Acute upper limb compartment syndrome in children: special focus on nerve recovery

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ABSTRACT

Background Many studies have discussed acute compartment syndrome in children associated with or without fractures and have given their visible perspectives. Little is known about the nerve involvement and the factors associated with recovery patterns in these patients. We intend to propose that ischemic nerve and muscles tend to regenerate after surgical decompression but in a different pattern and the given circumstances.

Methods Twenty-four children with acute compartment syndrome in the upper limb were analyzed between 2009 and 2015. Data included demographic features of these patients, the time interval between the injury and surgery, and the attempt to correlate with motor and sensory recovery.

Results The average follow-up was 67.3 months (range 59–80). Of the 24, 14 patients (58%) had immediate recovery of motor and sensory functions. The remaining 10 patients had variable recovery patterns with a mean time for the radial nerve, median nerve and ulnar nerve motor recovery of 6.0, 7.5 and 8.5 months, respectively, and sensory recovery at 12, 12 and 13 months, respectively. The overall study had a mean sensory recovery as per the Medical Research Council (MRC) of S3 in 3 (12%) and S4 in 21 (88%). The mean 2-point discrimination (2PD) was 6.9 mm (range 5–10). Twenty-one patients (88%) had a full range of movements at their final follow-up with a mean Visual Analog Scale score of 0.6; a quick Disabilities of the Arm, Shoulder and Hand score of 5.9 (range 2.3–25.0) and a Mayo wrist score of 79.

Conclusions There was a definite motor and sensory recovery in patients who underwent surgical decompression in acute compartment syndrome of the upper limb irrespective of age, gender, delay in presentation and various etiologies. The motor and nerve fibers can regenerate after ischemic sequela of compartment syndrome.

INTRODUCTION

Acute compartment syndrome in the forearm of children is an orthopedic emergency that needs urgent care to prevent irreversible nerve damage, muscle fibrosis, atrophy, contractures or deformities.^{1 2} The presentation of children with acute compartment syndrome is unique in many ways, including undue delay, unreliable presentations of pain, paresthesia, pallor, pulselessness and

Key messages

What is already known about this subject?

- ▶ Acute compartment syndrome in the forearm of children is an orthopedic emergency that needs urgent care to prevent irreversible nerve damage, muscle fibrosis, atrophy, contractures and deformities.
- ▶ The presentation of children with acute compartment syndrome is unique in many ways, including undue delay, unreliable presentations of pain, paresthesia, pallor, pulselessness and paralysis and capacity to communicate because of anxiety, agitation and increased analgesic requirements.
- ▶ Early decompression of the affected forearm is mandatory to prevent paralysis and contractures.

What are the new findings?

- ▶ We found the statistical significance of tight oil bandage association with paralysis and high-energy mechanism of RTA/crush or fall presenting with severe pain and paralysis.
- ▶ Single-incision fasciotomy was done to decompress all compartments, and the median and ulnar nerves were severely compromised at their entrapment sites in the wrist, forearm and elbow. Hence, adequate neurolysis from the carpal tunnel to the cubital tunnel should be done in all patients.
- ▶ There was a statistical significance ($p < 0.5$) assessed by Fischer's exact test for the association between intervention < 24 hours and > 24 hours after injury of compartment syndrome to functional outcomes.
- ▶ The mean times for radial, median nerve, and ulnar nerve motor recovery were 6.0, 7.5 and 8.5 months, respectively. The sensory recovery was in the proximal direction. It was complete recovery in the forearm at a mean of 10 months after injury (range 7–12) and in the hand at 13 months (range 10–14).

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paralysis (5 Ps) and capacity to communicate, owing to anxiety, agitation and increase in analgesic requirements.^{3 4} Early decompression of the affected forearm is mandatory to prevent paralysis and contractures.⁵ Volkmann's contracture is defined as the end result of an ischemic injury to the muscles and nerves of the limb. Volkmann's ischemia is the acute episode of pain, aggravated by passive stretching and neurological deficit

Key messages

How might it impact on clinical practice in the foreseeable future?

