ORIGINAL COMMUNICATIONS

Pectoralis major transplantation to restore elbow flexion to the paralytic limb

In four patients, two with brachial plexus palsy and two with arthrogryposis, the entire pectoralis major muscle was transplanted to act as an elbow flexor, rotating it on its neurovascular pedicles and attaching the tendon to the acromion and the muscle origin to the tuberosity of the radius. Excellent motion and power was restored in three patients. One procedure failed due to fibrofatty degeneration of the transplanted muscle.


Reconstitution of the function of the biceps brachii in cases of severe paralysis of the upper limb has received considerable attention in the literature over the past half century. The functional mobility of the entire limb depends significantly on the integrity of controlled active elbow flexion, and ingenious methods for restoring this function have been proposed and tested using a variety of motor transfers (Table I): (1) lateral and proximal advancement of the flexor-pronator forearm mass, described first by Steindler in 1919 and modified by Bunnell; (2) anterior transposition of the antagonistic triceps tendon, described first by Bunnell in 1948, then by Carroll in 1952, and later by Carroll and Hill in 1970; (3) transfer of the lower sternocostal origin (medial pectoral nerve innervated) of the pectoralis major to the biceps tendon, based on Keith’s work in embryology and comparative anatomy, which Clark proposed in 1946; (4) use of the entire pectoralis major tendon to a paralytic biceps brachii following complete devascularization of the latter; (5) two-staged shoulder arthrodesis and sternocleidomastoid transfer with fascia lata graft; (6) the latissimus dorsi transfer for either restoration of elbow flexion or extension; and (7) transfer of the pectoralis minor with a fascia lata extension for active elbow flexor control, as reported by Spiro in 1957.

Table I. Substitutions for biceps brachii function

<table>
<thead>
<tr>
<th>Substitution</th>
<th>Author</th>
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<tbody>
<tr>
<td>Flexor-pronator mass</td>
<td>Steindler</td>
</tr>
<tr>
<td>Triceps</td>
<td>Bunnell, Carroll</td>
</tr>
<tr>
<td>Pectoralis major (sternocostal head)</td>
<td>Clark</td>
</tr>
<tr>
<td>Pectoralis major (tendon to biceps)</td>
<td>Brooks &amp; Seddon</td>
</tr>
<tr>
<td>Pectoralis minor</td>
<td>Spirito</td>
</tr>
<tr>
<td>Sternocleidomastoid</td>
<td>Bunnell, Carroll</td>
</tr>
<tr>
<td>Lastissimus dorsi</td>
<td>Hovnanian, Zanocelli &amp; Mitre</td>
</tr>
</tbody>
</table>

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Fig. 1. Evaluation of muscle expendability. The triceps cannot be transferred to restore active elbow flexion if the patient relies on this muscle as shown.

trauma to the brachial plexus are physiological insults which can result in spotty or complete upper limb motor deficits which can make certain desirable transfers unlikely, due to involvement of the transferrable motor with the primary disease process or injury. For example, the well proven Steindler flexorplasty cannot be used if the forearm flexors have been weakened either by paralysis, by traumatic loss of substance, or by contracture.

The expendability of any motor selected for transfer is also of paramount importance. For example, anterior transposition of the triceps tendon would be ill-advised if loss of extensor power at the elbow significantly compromised a patient’s routine activities, e.g., pushing himself out of a wheelchair (Fig. 1).

In considering the availability or expendability of a specific motor to restore elbow function in the paralytic limb, the cosmetic effects on the patient also should be taken into consideration. Although biomechanically effective, a sternocleidomastoid transfer may be significantly disfiguring to a young female patient and should only be considered if there are no available alternatives for transfer.

