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Microvascular free functioning gracilis transfer with nerve transfer to establish elbow flexion☆

S. Kay [a], R. Pinder [a,*], J. Wiper [a], A. Hart [a], F. Jones [b], A. Yates [c]

[a] *Department of Plastic and Reconstructive Surgery, Leeds General Infirmary, Great George Street, Leeds LS1 3EX, UK*
[b] *Department of Physiotherapy, Leeds General Infirmary, Great George Street, Leeds LS1 3EX, UK*
[c] *Department of Anaesthesia, Leeds General Infirmary, Great George Street, Leeds LS1 3EX, UK*

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Summary The loss of elbow flexion is an uncommon, but devastating consequence of injury to the upper limb and a complex problem to manage. This paper describes our experience with free functioning gracilis muscle transfer (FFGMT) to the upper limb for elbow flexion.

33 patients were followed up after FFGMT for elbow flexion. 26 patients were male, and 20 were children. Indications for FFGMT included obstetric brachial palsy ($n = 13$) and adult brachial plexus injury ($n = 12$), arthrogryposis ($n = 4$), sarcoma, polio and radial dysplasia. Seventy percent ($n = 23$) of patients had a successful outcome. Power comparable to the other side (M5) was recorded in two patients, 19 patients scored M4, and three scored M3. FFGMT in the OBP group alone ($n = 13$) was the most successful; all had a pre-operative score of M2 or less and post-operatively 12 (92%) achieved a score of M4 or greater. A greater increase in Medical Research Council (MRC) grade for elbow flexion was achieved when intercostal nerves (ICN) were transferred to innervate the gracilis flap (mean gain three points, SD1.3), than ulnar fascicles (mean gain 1.75 points, SD2.3), $P = 0.05$.

With a multidisciplinary team approach involving experienced surgeons, theatre staff and therapists, a significant, reproducible and measurable improvement in elbow flexion can be achieved by FFGMT.

Elbow flexion is an important function to restore.[1–4] Microvascular free functioning muscle transfer (FFMT) is a treatment option either when muscles are absent or when time from nerve injury means that irreversible changes of denervation preclude direct repair.[1,4,5] This paper describes the senior author's experience with free functioning gracilis muscle transfer (FFGMT) to the upper limb for elbow flexion.

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* Corresponding author. Tel.: +44 113 2432799; fax: +44 113 3922941.
E-mail address: rich.pinder@doctors.org.uk (R. Pinder).

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Methods and materials

Ethical Committee approval was obtained to review retrospectively case notes and assess prospectively all cases of FFGMT undertaken within the St James' University Hospital Plastic Surgery Unit over a 14-year period from 1991 through to 2005. To make the sample group as homogenous as possible the FFGMTs for elbow flexion were selected, and this group further examined by indications and technique.

Data collection

The patients were identified from a prospectively-collected database of all free tissue transfers carried out in the Leeds Plastic Surgery Unit since 1985. Pre-operative details, including the diagnosis, pre-existing elbow function, previous surgeries and comorbidities, were obtained from the case notes. Intra-operative information was taken from the database and case notes, including survival, or otherwise, of the transfer. Patients were then assessed in the outpatient department, seeking the patient's opinions on the surgery, the subsequent function and any donor/recipient site problems. A physical examination was included to assess the function of the transfer and range of elbow flexion, using the Medical Research Council (MRC) grading system (Figure 1).[6] Success was defined as a gain in MRC grade of one or more to grade M3 or greater.

Microsoft Access and Excel™ databases were used to organise the data, and a hospital-affiliated statistician advised on analysis.

Anaesthesia and per-operative care

All cases involve a dedicated microsurgical team. Under general anaesthesia augmented by regional anaesthesia, with invasive monitoring, surgery is carried out in a warmed theatre (27 °C). The target for central–peripheral temperature difference ($\triangle T$) is <1 °C during the procedure and the subsequent high dependency unit care.

Operative method

A senior surgeon operates with assistance and does not use a double team approach. With the patient supine, the recipient arm is explored and adequate vessels and nerves are prepared. After complete preparation of the recipient bed and vessels, the gracilis is harvested, and to this end the lower limb is draped so that it may be moved independently as required.