- Our study proves that surgical decompression plays a vital role in the recirculation of blood supply to the ischemic nerves and muscles, thereby preventing muscle fibrosis, atrophy, contractures and deformities. We also proved that fibrotic muscle regains recovery over some time (6–12 months) based on radial, median and ulnar motor recoveries, producing full and excellent functional recovery in 21/24 (88%) children. The sensory recovery (proximodistal) was also seen in all patients (100%) with an average 2-point discrimination of 6.9 mm and an Medical Research Council grade of S4 in 88% and S3 in 12%.

resulting from ischemia of muscle and nerve.⁶ The extent of muscle recovery varies with the completeness of the destruction of muscle tissue and is directly related to the extent of motor recovery. Muscle regeneration seems to occur from a small number of subfascial fibers that survive the ischemic episode; regeneration is seen to be active even later than 76 weeks after injury.⁷ Several aspects of nerve and muscle recovery following fasciotomy have not been investigated. There seem to be associations between various additional factors affecting the functional outcomes in these patients. We propose that ischemic nerve and muscles tend to regenerate after surgical decompression but in a different pattern. Also, we analyze different factors contributing to functional recovery indirectly reflecting the ischemic nerve and muscle recovery.

METHODS

Patients and statistical analysis

We conducted a retrospective analysis of 24 children admitted between 2009 and 2015 with different features of acute compartment syndrome in the upper limb. Patients with a head injury and lower limb injuries were excluded from this study. All patients had basic blood investigation and radiographs of the involved upper limb. In addition, tests for myoglobinuria, troponin and blood lactate were done to investigate for late/missed compartment syndrome in these patients. Based on the arrival of the emergency with clinical features and the surgeon's discretion, 8 patients had compartment pressure measured, and the remaining patients were wheeled into the operating room at the earliest without compartment pressure management. Each patient's data for the study were collected at the hospital, and pictures were taken with the appropriate consent. No patient was lost to follow-up. Based on the age, injury pattern, associated soft-tissue injuries/fractures, the time interval between the injury and admission and the time interval between the injury and surgery, motor and sensor recovery of these children with their functional outcomes were interpreted. Qualitative (gender and side) and quantitative variables (age) were evaluated using t-test. A comparison

Figure 1 Schematic diagram showing the skin incision for surgical decompression for releasing carpal tunnel in the distal and up to cubital tunnel proximally if needed (drawn by the author).

of the variables was done using χ^2 . Fischer's exact test was used to compare the functional outcome in patients with a time of <24 hours from injury to fasciotomy to patients with a time of >24 hours to fasciotomy. Two-tailed p values of 0.05 or less were considered significant.

Surgical technique

All patients had single-incision fasciotomy as described by Henry (figure 1) under general anesthesia. The incision was extended proximally with slight curvilinear across the elbow flexion crease (oblique) and distally at volar wrist crease (Bruner) to decompress the lacertus fibrosus/antecubital fossa contents and the carpal canal, respectively. The advantage of the ulnar-side approach was that flexor tendons and ulnar and median nerves were left with good soft-tissue coverage in the area where necrosis was most likely to occur. Depending on the intraoperative findings and surgeon discretion, primary wound closure and delayed primary closure with or without skin grafting were done.

Case 1

A boy in his early childhood who had a road traffic injury and accidentally fell, injuring his left upper limb, went to a non-physician to have a tight oil bandage on the same day. He came to us 6 days after the injury with numbness and paralysis of the entire upper limb. Radiographs of the left elbow showed an intra-articular olecranon fracture. Examination revealed complete motor and sensory loss in the entire upper limb with warm hand and good capillary refill. Considering the clinical findings and tense forearm, he was taken for immediate fasciotomy through the volar incision (Henry's). Adequate decompression was done. Delayed primary closure was done at the fifth postoperative day (figure 2A). Minimal wound gaping was seen during the follow-up, and the wound healed with regular dressings. Wrist and finger extension was seen in the immediate postoperative period with a claw hand. He was put on regular passive therapy and claw splints in between therapy. At 8 weeks, the claw deformity improved with median (flexor digitorum superficialis, FDS) and ulnar nerve innervated muscles (finger abduction/adduction) recovering (figure 2B), and the skin had multiple raw areas around the suture lines. Median

Figure 2 Intraoperative, clinical and follow-up pictures of an 8-year-old boy. (A) Intraoperative pictures showing adequate surgical incision and decompression of both median and ulnar nerves in an 8-year-old boy who came to the emergency room 6 days after the initial injury with complete paralysis of the upper limb. (B) Clinical pictures of motor recovery and multiple raw areas around the suture lines. Recovering median and ulnar innervated muscles showing a combined claw hand picture. (C) Full functional motor recovery at 8 months after surgery with wounds healed. (D) Full functional motor recovery (median and ulnar nerves) at 4 years following fasciotomy.

and ulnar nerve recovery was complete at 8 months of follow-up. He had excellent functional recovery with a Visual Analog Scale (VAS) score of 0, a quick Disabilities of the Arm, Shoulder and Hand (DASH) score 2.3 and a Mayo wrist score of 85, and returned to school at 9 weeks. Sensory recovery was S4 with 2-point discrimination (2PD) of 5 mm at the final follow-up (figure 2C,D).

