Upper Limb Surgery for Tetraplegia: A 10-Year Re-Review of Hand Function

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Purpose: To perform a 10-year re-review of hand function outcome for 24 tetraplegic persons who had received bilateral tendon transfers and tenodeses.

Methods: The Lamb and Chan questionnaire with additional questions, the Quadriplegic Index of Function (QIF), the Swanson sphygmomanometer technique for hook grip, the Preston Pinch Meter (PP) for key pinch, and a digital analyzer (DA) for both hook and key pinch were the test instruments used. The QIF and DA had not been used previously.

Results: Levels of functional independence and expectations were maintained. Mean hook grip values were maintained for the right hand but increased significantly for the left to reach right hand values. Mean pinch grip values decreased significantly. DA measurements confirmed similar hook grip values for both hands but key pinch values were significantly higher than the PP values. Active transfers averaged approximately twice the strength of tenodeses.

Conclusions: Hand function improvements gained from tendon transfers and tenodeses are maintained over time. (J Hand Surg 2003;28A:489–497. Copyright © 2003 by the American Society for Surgery of the Hand.)

Key words: Tetraplegia, upper limb surgery, tendon transfers, hand function.

The benefits of reconstructive surgery of the upper limb for tetraplegia have become well established after the pioneering work of surgeons such as of Freehafer et al,[1] Moberg,[2] Zancolli,[3] House and Shannon,[4] and Lamb and Chan.[5] The main aims are to provide active elbow extension, key pinch, and hook grip, and the ability of the surgeon to provide this depends largely on the level of the spinal cord injury.

In 1992 Mohammed et al[6] published results of reconstruction of 97 limbs in a consecutive series of 57 tetraplegic persons treated between 1982 and 1990. Seventy percent had good or excellent subjective results in terms of significantly improved performance of activities of daily living and the objective measurement of key pinch and hook grip compared favorably with other published series. It was reported that those who had bilateral upper-limb surgery had better results than those who had unilateral surgery.

The possible reasons for this were not discussed in that report but could be explained in 2 ways. First in some patients who had unilateral surgery the other hand already functioned sufficiently well not to require further reconstruction. Accordingly there was

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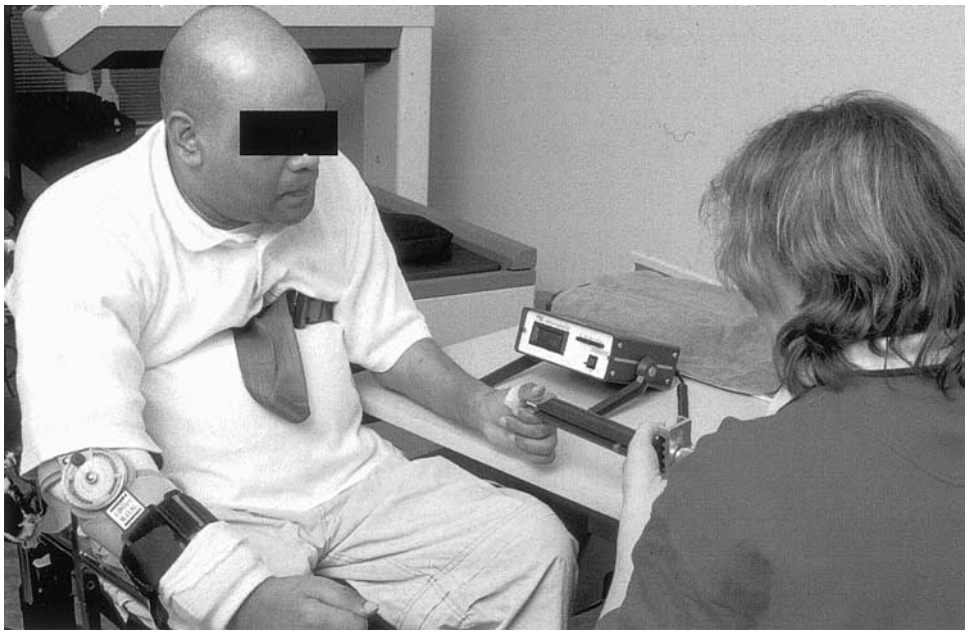

Figure 1. Measurement technique for key pinch using the DA.

not the same incentive to rehabilitate the reconstructed hand as fully as possible and gain maximum use from it. Second there was the group in which neither hand had any significant function. In this situation restoring function to one side only did not result in independent hand function but in somewhat limited combined hand function. This restricted the range of activities available to the tetraplegic person, which would be reflected by the poorer scores in the outcome measurements used.