This paper describes the surgical details and biomechanical advantages of an alternative surgical approach to the difficult problem of restoring active elbow flexion. The method to be described employs the entire mass of the pectoralis major muscle, used as a total muscle transplant, transposing both the tendon of insertion and the motor origins in a manner which effectively accomplishes the following: (1) as much expendable muscle mass as possible is used as the new motor; (2) the mechanical advantage of the transplant surpasses other previously described uses of the pectoralis major as an elbow flexor; (3) the entire force of the transplant is directed toward the development of torque around the elbow axis of rotation and no energy is lost at the shoulder; (4) the stability of the glenohumeral joint is reinforced.

This technique now has been used in four of our
Figs. 3 and 4. Schematic and cadaveric anatomy of the neurovascular supply to the pectoralis major muscle (pectoralis major muscle not included in schematic view; pectoralis major reflected laterally off chest wall and clavicle on cadaveric view). (A, axillary artery; B, lateral pectoral nerve; C, medial pectoral nerve; D, lateral thoracic artery; E, pectoral branch of thoracoacromial trunk; F, thoracoacromial trunk; G, lateral cord; H, medial cord; I, medial anterbrachial cutaneous nerve; J, musculocutaneous nerve.)

Surgical technique

The procedure is performed with the patient in a supine position and a flat bolster under the blade of the scapula. The upper limb is draped to allow complete freedom of motion of the elbow and shoulder.

A long curvilinear incision is first made from the seventh sternocostal joint cephalad, two fingerbreadths inferior to the clavicle (Fig. 2). The incision continues laterally to the coracoid process, then distally along the anteromedial aspect of the arm to the level of the axilla, with the forearm held in neutral position.

The fascia overlying the entire pectoralis major muscle is exposed then by elevating this broad, inferior-based flap to the nipple line. The deltopectoral groove is delineated carefully and the anterior deltoit and cephalic veins retracted laterally to expose the clavipectoral fascia and the glenohumeral joint capsule, proximal to the anterior acromion. Depending on the degree of paralysis, the anterior deltoid may or may not have to be detached from the anterolateral clavicular border and the margin of the acromion to allow for sufficient exposure. In the four patients treated in this manner, exposure has not been a problem.

With the acromion and entire pectoralis major exposed, a second curvilinear incision is made over the antecubital fossa with the transverse limb across the fossa and the longitudinal limb extending medially and distally 6 cm. The biceps tendon is exposed by dividing the lacertus fibrosus and bicpital aponeurosis.

The entire mass of the pectoralis major muscle then is detached from its origin along the medial half of the clavicle and its sternocostal border. Using sharp and blunt techniques, the muscle is elevated with a 10 by 4 cm strip of attached anterior rectus abdominis fascia, as originally described by Seddon and popularized in Great Britain by Lloyd-Roberts and in this country by Holtmann et al.

In the process of freeing the pectoralis major from the chest wall and underlying pectoralis minor, meticulous care must be given to preservation of its neurovascular pedicles. The lateral pectoral nerve from the lateral cord of the brachial plexus (C₅, ₆, ₇) innervates the clavicular and upper sternocostal heads of the pectoralis major, coursing with the large and constant pectoral branch of the thoracoacromial trunk (Fig. 3). The medial pectoral nerve (Clark’s so-called anterior lateral thoracic nerve) from the medial cord of the brachial plexus (C₅, T₁) either pierces directly through the belly of the pectoralis minor or passes laterally to it.
a single absorbable percutaneous stay suture is tied over a rubber shod (Fig. 5, D).

Tension on the lateral and medial pectoral nerves (Fig. 5, B and C) must be minimal as the broad tendon of insertion is next detached from the humerus, directed cephalad, and anchored securely to the anterior aspect of the acromion. The tendon passes directly across the anterior glenohumeral capsule and then is attached to bone by nonabsorbable sutures through drillholes (Fig. 5, A).

The final position of the transplanted pectoralis major is collinear with the anatomic origin and insertion of the biceps brachii.

After 6 weeks with the elbow still flexed at 135° and the limb immobilized in a cuff-and-collar with swathes, the patient begins a vigorous program of rehabilitation and muscle re-education.