MRC Grade	
5	Normal power
4	Active movement against gravity and resistance
3	Active movement against gravity alone
2	Active movement, with gravity eliminated
1	Flicker or trace of contraction
0	No contraction

Figure 1 MRC grading system used in assessing elbow function.[6]

Donor nerve The selection of the nerve for transfer is important and will have been decided pre-operatively and confirmed during preparation of the recipient bed. Experience in planning is required to determine the likely level of neurosynthesis and so set the level at which the vascular repair is made. Donor nerves are either intercostal nerves (ideally three nerves; III–V), motor fascicles of the ulnar or median nerves, or rarely the spinal accessory or thoracodorsal nerve. The selection of donor nerve is based on the aetiology of the presenting condition.

Gracilis harvest With the hip abducted and the knee flexed, the gracilis muscle is harvested through an incision 2–4 cm posterior to a line joining the palpable anterior limit of the adductor origin with the medial tibial tubercle. A short incision centred on the junction between the upper and middle thirds of the muscle is sufficient, and experience will show that the muscle can be safely raised without time consuming endoscopy through a very short incision. Three steps are used to confirm the identity of the gracilis muscle when using a short incision: firstly it is the only muscle in this location to change length with knee flexion and extension; secondly the pedicle is consistently at the junction of middle and proximal third; and thirdly the branch of the obturator nerve joins the vascular pedicle at a characteristic oblique angle lying upon the adductor (Figure 2). The muscle is usually harvested without skin paddle for monitoring, although that option exists. It remains attached both distally and proximally until the neurovascular pedicle is dissected completely. A nerve pedicle of up to 10 cm in length can be harvested. Once the muscle is isolated on the neurovascular structures its insertion is divided, after first tensing the distal tendon, by percutaneous tenotomy. The origin may then be divided under direct vision taking care to maintain the fibrous tissue of attachment. Finally the vascular pedicle is carefully divided conserving as much length as possible. This requires powerful retraction aided by hip abduction.

We believe that warm ischaemia time should ideally be kept to less than 1 h, and so the insetting of the muscle must be planned and prepared before the pedicle is divided. Muscle force is proportional to cross-sectional area, but work capacity is related to the volume of muscle units in line with the vector of pull, and so we do not wrap the muscle around the clavicle or use other methods of proximal attachment that sacrifice volume. In most cases we make use of the tendinous origin of the muscle to fix it either with bone anchors or direct per-cartilaginous sutures (in the child) to the coracoid process.

The distal insertion is equally important. Where a healthy biceps tendon exists, the gracilis muscle is woven into it with the elbow flexed at 45° and under considerable tension (Figure 3). Our commonest mistake in early years

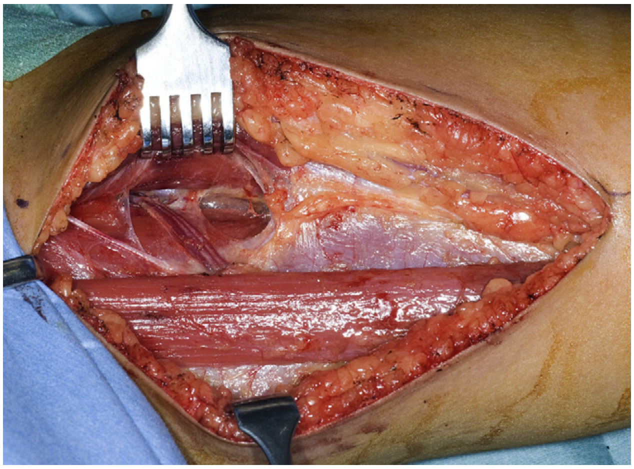

Figure 2 The position of the pedicle lying upon adductor at a characteristic oblique angle.

was to place the muscle under too little tension, in part trying to avoid a flexion contracture post-operatively, and in part worrying that more tension would move the vascular pedicle too distally for neurosynthesis. Gracilis has a great excursion, and so can accommodate to mismatch in tension better than many muscles, but the occurrence of a slight elbow contracture is only beneficial in these cases, facilitating the initiation of elbow flexion.