The maintenance or otherwise of the strength of key pinch and hook grip over time has not been established for this unique group of individuals who now have a near-normal life and often work time expectancy. Accordingly it was felt that a re-review of the cohort of tetraplegic persons who had bilateral upper-limb surgery 10 years after the initial review was timely and would help to answer this question.

Patients and Methods

The cohort of 29 tetraplegic persons who had received bilateral forearm tendon transfers between 1982 and 1990 and had been reviewed in 1991 by Mohammed et al[6] formed the study group for a re-review in 2001. Patient records confirmed that 25 of the 29 still were alive and residing in New Zealand and 24 with 48 hand reconstructions agreed to participate after national ethical approval had been obtained. Most of the participants still were regular, manual wheelchair users.

In the 1991 review the Lamb and Chan[5] questionnaire with an additional 10 Burwood questions (Appendix A; this appendix can be viewed at the Journal's Web site, www.jhandsurg.org) was used for the subjective assessment and for objective measurement, the Swanson sphygmomanometer (SGM) (Slim Line Pymahcorp, Somerville, NJ) was used for hook grip, and a pinch meter (Preston Pinchmeter [PP] (European Bissel Health Care Ltd., Winchester, England) was used for key pinch. For 4 of the 24 subjects, 1991 objective data was missing.

The same instruments were used in the review with the addition of the following: for additional subjective review the participants were asked to complete the Quadriplegic Index of Function (QIF)[7] (Appendix B; this appendix can be viewed at the Journal's Web site, www.jhandsurg.org). This was considered necessary to determine the current level of functional independence rather than relying solely on either long-term memory or perceptions of changes owing to surgery. Further objective measurement for both key pinch and hook grip was obtained with a digital pinch and hook grip. An analyzer (Digital Analyzer [DA]; MIE Medical Research Ltd., Leeds, England) that used a torsion dynamometer linked to a microprocessor digital analyzer was used (Fig. 1).[8]

Data collection was performed by one person who had no knowledge of the previous surgical procedures or previous measurement results. Furthermore she was unknown to any of the subjects. An interrater

Table 1. Subject Demographics

	Mean	Minimum	Maximum
Age	42.9	37	66
Years after spinal cord injury	20.5	14	29
Years after surgery	15.13	12	18

Table 2. Cause of Spinal Cord Injury

Categories	n
Motor vehicle accident	9
Rugby (union)	10
Rugby (league)	1
Falls	1
Diving/swimming	3
Total	24

reliability test was done with 5 subjects as a pretest pilot study before data collection. The American Society of Hand Therapists (ASHT) standardized positioning protocol endorsed by Mathiowetz was used,[9] in which the subject is seated with shoulder adducted in neutral rotation, elbow flexed 90°, forearm in neutral rotation, and wrist between 0° to 30° extension and 0° to 15° ulnar deviation. For pinch grip the PP and DA were held by the investigator and positioned between the thumb and fingers if necessary. Grip aids were not allowed and no assistance was given for position maintenance.

The same measuring equipment, which was checked for reliability, was used for all 24 subjects. Each strength test was done for each hand with the subject seated in his or her wheelchair with a table to allow elbow support. Three readings were recorded for each strength test, with the maximum taken for analysis. Completion of the questionnaires between the strength measurements provided appropriate rest periods.

The data were transferred to a spreadsheet (Excel 97 SR-2, Microsoft Corp, Redmond, WA) and matched to the 1991 results and the previous surgical procedures by a different investigator.

Statistical Analysis

Descriptive statistics were used to organize, describe, and summarize the data for age, cause of spinal cord injury, years after spinal cord injury, and years after tendon transfer surgery. Appropriate nonparametric tests were used for nonnormally distributed variables. For the hook and pinch grip data the paired *t* test was used. For all tests the level of significance was set at .05.