Results

Three of the four patients in whom this procedure has been used have been rated as excellent by the criteria established by Segal, Seddon, and Brooks in 1959. To qualify as an objectively excellent result, the useful arc of motion must be greater than 60° and must include a position of forearm flexion of not less than 120°, which enables the patient to place his hand to his face or mouth for personal hygiene or feeding (Figs. 6, 7, and 8).

One patient with arthrogryposis multiplex congenita had significant fibrofatty infiltration in the transplanted muscle mass; he eventually underwent formal elbow arthrodesis in a position of function following transplant failure.

Discussion

Transplantation of the entire mass of the pectoralis major muscle in the manner described above reproduces the flexor action of the biceps brachii by inserting into either the biceps tendon or directly into the bicipital tuberosity of the radius. The transplant produces the ability not only to flex the elbow efficiently, but also to supinate the forearm as the hand is brought to the face.

Provided that the force of contraction and excursion are sufficient, any tendon transfer which utilizes either the biceps tendon or the bicipital tuberosity of the radius for insertion will satisfy the criterion for functional elbow flexion; however, by transposing the pectoralis major tendon from its insertion on the humerus cephalad to the anterior acromion (10 to 15 cm in the normal adult), the biomechanical effective site of origin from which the transplant exerts its pull is changed considerably (Fig. 9).
In theory, the force necessary to balance a given weight applied at a certain fixed distance from the axis of rotation of the elbow (namely, the weight of the loaded hand) is reduced significantly by a more proximal effective site of origin, e.g., the anterior acromion. By detaching the pectoralis tendon from the humeral shaft and relocating it proximally under tension, we effectively increase the mechanical advantage of the muscle transplant. The force (F) which remains constant now acts from a more proximal and anterior effective site of origin, increasing the “lever distance” (D₁), which, by definition, is the perpendicular distance arm through which torque will develop around a joint due to the action of the transplanted muscle.

The mechanical advantage of this muscle transplantation is theoretically greater than that of either the Clark⁶ sternocostal or the Brooks-Seddon⁷ tendon transfer, based not only on the effectively lengthened lever distance for flexor motion of the forearm at the elbow, as noted above, but also by the incorporation of the entire mass of the pectoralis major muscle, detached from both its clavicular and sternocostal origins. The independently innervated lower sternocostal head of the pectoralis major utilized by Clark⁸ in his ingenious transfer in 1946 has an effective work capacity of 10.4 meter-kgs, as compared to the normal 4.8 meter-kgs generated by the combined short and long heads of the biceps brachii in flexing the elbow.¹⁷ The entire mass of the pectoralis major muscle has a total potential work capacity of 16.5 meter-kgs as detailed by von Lanz and Wachsmuth¹⁷ in 1959 (Table II). Bunnell¹ has noted, based on the original studies by Steindler, that the absolute number of viable muscle fibers in cross-section determines the power of the muscle to be transferred (3.65 kg × sq cm).¹⁸ The amplitude of contraction which this muscle can deliver to a tendon is determined by the muscle fiber length (pectoralis major fiber length, 15 cm). The work capacity of a muscletendon unit, then, will simply be determined by the force the motor can generate, multiplied by the amplitude or
**Fig. 9.** Transposition of force vector ($F_1$) from effective site of origin to a more proximal site at acromion with new force vector ($F_2$). Note the increase in the lever distance ($D_{l1}$ vs. $D_{l2}$) for elbow flexion resulting from proximal transposition of the pectoralis major tendon as described.

**Fig. 10.** Torque is normally generated around both the shoulder (glenohumeral joint) and the elbow when only the pectoralis major tendon is used for transfer. The unstable situation is eliminated by reducing the lever distance ($D_L$) at the glenohumeral joint (see text).