Where a healthy biceps tendon does not exist (for example, in arthrogryposis) we fix the tendon through a drill hole in the ulna at the level of the coronoid process. This denies the supinating activity of biceps but provides a strong attachment with ability to adjust length accurately. So far growth has not caused significant distal migration of this attachment nor necessitated reattachment more proximally.

The arterial vascular anastomoses are made either end to side to the brachial artery or end-to-end if a suitable branch presents itself (which is often the case as the posterior branch to triceps frequently lies at the desirable level). This branch is of course prepared in advance to conserve warm ischaemia time. Venous anastomoses are end-to-end and only one vein need be repaired, usually to the vena comitans of the brachial artery, and not to the thick walled cephalic vein, tempting though its length and position may be. Flaps are raised, inset and revascularised by the same surgeon, almost entirely using diathermy dissection (monopolar & bipolar) to facilitate haemostasis. Loupe magnification (3.5×) is employed for raising flaps, and microscope magnification (×6–×15) for anastomoses. Heparinised irrigation is used at the site of anastomoses. Topical Verapamil Hydrochloride (0.125 mg/ml, Securon®IV, Abbott Laboratories Ltd.) and warm saline packs are applied after clamp release. Systemic anticoagulation is not routinely used other than thromboprophylaxis to prevent lower limb thromboembolism.[7]

Following vascular anastomosis the lower limb is closed over a drain, and then the nerve is repaired. This allows some 30–40 min to pass and the vascular anastomosis is then reviewed. If all is well, the upper limb skin is closed over a drain, and dressed with the elbow in 90° of flexion, with additional strapping to maintain shoulder adduction. In children a suture from wrist to abdomen is useful, and is mandatory where intercostal nerves have been used. We have experience of well-intentioned axillary wound care with the shoulder briefly abducted being responsible in all probability for failure to reinnervate, only recognised months later. Adduction dressings should not be such as to compress the vascular pedicle.

Post-operative care

After surgery, all patients are transferred directly to the adjacent High Dependency Unit (HDU). On the HDU the aim is to keep the patients warm, well-perfused and comfortable. FFGMTs are not routinely raised with skin paddles. Analgesia is by a continuous regional local anaesthetic blockade and/or continuous morphine infusion. We believe that a successful vascular anastomosis flowing at 40 min will continue to flow unless mechanically compromised or the patient is systemically challenged, as by cold, pain or hypovolaemia. In most cases invasive systemic monitoring of blood pressure and central venous pressure is discontinued after 24–72 h.

Following discharge

The splint and dressings remain in place for four to six weeks. Thereafter, gentle passive extension is encouraged. As most patients live outside our locality, once contraction is noticed in the muscle, progressive resistance programs and hydrotherapy are instigated as appropriate by local therapists in contact with our unit. Dedicated physiotherapists review patients' progress at intervals along with medical review in the outpatient department. A specific regimen for intercostal nerve transfers is instigated, following the recommendations of Chuang involving exercise to breathlessness in the first phase, and then retraining in the second.[8]

Results

There were 37 FFGMTs carried out for elbow flexion, all by one surgeon and team. Results are reported for 33 patients who were followed up and reassessed a mean of 89 months after FFGMT. One patient now lives abroad and could not be contacted, and the case notes of three patients had been destroyed.

Demographics and indications for FFGMT

Out of the 33 patients, 26 (79%) patients were male, and seven were female. Twenty (61%) were children (under 16 years of age at operation). Indications for FFGMT in children (median age 4.8 years, range 23 months to 12 years) were obstetric brachial palsy (OBP, $n = 13$), arthrogryposis ($n = 4$), sarcoma ($n = 2$), and radial dysplasia ($n = 1$). The indication in adults (median age 34, range 23–44) was brachial plexus injury (ABPI) secondary to a road traffic accident (RTA, $n = 12$), except one case secondary to polio.

Figure 3 a) Typical inset of the gracilis to the right upper limb. b) Contrary to common practice, only a short scar is needed children for harvest of the donor intercostal nerves.