Results

Subject Demographics

The mean age of the 24 subjects was 42.9 years, the mean time since onset of tetraplegia was 20.5 years, and the mean time since surgery was 15.1 years (Table 1). The majority of injuries to the spinal cord within this sample of tetraplegic persons resulted from recreational or sporting injuries (62.5%) with only 37.5% as a result of motor vehicle accidents (Table 2). All except 2 subjects originally were right hand dominant. The preoperative international classification (Appendix C; this appendix can be viewed at the Journal's Web site, www.jhandsurg.org) of the subjects ranged from O1 to OCu6 with the largest group being OCu4 (Table 3). Twelve of the subjects were fully employed at the time of the interview, 4 had retired from full employment, 4 did voluntary work, 2 were students, and 2 were unemployed.

Previous Surgical Procedures

The previous surgical procedures were described in detail previously with the objectives being to achieve key pinch for the thumb and hook grip for the fingers.[6] The most frequent procedures used were transfer of brachioradialis to the flexor pollicis longus (FPL) for key pinch and transfer of extensor carpi radialis longus to the flexor digitorum profundus for hook grip. When too few muscles were available for active transfers, tenodeses of FPL for key pinch and flexor digitorum profundus for hook grip were used (Table 4). Provision of active elbow extension by deltoid to triceps transfer was performed bilaterally in 9 of the 11 subjects who did not have an active triceps.

Table 3. International Classification for 24 Subjects

Classification	Right	Left	Total
01	3	3	6
02	1	2	3
03	3	2	5
OCu2	1	1	2
OCu3	2	4	6
OCu4	10	7	17
OCu5	4	4	8
OCu6	0	1	1
Total	24	24	48

Table 4. Surgical Procedures

Key Pinch		Hook Grip	
BR to FPL	29	ECRL to FDP	22
PT to FPL	6	BR to FDP	9
FPL tenodesis	9	FDP tenodesis	7
Total	44	Total	38

BR, brachioradialis; ECRL, extensor carpi radialis longus; FDP, flexor digitorum profundus; PT, pronator teres.

Pinch Grip and Hook Grip Measurements

The PP measurements in kilograms were each multiplied by 9.81 to convert them to Newtons to enable comparisons with measurements recorded by the DA. It was not possible, however, to convert the SGM measurements in mm Hg to Newtons. The thumb was included in all hook grip measurements. In 2001 several of the subjects had great difficulty performing a pinch grip with the PP even with the assistance of the investigator but there were no problems with the other assessment instruments.

Hook Grip.

For the 17 right hands that had either active transfers or tenodeses to provide hook grip the average grip of 46.2 mm Hg in 1991 had improved slightly over the 10 years as measured by the SGM but the increase was not statistically significant ($p = .30$). For the 15 left hands there was a very significant ($p = <.001$) increase in hook grip strength from an average of 28.7 mm Hg to 53.2 mm Hg (Table 5). There is no statistical significance between right and left hook grip measurements as measured by both the SGM and DA in 2001 ($p = .93$ and .97, respectively)

Key Pinch.

The average key pinch for 20 right thumbs measured with the PP in 1991 was 25.8 N and with the same instrument had decreased to an average of 13.9 N over the 10-year period. This was a very significant decrease ($p = <.001$). Similarly the average pinch strength for the 18 left thumbs decreased over the 10 years from 17.7 to 8.8 N, which again was a very significant decrease ($p = <.001$) (Table 5). The average pinch grip as measured by the DA showed an increase in key pinch strength when compared with the 1991 PP results, which was significant for both right ($p = .01$) and left ($p = .01$) thumbs (Table 6).

Active Transfers Versus Tenodeses

The tenodeses were separated out from active transfers and results for both hands were combined.

Cross-Sectional Comparisons.

The hook grip measurements showed that active transfers provided approximately twice the strength of tenodeses in both 1991 ($p = .05$) and 2001 ($p = .03$). The results were similar for pinch grip when comparing 1991 data ($p = <.001$), but the 2001 data does not follow this trend, which almost certainly is related to the difficulty subjects had using the PP. In fact only 2 of the subjects with FPL tenodeses were able to produce a reading. The 2 to 1 trend was restored when comparing the 2001 DA data but did not quite reach statistical significance ($p = .06$) (Tables 7, 8).

Longitudinal Comparisons.

