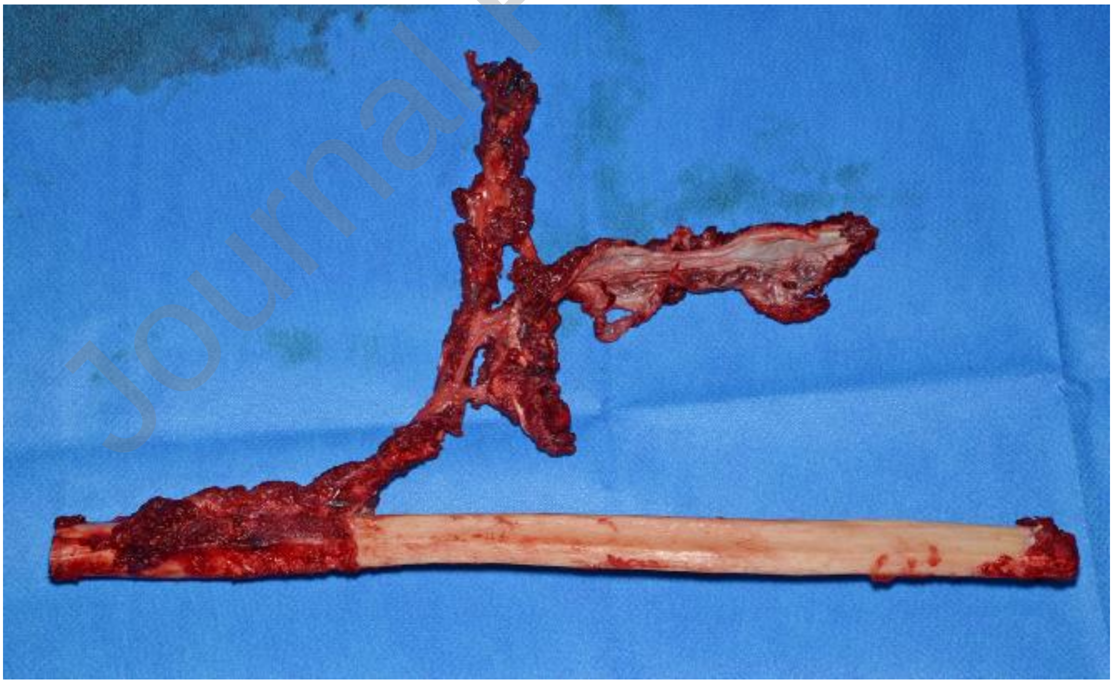


Figure 4: Raising the periosteal flap on a discrete periosteal vessel. The fibula was split into a periosteal flap proximally and osseus component distally.