Case 2

A boy in his middle childhood fell from his father's bike and injured his left elbow. He was taken immediately to a hospital, where radiographs were not taken, and instead he was given analgesics. Despite a high dose of oral analgesics, he had severe pain, swelling and subsequent weakness and paralysis. All of this occurred about 1 day after injury, and the boy presented in our emergency room with complete motor and sensory loss. The limb was pink but pulseless. Serum myoglobinuria, lactate level and troponin were found within normal limits. Radiographs showed a displaced supracondylar (SC) humerus, which was stabilized and fixed with Kirshner wires (K wires). The thrombosed small segment brachial artery was excised, and an end-to-end microsurgical anastomosis was done. Fasciotomy was done, and the wound was closed primarily (figure 3A). He subsequently developed superficial skin necrosis, which settled with regular dressings. He developed claw hand (combined median and ulnar nerve involvement) in the immediate postoperative

period (figure 3B) and was put on aggressive hand therapy with splints in between. He regained motor and sensory recovery with a full range of movements at the seventh month of follow-up. His sensation was normal S4 with 2PD 6 mm at the final follow-up (figure 3C).

RESULTS

The most common mode of injury was road traffic injury and fall over the hand. There were 19 male children with a mean age of 8.6 years and 5 female children with a mean age of 8 years (tables 1 and 2). Thirteen children had right-side involvement. The age ($p=0.23$), side involved ($p=0.64$) and gender ($p=0.52$) had no statistical significance to outcomes in this study.

ETIOLOGY

Most of the patients developed compartment syndrome secondary to high-energy mechanisms of injury, with the most common being road traffic accident (RTA) in 17/24 (70%) of the cases. Five children had fallen from height, injuring the upper limb and subsequently developing compartment syndrome in the setting of fracture. Two children had intravenous infiltrations during their stay in the intensive care unit (ICU) and developed compartment syndrome with pressure of >40 mmHg. The mode of injury did not have significance to the outcome in this study ($p=0.73$).

Figure 3 Preoperative, clinical, intraoperative, nerve recovery pattern of a 5-year-old boy following a tight oil bandage treatment. (A) A 5-year-old boy who had fell from height managed initially with tight oil bandages came to us >24 hours after injury. Radiographs revealed displaced SC fracture humerus. The upper limb with pink, pulselessness and paralyzed. SC fracture was reduced and stabilized with K wires. Brachial artery was repaired. Fasciotomy was deferred based on the intraoperative findings of the supple forearm. (B) Postoperative pictures showing recovering FDS (median nerve), finger flexion on MCP joint flexion (ulnar nerve) with radiographs showing healed SC fracture with unstable scar over the elbow. (C) Full functional motor recovery (median and ulnar nerve) at 3 years following fasciotomy. FDS, flexor digitorum superficialis; K wires, Kirshner wires; MCP, metacarpophalangeal; SC, supracondylar.

CLINICAL PRESENTATION

Classically, a compartment syndrome diagnosis is associated with the 5 Ps. Severe pain was the initial presentation in our study in 19/24 patients (76%) associated with one or more 5 Ps. However, all patients had paralysis of the upper limb (complete motor and sensory loss) at presentation in the emergency room. We found no statistical significance of tight oil bandage association with paralysis and high-energy mechanism of RTA/crush or fall presenting with severe pain and paralysis ($p>0.05$). Two patients who were getting treatment in the ICU were referred for sudden onset of forearm swelling around the intravenous infusion area. They were operated on within 6 hours of the incident and had an excellent functional outcome at the final follow-up (table 3).

Tight oil bandage and undue delay in presentations

A special focus of attention towards this native oil bandage, which was applied by the non-physicians in the near vicinity, was the reason for the delay in presentation to the hospital. An oil bandage was traditionally used to

treat fractures by the local people that had no medical background and had limited access to medical care. They applied oil and tried to set the bone with tight bamboo sticks or native dressings, which could have triggered the vicious cycle of compartment syndrome leading to development of transient/irreversible ischemic damages to nerve and muscle ($n=7$). All of these children had a trivial injury and sustained undisplaced olecranon fractures ($n=2$), SC fractures ($n=2$), radial head ($n=1$), proximal ulna ($n=1$) and distal radius fracture ($n=1$). The average time between injury and admission was 82 days (range 1–144) in these patients. Single-incision fasciotomy was done to decompress all compartments. Intraoperatively, the median and ulnar nerves were severely compromised at their entrapment sites in the wrist, forearm and elbow. Hence, adequate neurolysis from carpal tunnel to the cubital tunnel was done in all these patients.