Perioperative details

The contralateral gracilis was transferred in 67% of cases. The mean total anaesthetic time from induction to reversal of general anaesthesia was 347 min (SD109), and the mean time from dividing the flap pedicle until a definitive vascular anastomosis was finally established was 75 min (SD31); this figure includes cases where the primary anastomosis was revised. Evidence of a learning effect in FFGMT surgery is evident in the duration of flap ischaemia, and to a lesser extent in total duration of the procedure, when the entire series is examined (Figure 4). Median flap ischaemia time for the first six cases was 105 min (range 90), and 61 min (range 68) for the final six cases, suggesting a clinically significant reduction in the duration of flap ischaemia. When assessed similarly, median duration of anaesthesia reduced from 390 min (range 400) to 310 min (range 300).

There were three microvascular failures, all within the earlier cases of FFGMT (Figure 5); two were a result of arterial occlusion and one secondary to venous insufficiency. Six cases of recipient site haematoma formation were recorded and all these transfers subsequently survived. Wound infection complicated three cases, involving only the donor site, which settled with antibiotic treatment. There was a single case of recipient site wound dehiscence which required surgical intervention (washout and subsequent split thickness skin graft).

Function

Pre-operative Pre-operative function was obtained from case notes. Over 90% ($n = 31$) of patients had a grade of M2 or less, with no cases having M4 or higher, unsurprisingly (Figure 6). Median pre-operative MRC grade was 1 (range 0–2) for OBP, 0 (range 0–2) for arthrogryposis, and 0 (range 0–3) for RTA cases.

Post-operative Post-operative functional outcome was assessed for all groups of patients undergoing FFGMT, at a mean follow-up period of 89 months (SD84; Figures 6 and 7). Seventy percent ($n = 23$) of patients had a successful outcome. Power comparable to the other side (M5) was recorded in two patients, 19 patients scored M4, and three scored M3. The remainder scored M2 or less.

The majority of patients (80%) had returned to mainstream school or work at follow-up and 70% found their FFGMT useful, commenting that it enabled them to carry out more, particularly activities of daily living. Eighty percent of patients were glad they had the operation, and 73% would have the operation again.

Adults

Twelve out of 13 cases of FFGMT in adults were to address the consequences of road traffic accidents, and achieved a median two point gain in MRC grade for elbow flexion to reach a median of 3 (range 0–5). Of the 13 FFGMTs performed in adults, 7 of 13 recovered function to ≥M3 and 6 of 13 to ≥M2 (Figure 7).

Children

The post-operative results for FFGMT for children ($n = 20$) are shown in Figure 8. This group included surgery for OBP ($n = 13$), who obtained a median 3 point gain in MRC grade to reach a median post-operative MRC grade of 4 (range 1–4), and to reconstruct elbow flexion in four arthrogryposis patients (median MRC gain four points, range 2–4, to reach median MRC grade of 4, range 0–4) and other causes ($n = 3$). A score of M4 or greater was achieved in 85% ($n = 17$). Only three cases (15%) were unable to flex the reconstructed elbow against gravity.

Examining the OBP group alone ($n = 13$), all had a pre-operative score of M2 or less. On post-operative assessment, 12 (92%) had a score of M4 or greater (Figure 9).

Nerve transfers

The nerves used to reinnervate the FFGMT were intercostal nerves (ICN) (18), fascicles of the ulnar nerve (12), and in adults only the spinal accessory nerve (with an interposition nerve graft) was used twice, and the thoracodorsal nerve once.