The hook grip strength for the 25 hands that had had active transfers showed a significant increase from 42.1 to 60.2 mm Hg ($p = <.001$) and similarly there had been an increase from 24.0 to 38.4 N for the pinch grip for the 31 thumbs that had had active transfers when using the 2001 DA data ($p = .03$).

The data also show that the hook strength obtained via a tenodesis in the 7 hands did not weaken over time ($p = .05$) but the pinch strength via a tenodesis in the 7 thumbs significantly increased over the 10-year period ($p = <.001$) when using the 2001 DA results (Tables 7, 8).

Table 5. Objective Measurements for 20 Subjects in 1991 and 2001

Hook grip	1991 (R) SGM	2001 (R) SGM	2001 (R) DA	1991 (L) SGM	2001 (L) SGM	2001 (L) DA
Hands	17	17	17	15	15	15
Average	46.23	53.24	54.76	28.73	53.20	48.26
SD	22.36	31.05	31.31	16.40	29.08	34.75
Pinch grip	1991 (R) PP	2001 (R) PP	2001 (R) DA	1991 (L) PP	2001 (L) PP	2001 (L) DA
Hands	20	20	20	18	18	18
Average	24.32	13.95	32.25	18.22	8.78	27.0
SD	19.822	18.72	19.14	12.62	13.31	16.12

SGM measurements in mm Hg. DA and PP measurements in N.

Table 6. Objective Measurement for 24 Subjects in 2001

Hook grip	2001 (R) SGM	2001 (R) DA	2001 (L) SGM	2001 (L) DA
Hands	20	20	18	18
Average	49.85	52.40	50.44	50.78
SD	30.82	32.45	27.56	33.14
Pinch grip	2001 (R) PP	2001 (R) DA	2001 (L) PP	2001 (L) DA
Hands	24	24	22	22
Average	12.2	30.93	7.45	25.29
SD	17.66	19.46	12.56	16.30

Effect of Comorbidities

Three participants who had developed significant comorbidities that made them totally or mostly power wheelchair users were certain that their hand grip strength had deteriorated greatly but in fact in none of them was there a significant change from the 1991 measurements.

Questionnaire Results

The Lamb and Chan[5] activity measure showed perceived improvement of functional activities as a result of hand surgery was significantly lower in 2001 ($p = <.001$). The QIF scores of current level of functional independence was statistically significantly better than the levels of change based on memory of preoperative function measured by Lamb and Chan[5] in 1991 ($p = .004$). The scores from the additional Burwood questions showed that levels of satisfaction, perceived expectation, gratification, and opportunity enhancement were maintained over time ($p = .281$).

Discussion

This 10-year review is a follow-up study of the outcome of bilateral hand surgery in a cohort of tetraplegic persons initially reported in 1992. The same methodology was used for both reviews with the addition of the QIF for subjective assessment and the use of the DA for measuring key pinch and hook grip.

The results from this review show that hook grip strength as measured by both the SGM and DA methods is maintained and even improved for at least 12 years and up to 18 years after surgery despite the fact that several of the participants are now into middle age, when normal muscle strength is decreasing.[10] The significant increase of left hook grip is interesting and may well represent a catch up of the nondominant hand with the dominant hand because from both the SGM and DA measurements there was no statistical difference between the right and left hook strength in 2001. This is supported by several of the participants who stated that since the surgery they did not regard one hand as being more dominant over the other. Just 2 of the 24 participants originally were left-hand dominant.

With regard to key pinch as measured by the PP there was a major reduction in the readings obtained between 1991 and 2001 but the readings taken by the DA paralleled those for hook grip when compared with the 1991 key pinch results. Many of the subjects stated that with the arm positioning protocol they found it very difficult to apply a key pinch when using the PP, especially those with an FPL tenodesis, when only 2 of 7 were able to register a reading. All participants found it easy to perform the tests with