Brachial artery injury was associated with paraesthesia and pain, with or without other 5 Ps in our study. The presence of these two symptoms confirmed the onset of ischemia sequela and compartment syndrome, producing

Table 1 Demographics and treatment

Patient number	Age (y)/gender	Side	Common presentation	Mode of injury	Treatment prior to diagnosis	Fracture/soft-tissue injury	Compartment pressure (mmHg)	Additional surgery	Time interval injury to admission (h)	Time interval admission to surgery (min)	Incision	Hospital stay (d)	Follow-up (mon)
1	8/M	L	Paralysis	RTA/fall	Tight oil bandage	Olecranon (intra-articular)	No	Delayed closure (5 d)	144	50	Single	9	72
2	5/M	L	Paralysis, pulselessness	Fall from height	Tight oil bandage elbow	SC fractures	No	Brachial artery repair, K wire fixation, SC humerus	24	60	Single	8	80
3	7/F	L	Pain, swelling, paralysis	Fall from height	No	Both bones forearm	40	Delayed closure (5 d)	9	50	Single	4	64
4	8/M	R	Swelling; pain; forearm; paralysis	Intravenous infiltrate/severe dehydration	No	Intravenous infiltrate	40	Nil	6	60	Single	4	72
5	3/M	L	Paralysis, swelling, tender	RTA/fall	Closed reduction for SC fractures	SC fractures	No	Redo K wire, delayed closure, skin grafting (6 d)	192	65	Single extension to arm	14	72
6	5/M	R	Pain; swelling; forearm; paralysis	Intravenous infiltrate in ICU/sepsis	Nil	Intravenous infiltrate	No	Nil	6	50	Single	13	64
7	6/M	R	Pain, wrist; swelling; paralysis	Fall from height	Tight oil bandage	Distal radius	No	Delayed closure, skin grafting (6 d)	96	45	Single	6	72
8	9/F	L	Pain, swelling, paralysis	RTA/car crush	Nil	Both bones forearms	40	Nil	6	50	Single	5	69
9	10/M	R	Pain, swelling, pulselessness, paralysis	RTA/fall	Nil	SC humerus	No	Brachial artery repair	12	45	Single	7	62
10	14/M	L	Pain, swelling, paralysis	RTA/crush injury	Nil	Distal radius	40	Nil	5	50	Single	4	70
11	9/M	L	Pain and swelling, paralysis	RTA/crush	Nil	Both bones forearm	40	Nil	6	55	Single	11	65
12	10/M	R	Pain, swelling, paralysis	Fall from height	Oil bandage	Proximal ulna	No	Delayed primary closure (5 d)	72	50	Single	9	72
13	11/M	L	Pain, swelling, paralysis	RTA/crush	Nil	Both bones forearm	No	Nil	5	50	Single	4	65
14	8/F	R	Pain, swelling, paralysis	RTA/fall from bike	Oil bandage	Undisplaced SC humerus fracture	No	Delayed primary closure (5 d)	51	50	Single	9	71
15	7/M	L	Pain, swelling, tenderness, paralysis	RTA/fall	Nil	Both bones forearm	No	Nil	7	55	Single	5	56
16	16/M	R	Pain, swelling, tenderness, paralysis	RTA/crush	Nil	Distal radius	40	Delayed closure, skin grafting (6 d)	11	60	Single	5	60
17	8/M	R	Paralysis	RTA/fall	Tight oil bandage	Undisplaced olecranon	No	Delayed closure, skin grafting (6 d)	104	50	Single	6	72
18	14/M	R	Pain, swelling, paralysis	RTA/crush injury	Nil	Distal radius	40	Nil	5	50	Single	3	70

Continued

Table 1 Continued

Patient number	Age (y)/gender	Side	Common presentation	Mode of injury	Treatment prior to diagnosis	Fracture/soft-tissue injury	Compartment pressure (mmHg)	Additional surgery	Time interval injury to admission (h)	Time interval admission to surgery (min)	Incision	Hospital stay (d)	Follow-up (mon)
19	6/M	R	Paralysis	RTA/fall	Closed reduction for SC fractures, K wire over ulnar nerve	SC fractures	40	Debridement, drainage, skin grafting	171	65	Single extension to arm	19	72
20	7/F	L	Pain, swelling, tenderness, paralysis	RTA/fall	Nil	Both bones forearm	No	Nil	12	50	Single	5	59
21	7/M	R	Pain, swelling, tenderness, paralysis	RTA/fall	Nil	Both bones forearm	No	Nil	10	65	Single	5	69
22	9/F	R	Pain, swelling, paralysis	Fall from height	Oil bandage	Radial head	No	Delayed closure (5 d)	86	65	Single	10	60
23	7/M	R	Pain, swelling, tenderness, paralysis	RTA/crush	Nil	Both bones forearm	No	Nil	6	55	Single	4	65
24	8/M	L	Pain, swelling, tenderness, paralysis	RTA/fall	Nil	Both bones forearm	No	Nil	8	50	Single	5	64
Mean	8.5								44	54		7.3	67.3