Considering the cohort overall, a greater increase in MRC grade for elbow flexion was achieved when ICN were transferred to innervate the gracilis flap (mean gain 3

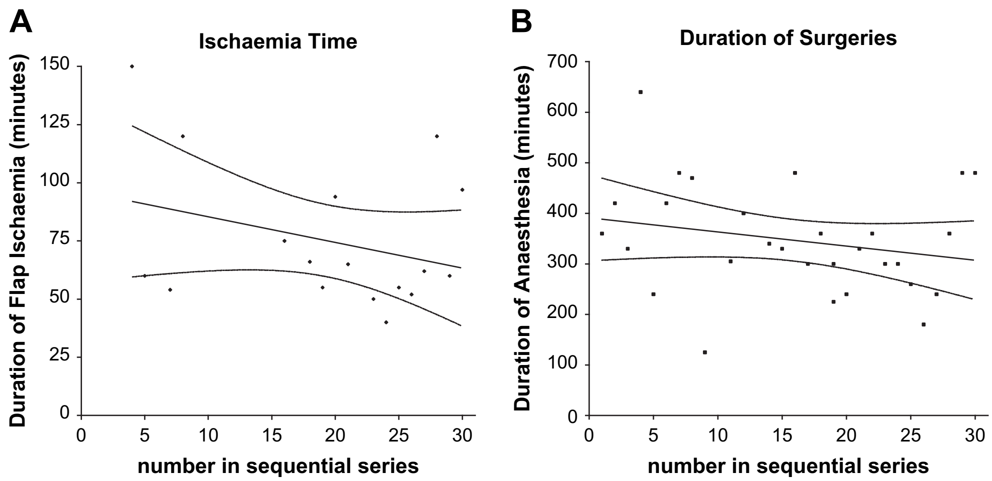

Figure 4 Evidence of learning effect in performing free functioning gracilis muscle transfer.

points, SD1.3), than ulnar fascicles (mean gain 1.75 points, SD2.3), $P = 0.05$. This difference persists when the OBP group is examined alone (ICN mean gain 3.4 points SD0.5; ulnar nerve fascicle transfer mean gain 2.83 points, SD1.2; $P = 0.04$). A similar magnitude of difference in final MRC score was found in adults, but numbers are too small for statistical comparison. Numbers are also too small to reach conclusions over whether the root value and total number of ICN transferred affects final gain in MRC score. Ulnar nerve fascicle transfers had a somewhat shorter mean follow-up time (62 months vs. 94 months for ICN transfers in the entire cohort; 53 months vs. 76 months in the OBP group), but the difference was not statistically significant ($P > 0.05$). There was no apparent difference in pre-operative MRC grade between the ICN and ulnar fascicle transfer groups.

Thoracodorsal nerve transfer delivered a 4 point gain in MRC grade, SAN transfer (plus graft) delivered at best a one point gain.

Discussion

The series we present is unselected and represents one surgeon's experience over a number of years with the technique of FFGMT. Thus it contains cases from which lessons have been learned and should not in its raw data indicate likely success rates with this surgery, since these are likely to be better at the current time or from this point forward.

Although the data include several different indications for this surgery, two main groups predominate. These are the adult brachial plexus injury (ABPI) ($n = 12$) and the obstetrical brachial palsy (OBP) ($n = 13$). Before we concentrate upon these groups we should mention the other groups. One adult patient had FFGMT to restore elbow flexion, lost as a result of childhood poliomyelitis. This was one of the earlier cases performed, and the spinal accessory nerve was used. His MRC grade at follow-up was 1 – the senior author does not now favour the spinal accessory nerve as a donor nerve for the FFGMT. Seven children had other indications for FFGMT; one suffered with radial dysplasia and underwent a successful FFGMT onto intercostals nerves with a resulting MRC grade of 5; one child had a resection of a malignant sarcoma of the brachial plexus and underwent two unsuccessful FFGMTs onto fascicles of the ulnar nerve, the first of which was a microvascular failure.

Four children underwent FFGMT for arthrogryposis. In arthrogryposis, the neuromuscular units affected are essentially deficient or absent. The involved upper limb has sparse resources within it and the options for muscle transfers are limited. In many cases where passive elbow

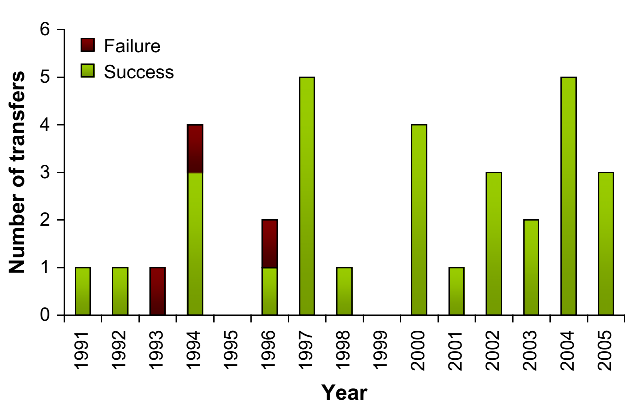

Figure 5 Yearly distribution of FFGMTs, including failures.