Table 7. Active Transfers Versus Tenodeses: 20 Subjects in 1991 and 2001

Hook grip	*Tenodeses both hands*			*Active transfers both hands*		
	1991 SGM	2001 SGM	2001 DA	1991 SGM	2001 SGM	2001 DA
Hands	7	7	7	25	25	25
Average	23.57	28.14	34.43	42.08	60.24	67.52
SD	18.87	23.78	16.50	19.83	30.30	36.23
Pinch grip	*Tenodeses both thumbs*			*Active transfers both thumbs*		
	1991 PP	2001 PP	2001 DA	1991 PP	2001 PP	2001 DA
Hands	7	7	7	31	31	31
Average	9.86	1.57	19.14	24.03	13.74	38.42
SD	5.49	3.74	9.77	16.65	16.58	18.00

Table 8. Active Transfers Versus Tenodeses: 24 Subjects in 2001

Hook grip	*Tenodeses both hands*		*Active transfers both hands*	
	2001 SGM	2001 DA	2001 SGM	2001 DA
Hands	7	7	31	31
Average	28.14	34.43	55.10	55.52
SD	23.78	16.501	27.94	33.6
Pinch grip	*Tenodeses both thumbs*		*Active transfers both thumbs*	
	2001 pp	2001 DA	2001 pp	2001 DA
Hands	7	7	39	39
Average	1.57	19.14	11.44	29.87
SD	3.74	9.78	16.29	18.78

the DA and the SGM. The investigator for the original study was located and it was confirmed that the ASHT protocol was not used and the individual was free to place his arm in the most advantageous position for each test. In addition they had been allowed to wear gloves or lick their fingers to minimize slipping. It is disappointing that this detail in the methodology was neither documented nor reported until the testing program was completed. Unfortunately it was not possible to retest the participants. In addition, several participants volunteered that thumb control had decreased over time, which made it even more difficult to properly position the PP. A probable reason for this is that none of the subjects had a thumb carpometacarpal joint fusion and an extensor pollicis longus tenodesis, which provides much more precise thumb positioning for key pinch and reliable thumb opening when the wrist is gravity flexed. These procedures were not adopted routinely until the early 1990s. The thumb problems, however, did not provide any barriers to using the DA. The earlier factors probably are responsible for the discrepancy of results from the DA and PP, which was rechecked for accuracy. On the other hand all participants found the DA to be very user friendly. Accordingly we believe it is valid to accept the DA key pinch data as more accurately reflecting the change in key pinch strength over the 10-year period. The difficulties reported by the participants in using the PP highlight the importance of using standardized measurement techniques, careful documentation, and functionally appropriate user-friendly measuring devices. The MIE digital analyzer meets these requirements.[8]

It is again noteworthy that when the tenodeses were separated out from active transfers that neither FPL nor flexor digitorum profundus tenodeses failed over time. Tenodesis strength is reliant on wrist extension torque and the length and fixation of the tenodesed tendon. These results confirm that none of these factors changed and in particular there was no stretching of the tenodesed tendon that had been thought to be inevitable.

Four of the 6 limbs (3 subjects) classified 01 (Table 3) had had a brachioradialis to ECRB transfer. The other 2 limbs in the 1 subject were graded as a power 3+ for wrist extension, which was deemed to be of sufficient strength to enable adequate key pinch with a FPL transfer. These 3 subjects had become significantly weaker over the 10-year period and in addition 2 of them were the only subjects who did not have elbow control either through a deltoid to triceps transfer or retention of triceps function. These poorer results probably reflect the effect of the high spinal cord injury but the numbers are too small to draw firm conclusions. Nevertheless the 3 tetraplegic persons have maintained hand function benefits despite a fall-off in strength measurements.

Analysis of the activity-related questionnaires produced some interesting results. The Lamb and Chan[5] activity questionnaire based on memory of preoperative function showed a decrease in the level of perceived improvement despite the fact that current levels of functional independence were higher than expected. The current level of independence tested using the QIF inquires about the same activities tested by Lamb and Chan.[5] It is of interest that there was no agreement between these 2 results; it suggests that reliance on memory of functional well-being is unreliable. Neither age nor duration of tetraplegia appeared to be a factor in any circumstance. Of the 24 individuals within this cohort 22 considered their vocational opportunities to be improved markedly as a direct consequence of the improved hand function. Considerable employment versatility was shown by a significant number of the participants after upper-limb surgery and several had retrained successfully to find gainful employment. The fact that 90% of this cohort either were employed, retired from employ-

ment, or were pursuing vocational activity underscores their strong motivation, which is an important factor when selecting tetraplegic persons for upper-limb reconstruction. The maintenance of functional independence over time shown by the QIF scores in 2001 complements the findings from the Burwood appendix scores that levels of satisfaction, the meeting of expectations, and perception of an increase in opportunity also had been maintained over the 10-year period. A more in-depth analysis of the questionnaire results will be reported in the near future.