ICU, intensive care unit; L and R, left and right; M and F, male and female; RTA, road traffic accident; SC, supracondylar; K wire, Kirshner wire.

motor and sensory deficits. Six out of seven children (olecranon, n=2; SC humerus, n=1; with brachial artery, n=1; radial head, n=1; proximal ulna, n=1; distal radius, n=1) with a tight bandage and delay in presentation had immediate recovery of radial nerve, but claw deformity persisted.

Nerve involvement and recovery

Of the 24 patients, 14 patients (58%) had immediate recovery of motor and sensory functions. Ten (42%) patients had varied patterns of recovery of radial, median and ulnar nerves, of which, three (13%) had radial, median and ulnar nerve palsies, six (25%) had combined median and ulnar nerve palsies, one patient (4%) had median nerve injury alone.

1. Radial nerve

The mean time to appreciate thumb extension (extensor pollicis longus) was 12 weeks (range 8–16), and the sensation was 24 weeks (range 16–32). The motor recovery was complete at a mean of 6 months (range 5–8) after injury. The sensory recovery was complete in the forearm at a mean of 7.5 months (range 6–9) after injury and in the hand at 12 months (range 10–13).

2. Median nerve

The mean time to appreciate FDS flexion in fingers was 10.3 weeks (range 2–20) and the sensation was 13 weeks (range 2–20). By 3 months, all of them had claw hand, which explains the common involvement with the ulnar nerve. The motor recovery was complete at a mean of 7.5 months (range 6–9) after injury. The sensory recovery was complete in the forearm at a mean of 10 months (range 7–12) after injury and in the hand at 13 months (range 10–14).

3. Ulnar nerve

The mean time to appreciate finger abduction/adduction was 12 weeks (range 2–26), and sensation was 19 weeks (range 2–26). The motor recovery was complete at a mean of 8.5 months (range 7–12) after injury. The sensory recovery was complete in the forearm at a mean of 10 months (range 7–12) after injury and in the hand at 13 months (range 10–14).

Among the childrens with acute compartment syndrome and nerve injuries, one patient (4%) who had been treated elsewhere for displaced SC humerus fractures had superficial and deep infection. No motor or sensory recovery was seen immediate to the surgery. Partial radial nerve (active thumb extension) recovery was seen at 12 weeks, median nerve at 16 weeks and ulnar nerve at 20 weeks. Despite this recovery, the patient still had claw hand and stiff metacarpophalangeal and proximal interphalangeal joints.

One patient (4%), who came 171 hours after injury and had K wires driven through ulnar nerve and radial nerves, developed septic arthritis, triggering compartment syndrome. The abscess was drained, and the K wires were removed with adequate decompression and neurolysis. Postsurgery, there was no immediate motor and sensory recovery. Partial radial nerve recovery was seen at