<table>
<thead>
<tr>
<th></th>
<th>Clavicular</th>
<th>Sternocecal</th>
<th>Abdominal</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>Flexion (70°)</td>
<td>0.8</td>
<td>0</td>
<td>0</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>1.9</td>
<td>2.8</td>
<td>0.1</td>
<td>3.9</td>
</tr>
<tr>
<td>Extension (37°)</td>
<td>1.1</td>
<td>2.8</td>
<td>0.5</td>
<td>4.9</td>
</tr>
<tr>
<td>Abduction (88°)</td>
<td>1.2</td>
<td>9.5</td>
<td>0.5</td>
<td>11.2</td>
</tr>
<tr>
<td>Adduction (8°)</td>
<td>0.2</td>
<td>0.4</td>
<td>0.1</td>
<td>0.6</td>
</tr>
</tbody>
</table>

*From von Lanz and Wachsmuth.¹⁸

fiber distance over which this force can be delivered.

Because of the increase in the approach angle of the motor on its point of insertion, the mechanical advantage of the transplanted pectoralis major muscle is greater than that of any of the choices of motors used for restoration of active elbow flexion by tendon transfer (Table I). With the forearm held flexed at 90°, the normal approach angle of the biceps brachii on the forearm is as close to perpendicular as is anatomically possible, making this muscle normally an extremely efficient elbow flexor and forearm supinator. Transplanting the effective site of origin of the pectoralis major cephalad to the acromion maximizes its mechanical advantage in the same way, but the total work capacity of the muscle is enhanced by moving the entire mass off the chest wall.

Shoulder instability at the glenohumeral joint has been a frequent problem in cases of injury to the brachial plexus or poliomyelitis.¹ ³ ¹⁷ This instability has been circumvented in the past by shoulder arthrodesis. We have found that advancement of the broad pectoralis major tendon across the anterior capsule of the glenohumeral joint reinforces its intrinsic stability, and
in the experience of these authors arthrodesis of the shoulder has not been necessary either prior to or after transplantation of this muscle for elbow flexion.

Brooks and Seddon have shown clearly that, when the clavicular portion and upper sternocostal origins of the pectoralis major are left intact, the force generated by contraction of the transferred muscle is distributed between the elbow and the glenohumeral joints (this can be seen using either the Clark or the Brooks-Seddon transfers). Not only is torque generated around the axis of rotation of the elbow, but a similar situation exists at the glenohumeral joint, with the effective site of origin being somewhere between the clavicle and the chest wall (Fig. 10). The lever distance (Dx) now becomes the perpendicular distance between the shoulder axis of rotation and the line of force generated by the transferred motor.

Instability which results from having the work capacity of the transfer divided in this way can be eliminated by arthrodesis, which then directs the entire force of the transfer toward the forearm for flexion and supination. This same instability, however, can be significantly reduced or eliminated by shortening the lever distance from the glenohumeral joint to a point at which the torque created around this joint is minimal. Transplanting the pectoralis major tendon to the acromion and detaching its origins from the chest wall essentially reduces this glenohumeral lever distance to zero. The propensity for shrugging, adduction, and internal rotational movements, often described in the past as associated with the use of the pectoralis major as a muscle transfer, are thereby reduced by transplantation of both the insertional tendon and the origins to restore elbow flexion.

Conclusion

Transplantation of the pectoralis major muscle to restore elbow flexion to the paralytic limb affords certain distinct advantages over previously described procedures. Use of the entire active muscle mass is more desirable when recovery after nerve trauma is incomplete, or if both heads of the pectoralis are essentially uninvolved in the disease process and are available for transfer.

Transposition of the tendon of insertion cephalad increases the lever distance from the axis of rotation of the elbow and decreases the lever distance from the axis of the shoulder. In this way the mechanical advantage of this motor is augmented considerably. The stability of the shoulder is increased concomitantly, and gleno-humeral arthrodesis has been found to be unnecessary.

We feel that this technique should be an important consideration in the evaluation of available and expendable motors for use in restoring active elbow flexion to the paralytic upper limb.

REFERENCES