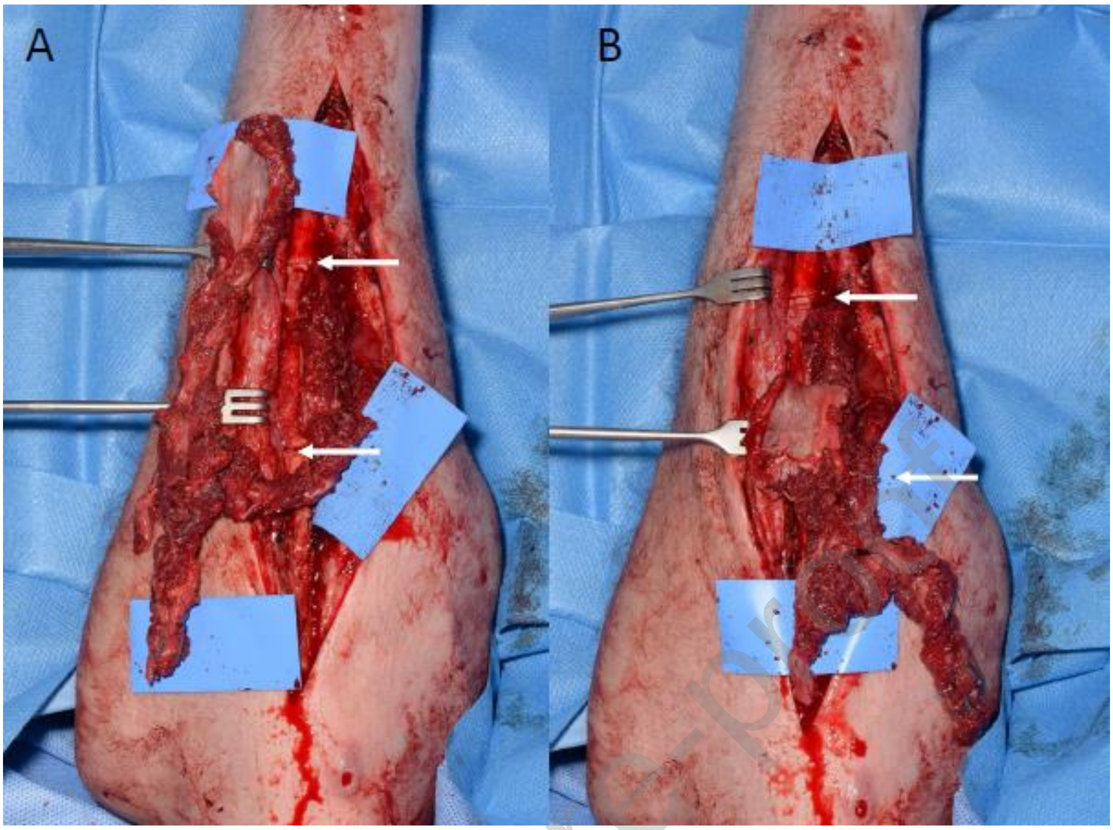


Figure 5: Insetting periosteal flap around fibula-ulna osteotomies. A) Prior to insetting. The periosteal flap is outline in yellow, fibula in pink and the vascular pedicle in green. Osteotomy sites indicated by white arrows. **B)** Periosteal flap is long enough to cover both osteotomy sites. Here it is folded on itself with the distal osteotomy exposed.