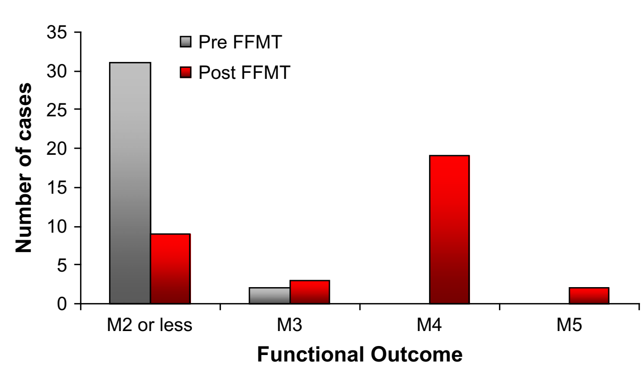

Figure 6 Pre- and post-operative MRC grade (all cases).

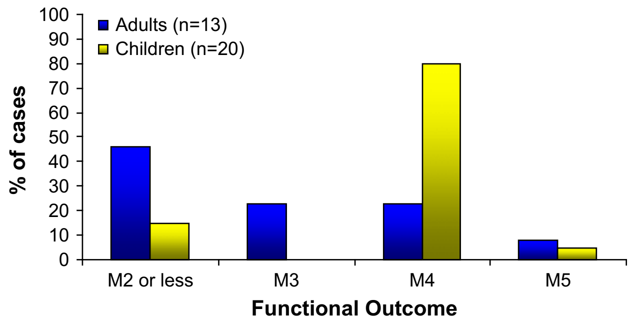

Figure 7 Post-operative MRC grade in adults compared to children.

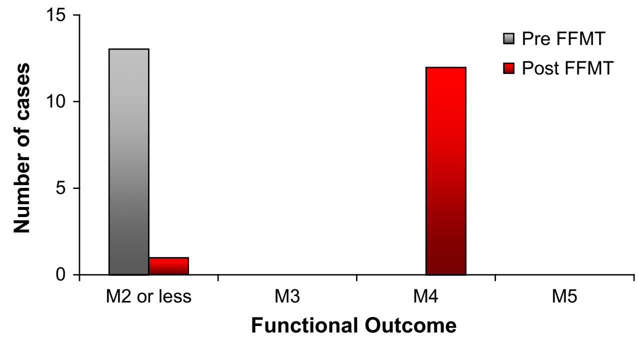

Figure 9 Post-operative MRC grade for OBP cases ($n = 13$).

flexion can be established, we have favoured pectoralis major transfer through small or minimal access incisions and this can be an effective transfer. However it does rearrange a resource already available to the limb and weakens adduction, as well as placing visible scarring on the chest and creating a chest wall deficiency unappealing to some patient groups in particular. The latissimus dorsi muscle has also been used to restore elbow flexion, but again it utilises pre-existing upper limb musculature, potentially further affecting function.

The ABPI and OBP groups form the majority of patients in this series. However they have fundamental inherent differences. It is well known that the functional outcome in children, in particular in peripheral nerve injuries, is better than in the adult for several reasons; in children the distance between donor nerve and target organ is smaller than adults, which increases children's neuromuscular regeneration potential; children are generally more motivated and intrinsically active; and the young brain has a superior capacity for functional remodelling and learning.[9—13] In general the ABPI group forms a more heterogenous group than the OBP. Adult patients with brachial plexus injuries have, by definition, sustained considerable trauma to the plexus and with it a varying degree of injury to a variety of surrounding structures. Adults are also generally more comorbid than children.