Table 2 Functional recovery and outcome

Patient number	Time to notice initial motor movements (wk)				Time for sensory recovery to be seen (wk)				Sensory recovery/static 2PD (final follow-up)	Range of movements	VAS score	Mayo Wrist score	Quick DASH score	Complications
	Radial	Median	Ulnar	Median nerve	Ulnar nerve	Radial nerve	Initial deformity seen at 3 mon							
1	Immediate/claw deformity hand	8	9	9	10	Immediate	Combined claw (median+ulnar)	S4 5mm	Full	0	85	2.3	Raw areas over the sutures which healed by scar	
2	Immediate/claw deformity hand	8	Immediate	9	Immediate	Immediate	Median claw and median nerve palsy	S4 6mm	Full	0	85	4.5	Unstable scar	
3	Immediate	4	4	8	10	Immediate	Nil	S4 5mm	Full	0	80	2.3	Nil	
4	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Nil	S4 5mm	Full	0	85	4.5	Superficial skin necrosis, settled with dressing alone	
5	12/claw deformity hand	16	20	20	26	24	Finger stiffness/combined claw	S3 9mm	Stiff MCP and PIP joints	4	40	18.2	Stiff joints, osteomyelitis humerus/non-union supracondylar humerus	
6	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Nil	S4 6mm	Full	0	85	2.3	Nil	
7	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Nil	S4 6mm	Full	0	85	4.5	Nil	
8	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Nil	S4 5mm	Full	0	80	2.3	Nil	
9	Immediate	Immediate/claw	Immediate/claw	2	2	Immediate	Mild combined claw	S4 6mm	Full	0	85	4.5	Nil	
10	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Nil	S4 5mm	Full	0	85	4.5	Nil	
11	Immediate	immediate	Immediate	Immediate	Immediate	Immediate	Nil	S4 5mm	Full	0	80	6.8	Nil	
12	Immediate	Immediate/claw	Immediate/claw	2	2	Immediate	Mild claw	S4 6mm	Full	1	80	4.5	Nil	
13	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Nil	S4 5mm	Full	0	85	4.5	Nil	
14	8	12	16	13	18	16	Combined claw	S3 7mm	Elbow stiff, stiff claw	4	50	22.0	Elbow stiffness	
15	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Nil	S4 5mm	Full	0	85	2.3	Nil	
16	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Nil	S4 6mm	Full	0	85	4.5	Nil	
17	Immediate/claw deformity hand	12	16	16	22	Immediate	Combined claw	S4 8mm	Full	1	80	4.5	Multiple small raw areas over edges/scars	
18	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Nil	S4 5mm	Full	0	85	4.5	Nil	
19	16/claw deformity hand	20	26	18	26	32	Combined claw	S3 10mm	Elbow stiff, MCP, PIP joint stiffness	4	45	25	Septic arthritis/multiple surgery	

Continued

Table 2 Continued

Patient number	Time to notice initial motor movements (wk)			Time for sensory recovery to be seen (wk)				Sensory recovery/static 2PD (final follow-up)	Range of movements	VAS score	Mayo Wrist score	Quick DASH score	Complications
	Radial	Median	Ulnar	Median nerve	Ulnar nerve	Radial nerve	Initial deformity seen at 3 mon						
20	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Nil	S4 5mm	Full	0	85	2.3	Nil
21	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Nil	S4 5mm	Full	0	85	4.5	Nil
22	Immediate/claw deformity	2/claw	2/claw	2	2	Immediate	Mild claw	S4 6mm	Full	0	80	2.3	Nil
23	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Nil	S4 5mm	Full	0	85	2.3	Nil
24	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Nil	S4 6mm	Full	0	80	2.3	Nil
Mean values										0.6	79	5.9	

Medical Research Council scale.

S0 is the absence of sensibility; S1 is the recovery of deep cutaneous pain; S2 is the return of superficial cutaneous pain and some degree of tactile sensibility; S3 is the return of superficial cutaneous pain and tactile sensibility without over-response; and S4 is the complete recovery.

DASH, Disabilities of the Arm, Shoulder and Hand; MCP, metacarpophalangeal; 2PD, 2-point discrimination; PIP, proximal interphalangeal; VAS, Visual Analog Scale.

16 weeks, median nerve recovery at 20 weeks and ulnar nerve at 26 weeks with a stiff elbow and stiff claw hands.

The average sensory recovery as per Medical Research Council (MRC) was S3 in 3 (12%) and S4 in 21 (88%). The average 2PD in our entire study was 6.9mm (range 5–10).

Compartment pressure measurement

Based on the clinical findings and surgeon's discretion, compartment pressure was not measured in 16 children. These children presented to the emergency room with acute compartment syndrome with motor and sensory paralysis (n=13), brachial artery injury with paralysis (n=2) and intravenous infiltrate in one child in the ICU. All of them were wheeled into the operating room at the earliest. had a compartment measurement recorder and were found to have >30mmHg. There was no statistical significance (p=1.0) for the association between clinical assessment and compartment pressure measurement test to functional outcomes (table 3).

Time to intervention

The average time interval between injury and admission in this study was 44hours (range 5–192), and the average time interval between admission and surgery was 54minutes (range 45–65). Eleven patients underwent surgical decompression >12hours after injury, and 8 patients (73%) had excellent motor and sensory nerve recovery. Among these patients, seven had a delay because of native tight oil bandage. There was a statistical significance (p<0.5) assessed by Fischer's exact test for the association between intervention <24hours and >24hours after injury of compartment syndrome to functional outcomes. Fifteen patients (63%) who were operated on within 24hours after injury had excellent functional outcomes. Of the 9 patients who were operated on >24hours after the injury, 6 (67%) had excellent motor and sensory recovery and 3 (33%) had good sensory recovery and partial motor recovery.