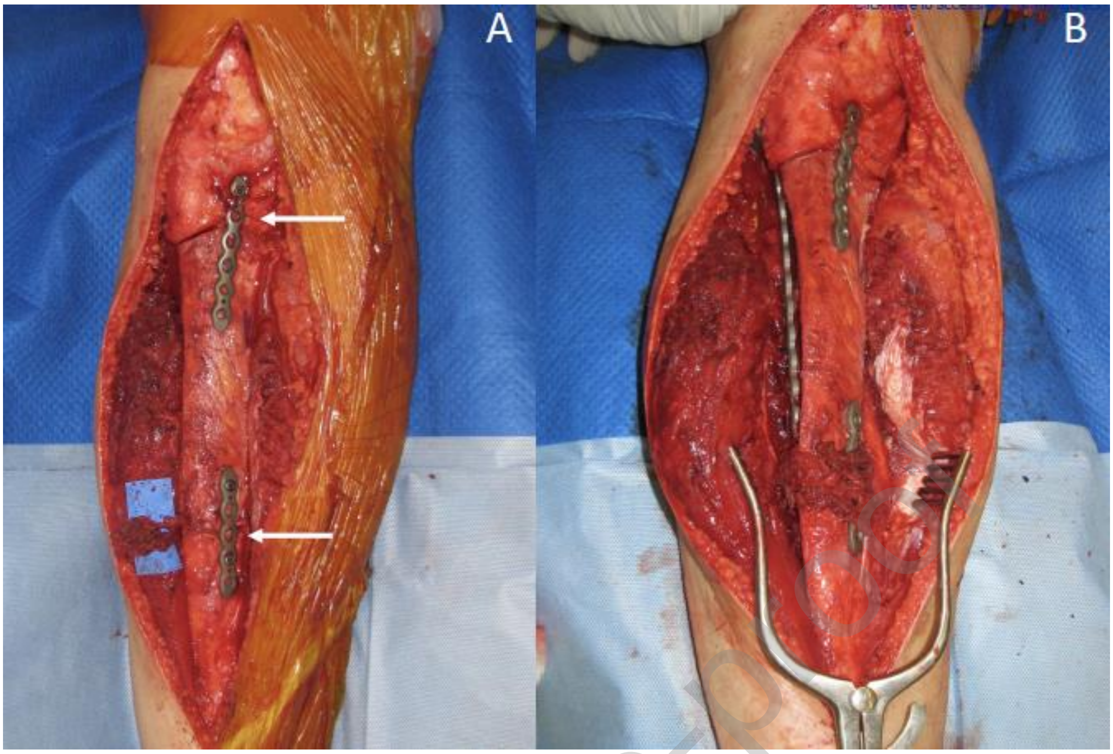


Figure 6: Extracorporeal irradiated tibial sarcoma with vascularised chimeric fibula-periosteal flap (Capanna technique). A) The fibula is placed within the irradiated tibial segment. A slot is cut to allow the pedicle and periosteal flap to exit the tibia (see Supplementary Figure 5). Periosteal flap outlined yellow, fibula pink and pedicle green. **B)** The chimeric periosteal flap is wrapped around the distal tibial osteotomy

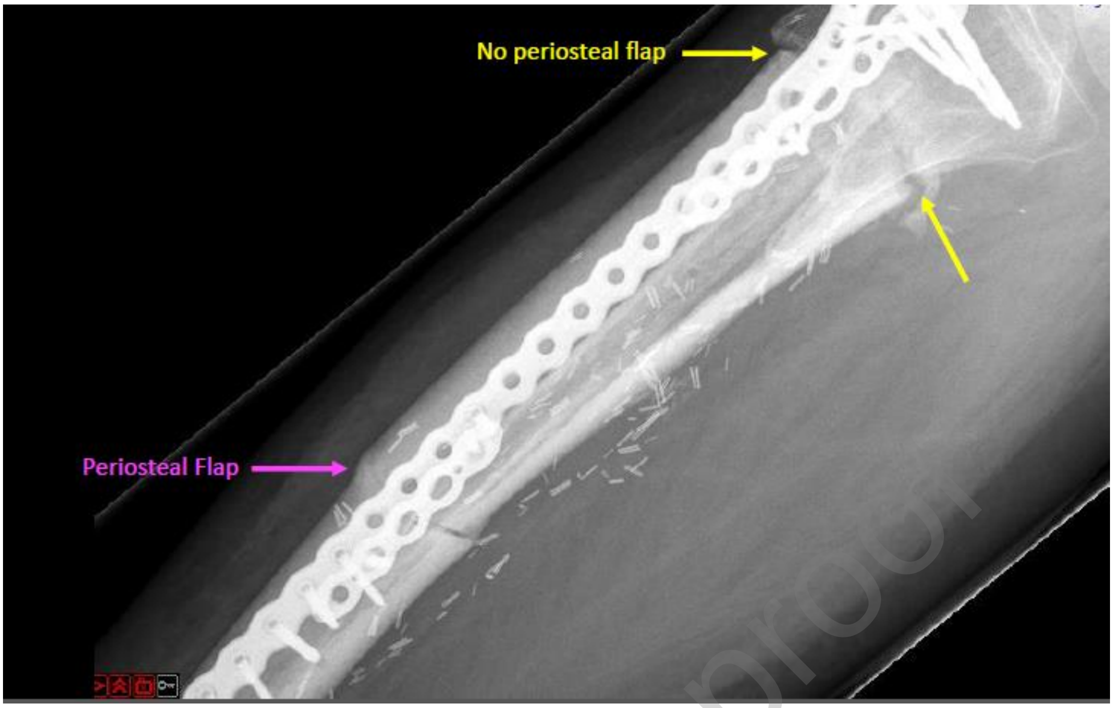


Figure 7: Radiographs of Capanna technique at 9 months. The diaphyseal (distal) osteotomy generally takes longer to unite at 16 months, than metaphyseal (proximal) at 6.5 months. However, in our case the distal osteotomy - covered by the periosteal flap - united more rapidly. The distal osteotomy anterior cortex is clearly united at 9 months, whilst the proximal osteotomy remained un-united. CT confirmed distal union at 9 months. The proximal osteotomy remained unhealed at 14 months.