There are several reconstructive options available to restore active elbow flexion to the upper limb, depending on the aetiology, ranging from reanimation of existing muscles with nerve transfers or grafts, local tendon and muscle transfers and free functioning muscle transfers. The

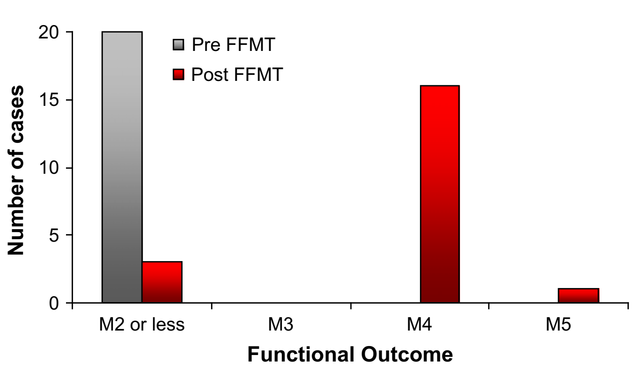

Figure 8 Post-operative MRC grade in all children ($n = 20$).

method employed is dependent on several factors, in particular the injury sustained and the time from injury to presentation or treatment. Procedures such as direct nerve repair or nerve transfer can be used in acute cases of plexus injury (up to 6 months post-injury) where there will be adequate time post-operatively for the nerve to reinnervate its length before the onset of motor endplate degeneration — by 18—24 months the irreversible changes in the muscle cells appear to deny the chance of motor recovery.[1,5] Early referral to a specialist unit is encouraged in all cases of brachial plexus palsy, but treatment can be confounded and options reduced by long time intervals to allow for resolution after injury.[4] If direct nerve repair fails to improve elbow flexion, muscle transfer, either local or distant, can be considered. Free functioning muscle transfer (FFMT) is the treatment of choice when delay in (or failure of) alternative treatments such as nerve transfers has resulted in atrophy of the target muscle and motor endplate degeneration, or there is lack of local muscle to transfer, or for salvage in complete brachial plexus avulsions.[4] Elbow flexion is central to upper limb function and its loss can leave patients with a profound disability. It is widely recognised as being an essential function to restore.[1—5] However, rarely is it the sole action to be lost, and treatment should not further compromise limb function.

Early in the current series the senior author explored the options of importing new resource to the upper limb without disturbing the existing motor function. FFGMT combined with intercostal nerve transfer offered this potential. However some caution is obviously necessary. Firstly does a gracilis muscle exist? Many children with arthrogryposis have no gracilis muscle and this should be established pre-operatively either by MRI scan (preferred for accuracy) or by ultrasound (if a confident interpretation can be gained). On occasions we have abandoned the proposed procedure because of absence of the gracilis muscle. Secondly, passive elbow flexion must be established first, as with any transfer. Finally the status of the intercostal muscles and nerves may be unknown. In all our cases these were established at exploration by stimulating the intercostal nerves during harvest and assessing the muscle contraction. No transfer was abandoned for this reason.

An intact donor nerve is a prerequisite for FFMT.[14] The choice of donor nerve coapted to the motor nerve of the gracilis depends on several factors such as trauma local to the donor nerve (e.g. chest trauma may preclude the use of intercostal nerves (ICN)), proximity of the intact donor nerve to the proposed site of coaptation to the recipient nerve (to eliminate the need for grafting if possible), or the extent of injury to other nerves. It has been shown that the number of functioning axons needed for active elbow flexion is several hundred (as opposed to the action of the intrinsic muscles that requires several thousand).[15,16] An average intercostal nerve has 1300 myelinated axons, a spinal accessory 1700 and a partial ulnar nerve 1600.[15,16] Nerves used to date, with varying degrees of success, include the intercostals nerves, spinal accessory nerve, thoracodorsal nerve, phrenic nerve, and fascicles of the ulnar nerve.[1–3,5,14,17–20] There is no consensus on the optimal donor nerve.