Fasciotomy and wound closure

Single-incision fasciotomies were performed in all patients as a definitive treatment of compartment syndrome. Two patients who had very late presentation (more than 7days after initial closed reduction and K wire for SC humerus fracture with motor and sensory deficits) had wider surgical incision extended to the arm. Overall, 14 patients had primary wound closure with skin suturing. Five patients required delayed primary closure at an average of 5days. Five patients also needed skin grafting at an average of 5days, considering the wound status. None had skin grating failure in our study. Of the 14, who had primary wound closure, two patients had superficial skin necrosis with multiple small areas in the follow-up that healed subsequently without any interventions. The average stay in the hospital was 7.3 days (range 3–19). Patients undergoing primary closure had a hospital stay of an average of 6 days when compared with

Table 3 Correlation of multiple variables with full/good functional recovery versus partial/poor functional recovery

Variables	Mean (SD)	Full functional recovery (n=21)	Poor functional recovery (n=3)	P value
Age (y)	8.5 (2.9)			0.11*
<8		11	3	0.23†
8–16		10	0	
Side				
Right		11	2	0.64‡
Left		10	1	
Gender				
Male		17	2	0.52†
Female		4	1	
Presentation				
Pain		15	0	<0.05‡
Pain, paralysis		2	1	
Pain, pulselessness, paralysis		1	0	
Paralysis		2	2	
Paralysis, pulselessness		1	0	
Mode of injury				
Fall from height		5	0	0.73*
Intravenous infiltrate		2	0	
RTA/fall		7	3	
RTA/crush		7	0	
Etiology (prior treatment)				
Tight oil bandage		6	1	0.86‡
No treatment/SC humerus fracture		15	2	
Time from injury to fasciotomy (h)				
≤24		15	0	<0.05†
>24		6	3	
Pressure measurement				
Clinical parameters		14	2	1.0‡
Pressure measurement test		7	1	
Associated injuries				
SC humerus		2	3	<0.05†
Others		19	0	

*t-test.

†Fischer's exact analysis.

‡ χ^2 statistics.

RTA, road traffic accident; SC, supracondylar; SD, standard deviation.

delayed closure with or without skin grafting of 11 days. One patient (4%) required debridement and drainage of the abscess and multiple surgeries for his left elbow operated on elsewhere with features of septic arthritis and stayed at the hospital for 19 days receiving intravenous antibiotics and dressings.

FUNCTIONAL OUTCOME

The mean follow-up was 67.3 months (range 59–80). Twenty-one patients (88%) had a full range of movement at their final follow-up with a mean VAS score of 0.6; quick

DASH score of 5.9 (range 2.3–25.0); and Mayo wrist score of 79. Full functional recovery, defined as the ability to return to preinjury levels of activity, was achieved in 21 of 24 patients (88%) in a mean time of 14 weeks (range 9–24).

ASSOCIATED INJURIES

There was a statistical significance to the outcome in the children with associated injuries involving SC humerus fractures in our study ($p<0.05$). This was because of its association with K wire-related nerve injuries and

infection sequela leading to partial motor nerve recovery with good sensation (S3).

DISCUSSION

There have been few publications about the diagnosis and treatment of acute compartment syndrome in children.^{8,9} The most common site involved is pedestrian injuries to the distal tibia followed by high-energy injuries to the upper limb.¹⁰ Various prognostic factors, such as age, gender, injury pattern, location and the clinical presentation, are discussed in the literature.^{11,12} In our study, age ($p=0.11$), gender ($p=0.52$), side ($p=0.64$), mode of injury ($p=0.73$), etiology ($p=0.86$) had no significant impact on the outcome. Supracondylar humerus, time delay >24 hours, clinical presentation had significant impact on the outcome ($p<0.05$) (tables 3 and 4).

There has been no mention of the nerve involved in the upper limb compartment syndrome and its recovery pattern. This became the prime focus of our study, in addition to other vital information. Intracompartmental pressure (ICP) measurement is recommended in young children, unconscious patients, patients with regional nerve blocks and when the clinical signs are equivocal. It may not be necessary if the diagnosis is clinically evident.¹³

The traditional hallmarks of vascular insufficiency include 5 Ps; however, acute compartment syndrome in children may not have all of these classic features, making the 5 Ps less reliable.⁴ The diagnosis of compartment syndrome, therefore, should not be excluded based on the false assurances gained from the absence of these clinical findings.¹² In our study, all of the patients had complete motor and sensory paralysis at the time of admission. Totally, 76% of our patients had pain as one of the initial complaints, in addition to a few of the other 5 Ps. Delay because of tight oil bandage by the traditional bone setter had paralysis (29 %) as the prime complaint, which is statistically significant in our study ($p<0.05$). Further, the presence of pallor, paraesthesia, paralysis and pulselessness indicates prolonged ischemia and more advanced disease.^{2,3}