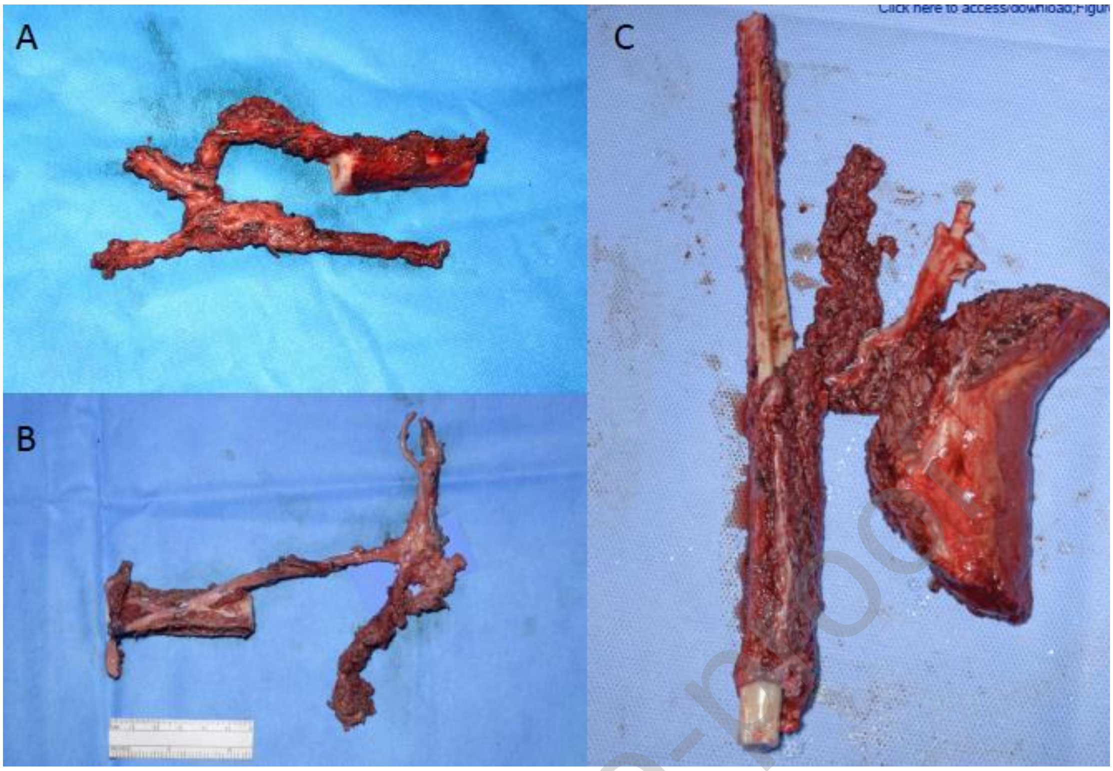
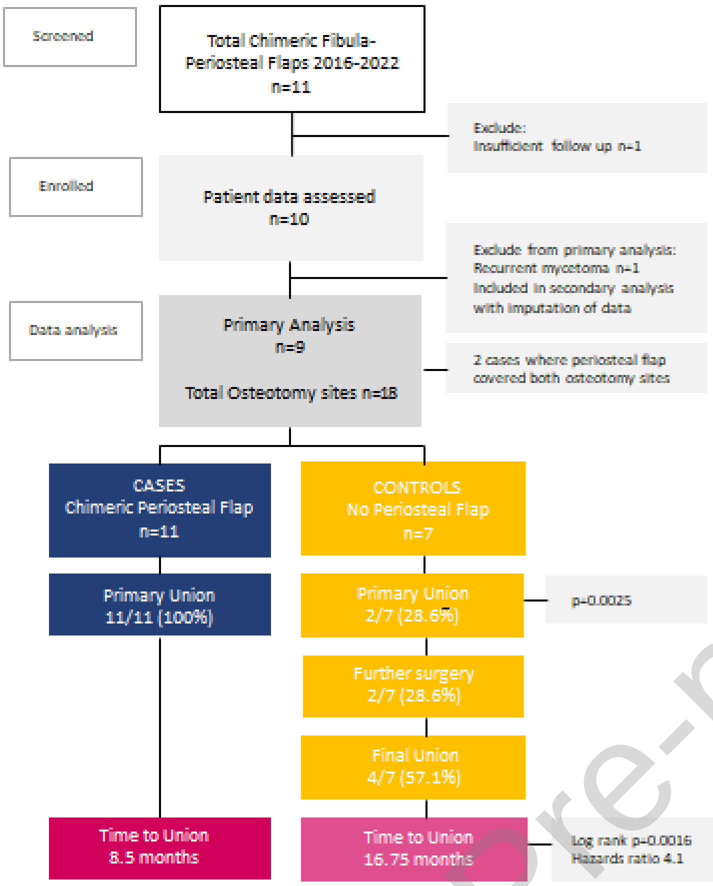