The strongly positive message from this review is that surgeons and other health care professionals involved in the care of persons with tetraplegia confidently can undertake and recommend reconstructive hand surgery knowing that the benefits gained from such surgery will be maintained for many years. This review also shows that single muscles can cope with the demands of an activity that normally requires 2 or more muscles without undergoing accelerated physiologic failure even in middle-aged or older tetraplegic persons who are manual wheelchair users. The review highlights the importance of having user-friendly measuring devices in association with clearly documented measurement protocols.

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Appendix A. Lamb and Chan Questionnaire With Burwood Additions

Activity	Response (%)				
	Much Worse	Worse	Unchanged	Improved	Greatly Improved
Mobility					
1 Raise yourself in seat					
2 Propel wheelchair on level ground					
3 Propel up and down a gentle slope					
4 Transfer from wheelchair to bed					
5 Drive a car					
Dressing					
6 Upper garments					
7 Lower garments					
Communications					
8 Using a telephone					
9 Writing or typing					
10 Handling money					
Washing and toileting					
11 Getting in and out of shower/bath					
12 Washing and drying upper limbs					
13 Washing and drying lower limbs					
14 Cleaning teeth					
15 Shaving or applying cosmetics					
16 Brushing hair					
17 Bladder: use of urodome or catheter					
18 Bowel: inserting suppositories and cleaning after bowel action					
Feeding and drinking					
19 Use of cutlery					
20 Cutting meal					
21 Holding a cup or glass					
Miscellaneous					
22 Making a meal or snack					
23 Reaching a shelf above					
24 Opening and closing drawers					
25 Operating buttons					
Burwood Additions					
26 Picking up things from the floor					
27 Using a key					
28 Putting a plug into a point					
29 Have your educational/vocational options changed					
30 Were your overall expectations met					
31 Have you become more independent					
32 Has your self-confidence changed					
33 Has the surgery changed your quality of life					
35 Any comments					

Points
Much worse =
Worse =
Unchanged =

Results
Improved =
Greatly improved =

Poor Good
Fair Excellent

Appendix B. Quadriplegia Index of Function: Component Activity Categories and Relative Weights of Each

Category	Component Activities of Category (Each Scored Separately)	Relative Weights of Category (percent)
I. Transfers	1. Bed-chair	8
	2. Chair-bed	
	3. Chair-toilet/commode	
	4. Toilet/commode-chair	
	5. Chair-vehicle	
	6. Vehicle-chair	
	7. Chair-shower/tub	
	8. Shower/tub-chair	
II. Grooming	1. Brushing teeth/managing dentures	6
	2. Brushing combing hair	
	3. Shaving (men)	
	4. Managing tampon (women)	
III. Bathing	1. Wash/dry upper body	4
	2. Wash/dry lower body	
	3. Wash/dry feet	
	4. Wash/dry hair	
IV. Feeding	1. Drink from cup/glass	12
	2. Use spoon/fork	
	3. Cut food (meat)	
	4. Pour liquids out	
	5. Open carton/jar	
	6. Apply spreads to bread	
	7. Prepare simple meals	
	8. Apply adaptive equipment	
V. Dressing	1. Upper indoor clothes on/off	10
	2. Lower indoor clothes on/off	

Appendix C. The International Classification for Surgery of the Hand in Tetraplegia

Sensibility	Motor Group	Characteristics*
O = Ocular afferents only	0	No muscle below elbow available
Cu = Cutaneous sensibility	1	Brachioradialis
2-point discrimination on the thumb tip to 1 cm	2	Extensor carpi radialis longus
	3	Extensor carpi radialis brevis
	4	Pronator teres
	5	Flexor carpi radialis
	6	Finger extensors
	7	Thumb extensor
	8	Partial digital flexors
	9	Lacks only intrinsics
	X	Exceptions

*A muscle must be at least grade 4 strength on the Medical Research Council scale to be considered available for transfer.
FCR, flexor carpi radialis.