In this series, in 18 cases the intercostal nerves were used (in three cases two ICNs, 15 cases used three ICNs) and in 12 patients selected motor fascicles of the ulnar nerve were the donor nerves. The remainder employed the spinal accessory nerve (2) or thoracodorsal nerve (1). We found a significant difference in the MRC gain in the overall cohort where ICNs were transferred versus ulnar nerve fascicles. In the most homogenous group (OBP), the apparent effect of ICN being better than ulnar nerve fascicles was greater still. Interpretation of statistical significance is limited by the small sample sizes, and the difference is small ($\sim$1 MRC point), but even that difference is functionally significant in this patient population. A potential confounding factor is that the ICNs had slightly longer follow-up (mean 94 months) than ulnar nerve transfers (mean 62 months), yet the regeneration distance for fascicular transfers is significantly shorter, reducing the magnitude of any potential confounding effect. It is likely that a FFGMT driven by ICN transfers will deliver slightly greater force to elbow flexion than if driven by fascicles from the ulnar nerve, but this cannot be categorically stated from the current data. The use of ICNs as the donor nerve for FFGMT induces no subjective respiratory deficit, and has several theoretical advantages over a fascicular transfer within the affected limb. It introduces a new resource of both nerve and muscle to the limb, and does not risk a reduction in hand function, and the more cranial ICNs (ideally III–V) lie in sufficient proximity that the transferred gracilis motor nerve can be repaired without graft. Given this it is our belief that although choice of donor nerve has less effect in adults, in children the use of intercostal nerves produces a better functional outcome.

In our series, 64% of patients obtained a good or excellent functional result (M4 or 5). This compares favourably to other published results.[1–3,17–21] It should be noted however that the patient groups in all of the published studies are by no means homogenous, making direct comparison difficult. Across the studies the demographics and indications for augmentation of elbow flexion are considerably different – the majority of our patients are children, and almost half of the FFGMTs were carried out for OBP. There is also a marked variation in the average time from injury to FFGMT in previous studies, the shortest being 8.8 months, compared to 89 months in our series.[1,2,18,20] As mentioned above an increased delay may affect the outcome of FFMT. We solely looked at gracilis muscle transfer – other studies included other muscle transfers such as rectus femoris and latissimus dorsi muscles – and we did not attempt to augment existing muscle function with donor nerve neurotisation of the musculocutaneous nerve, which was successful in other series, producing palpable biceps and brachialis function.[2,18] Time to follow-up also varied, but is considerable in this study. FFGMT is not a common operation, borne out by the fact that the larger series to date

Figure 10 Flexion and extension of the elbow with a 1 kg weight 9 years following free functioning gracilis muscle transfer.

have cases extending over several years (ours included). Reinnervation of transplanted muscle depends on various factors, such as patient age, post-operative vascular complications, the distance from nerve coaptation to muscle.[10,14,22] Therefore results will differ, and may improve with time. There is no consensus on when a functional muscle should start working. Authors suggest that contraction can be detected from 3 months following the transfer and it may take up to 2 years to achieve the maximum effect.[1,2,14] Although we did not specifically examine time from transfer to contraction in this study, on discussion with patients and parents it seems that this time varies considerably. One patient commented that 'it only started working after about 2 years [post-operatively]', and she now has MRC grade 4 power (Figure 10). We therefore suggest caution should be exercised before judging a FFGMT to be a failure within 2 years.

The loss of elbow flexion is an uncommon, but devastating consequence of injury to the upper limb and a complex problem to manage. In patients with a global dysfunction of the limb the primary aim is to restore motor power to enable elbow function, and in those with a functioning hand, the hand is useless without a flexing elbow.[16] When there is delay from injury to treatment few options remain for the restoration of elbow flexion using native muscles. In such cases free gracilis muscle transfer can transform the upper limb into a useful, functioning, arm. We believe that with a multidisciplinary team approach involving experienced surgeons, theatre staff and therapists a significant, reproducible, and measurable improvement in elbow flexion can be achieved.

Acknowledgement

Mr. P McShane, Senior Medical Stastician, Leeds General Infirmary, Great George Street, Leeds, LS1 3EX, United Kingdom.

Conflicts of interest

None.

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