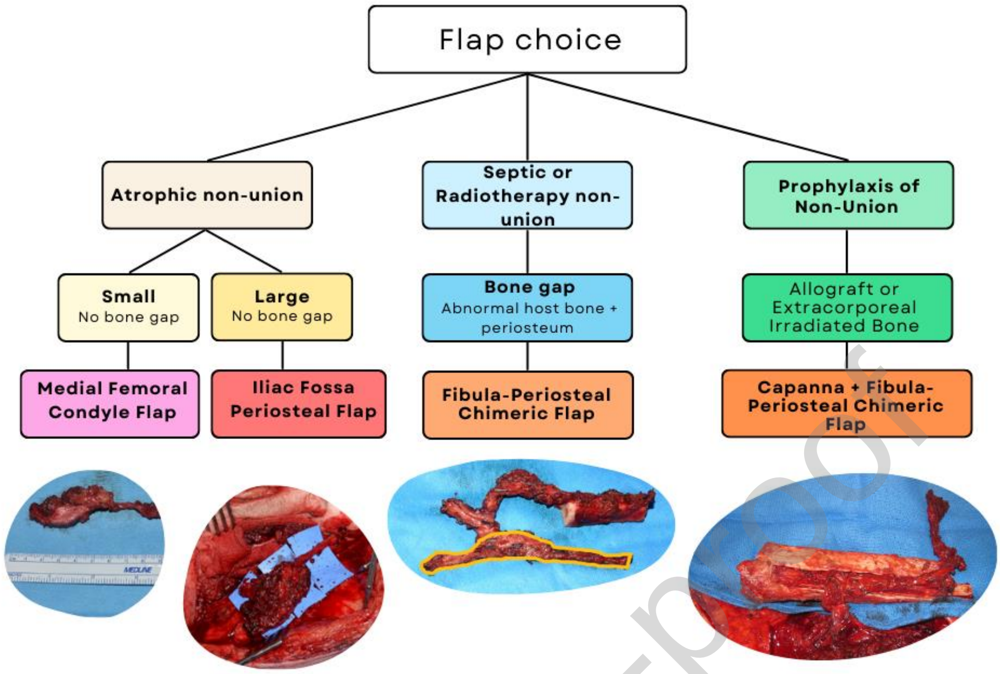


Figure 8: Variations. A) Long chimeric periosteal flap. If the bone segment is shorter than the periosteal flap, it is possible to cover both the proximal and distal osteotomies with the periosteal flap. **B) Chimeric periosteal flap with distal periosteal "sleeve".** The use of the "sleeve" technique was explored, but it was found not to inset around the osteotomy sites due to larger host bone diameter. **C) Chimeric fibula-periosteal-soleus flap.** Flap taken with segment of soleus for deadspace filling in multiply operated patient, with humerus non-union.



Flowchart 1: Recruitment Flowchart. Note that each patient has 2 osteotomy sites. Iin most cases one of these was covered by a periosteal flap and the other was a standard osteotomy.



Flowchart 2: Algorithm for Periosteal flap choice.

Graph 1: Cumulative Frequency Graph for primary union. Right censored data are indicated by black points on the graph. This indicates that a patient had non-union at their most recent follow up date. 100% of chimeric periosteal flaps had united by 13 months. The difference between curves is significant (Log rank p= 0.0016).

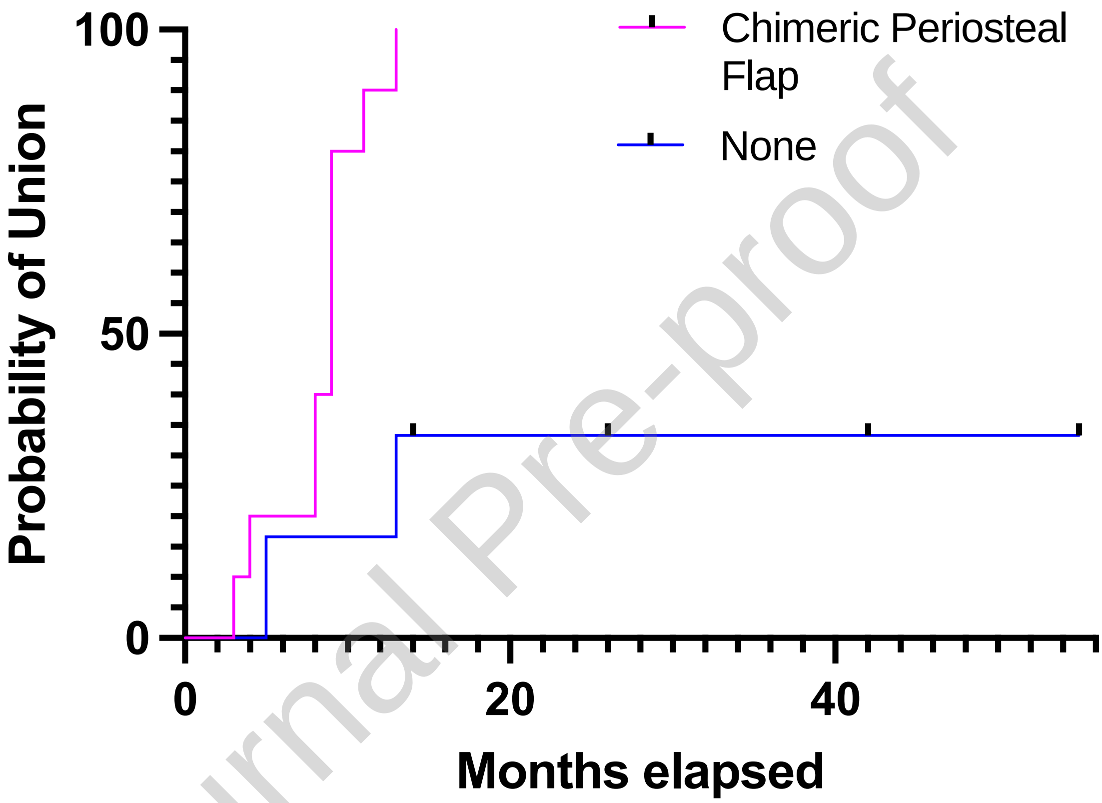


Table 1. Patient Demographics

Pt	Date of Surgery	Age and gender	Type of non-union (in bold) and clinical history	Bone Gap	Periosteal Flap size	Duration non-union prior to flap (months)	Operation	Osteotomy site for chimeric periosteal flap	Follow up imaging	Secondary Operations to help non-union	DASH score (at latest follow up)
1	Aug 2016	32 female.	**Infected non-union** Closed fracture treated in Sudan with intramedullary wires. Anaerobes/ proprinobacterium ecnes on bone culture and no atypical.	Left radius 5cm	8 x 2.5cm (20cm^2)	14	Left Radius Chimeric Fibula-periosteal flap	Both	Serial X rays	No	19.17

2	Nov 2016	40 female.	**Radiotherapy related atrophic non-union.** 2011 Fibromatosis excision + radiotherapy. Failed previous attempts 12/6/15 – ORIF and iliac crest bone graft. Right humerus osteoradionecrosis	Right humerus 7.3 cm	5 x 3cm ($15cm^2$)	17	Right humerus Chimeric Fibula-periosteal flap	Proximal	Serial X rays and CT	Distal non-union - June 2017 bone graft and ORIF - Sept 2017 non-union revision ORIF	4.16
3	April 2017	52 male	**Atrophic and Infected non-union.** Motorcycle accident at 90mph. Sept 2015, risk factors - smoker. Failed Previous failed ORIF and iliac crest bone graft (Masquelet technique) May 2016.	Right Ulna 5.4cm	5x 2cm ($10cm^2$)	19	Right Ulna Chimeric Fibula-periosteal flap	Proximal	Serial X rays	No	33.34
4	Oct 2017	56 female	**Infected non-union.** Right humerus Infected non-union after fall Jan 2017. Closed ORIF with secondary infection. Mar 2017 washout for infected metal work. April 2017: Exploration, bone debridement and washout	Right humerus 6 cm	10 x 2.5cm ($25cm^2$)	9	Right humerus Chimeric Fibula-periosteal flap	Distal	Serial X rays and CT	No	71.6
5	Apr 2018	53 female	**Infected non-union.** Left humerus fracture June 2017 (on holiday, alcohol related). Alcohol excess. Infected	Left humerus 5 cm	7 x 3cm ($21cm^2$)	10	Left humerus Chimeric Fibula-periosteal flap	Distal	Serial X rays and CT	N/A	83.6

			non-union with fungal infection. Managed in external fixator.								
6	Dec 2018	51 female	**Atrophic non-union** Left humerus – alcohol related fall Dec 2015. Risk factors include vegan, alcohol excess and Vit D deficiency. June and Oct 2016 failed ORIF.	Left humerus 10cm	7 x 2.5cm (17.5cm^2)	36	Left humerus Chimeric Fibula-periosteal flap	Distal	Serial X rays and CT	No	Not contactable
7	May 2019	46 male	**Atrophic non-union.** Right humerus fall Sept 2015 conservatively managed resulting in non-union. Nov 2016 ORIF with secondary infection. Risk factors include alcohol excess requiring antibuse implant. Jan 2017 exploration right humerus and failed ORIF. Dec 2018 removal of plate and broken screws right humerus, revision ORIF.	Right humerus 6.7cm	7x 3cm (21cm^2)	43	Right humerus Chimeric Fibula-periosteal-soleus flap.	Periosteal flap proximal	Serial X rays and CT	Sept 2020 medial femoral condyle periosteal flap to distal non-union.	22.41
8	Dec 2021	28 male	**Prophylaxis of avascular bone scaffold** Ewing's sarcoma right proximal tibial diaphysis, underwent wide local excision,	Right tibia 19cm	7x3cm (21cm^2)	N/A	Right tibia Chimeric Fibula-periosteal flap with Capanna technique (extra-corporeal	Distal	Serial X rays and CT	No	N/A (lower limb)

			extracorporeal irradiation, reimplantation and reconstruction with double barrel (Capanna) technique using ipsilateral vascularised fibula. Risk factors include adjuvant chemotherapy completed April 2022.				irradiation of proximal tibia)				
9	Feb 2022	33 male	**Infected non-union** Pathological fracture secondary to osteomyelitis in right ulna. Risk factors – smoker. May 2021- 6 weeks IV antibiotics. Dec 2021 debridment of ulna, cement spacer + external fixator.	Right ulna 5cm	9x3cm (27cm^2)	10	Right ulna Chimeric Fibula-periosteal flap	Both	Serial X rays	No	41.38
10	May 2022	52 female	**Infected non-union** Right ulna fracture ORIF Aug 21. Risk factors - smoker. Removal of metalwork and debridement of bone – Jan 2022. Infected non-union of right ulnar fracture with bone gap.	Right ulna 6cm	6x3cm (18cm^2)	9	Right ulna Chimeric Fibula-periosteal flap	Proximal	Serial X rays	No	61

Supplementary Figures

Supplementary Figure 1: Humerus radiotherapy related non-union. Note the abnormal bone devoid of periosteum.

Supplementary Figure 2: CT angiogram demonstrating periosteal branch in proximal fibula

Supplementary Figure 3: Close up of multiple periosteal branches

Supplementary Figure 4: Chimeric fibula-periosteal flap after fibula osteotomy. Note that the periosteal flap is removed from the normally discarded proximal fibula

Supplementary Figure 5: Capanna technique. The chimeric fibula-periosteal is placed within a slot cut in the irradiated tibial segment.

Supplementary Figure 6: Radiographs of Capanna technique. At 9 months the distal osteotomy (covered by chimeric periosteal flap) has united and the proximal remains unhealed.