Our studies (table 3) have found that age, gender, fractures or soft-tissue injuries (intravenous infiltrate) have no statistical significance ($p>0.05$) in terms of good or poor functional recovery. Prasarn *et al* found favorable outcomes in 6/14 patients operated on within 6 hours of injury.⁹ We found statistically significant ($p<0.05$) and excellent functional improvements in 15 patients (63%) operated on within 24 hours after injury. Three (13%) patients operated more than 24 hours after injury had good sensory recovery and partial motor recovery. SC humerus fractures associated with late presentation, oil bandage and iatrogenic K wires injuring nerves had statistically significant poor functional outcome.

What's more interesting in our study is the re-emergence of tight oil bandage in children with a paradigm shift in functional recovery. Sundararaj and Mani found tight bandage by the traditional bone setter to

the upper limb produces irreversible motor damage, causing various degrees of contractures, (mild, moderate and severe), wasting of forearm muscles with claw, and ape-thumb deformities.¹⁴ None had any surgical intervention. None of his patients had a motor recovery. He absorbingly noticed that sensory recovery in the forearm happened at 6 months and in the hand at an average of 12 months and had no reason except nerve regeneration (table 4).^{15,16}

In our study, tight oil bandage (29%) to the upper limb was associated with various fractures and caused motor and sensory paralysis. The average time between injury and admission was 82 days (range 1–144) in these 7/24 patients. Despite the delay, all seven patients underwent fasciotomy to have full functional recovery in (6/7) 86% of patients. Fifteen patients (63%) who were operated on <24 hours after injury and 67% of patients (6/9) who were operated on >24 hours after the injury had excellent functional outcome. The mean times for radial, median nerve and ulnar nerve motor recovery was 6.0, 7.5 and 8.5 months, respectively. The sensory recovery was in the proximodistal direction. It was complete recovery in the forearm at a mean of 10 months (range 7–12) after injury and in the hand at 13 months (range 10–14).

Our study proves that surgical decompression plays a vital role in the recirculation of blood supply to the ischemic nerves and muscles, thereby preventing muscle fibrosis, atrophy, contractures and deformities. We also proves that fibrotic muscle regains recovery over time (6–12 months) based on radial, median and ulnar motor recovery producing full and excellent functional recovery in 21/24 (88%) children. The sensory recovery (proximodistal) was also seen in all patients (100%) with an average 2PD of 6.9 mm and with an MRC grade of S4 in 87% and S3 in 13% (range 10–14 months after surgery) (tables 1 and 2). Totally, 12% of children had partial motor recovery despite multiple surgeries for soft-tissue infection, osteomyelitis and stiff joints in the subsequent days, compromising the nerve and muscle recovery but recovering S3 sensation. Both motor and sensory recoveries are from the newly regenerated nerve supply. Thus, our hypothesis was confirmed by the fact that motor fibers and sensory fibers after fasciotomy regenerated to produce 100% sensory recovery and 88% motor recovery in our patients.

The main limitations of our study were the small sample size and retrospective design. Since the nerve recovery does not follow Wallerian degeneration, axonal regeneration or end-organ reinnervation patterns, a histopathological examination can throw light on the recovery details. The muscles can be taken up for histopathological evaluation while doing fasciotomy to look for its vascularity, viability and regeneration. Again, the muscle may have a different level of ischemic injuries either completely or partly ischemic, so this becomes quite uncertain. Injury to the nerves can coexist with brachial artery injury or with compartment syndrome, and the clinical entities may overlap, making the diagnosis frequently difficult if

Table 4 Comparative study and literature review about acute compartment syndrome in the upper limb

Author	Upper limb cases (n)	Follow-up (mon), mean (range)	Mode of injury	Type of injury	Common presentation	Associated fracture	Compartment pressure	Compartment syndrome >12h after injury	Time to fasciotomy, mean (range)	Additional procedure	Wound closure	Time to motor/sensory recovery	Motor recovery	2PD	Range of movements	Complications
Bae <i>et al</i> ³	17	26.1 (3–79)	Crush/avulsion/clean/dog bite	Closed: 9, open injuries: 8	Pain (88%) paresthesia (61%) paralysis (36%)	Fractures (74%)	61%>30mmHg <2 with <30 mmHg	11	30.5 h* (range 3–144) 16 had >12 h	Skin grafting 3/17	12/17 delayed closure	NA	NA	NA	NA	Elbow stiffness, radial growth arrest
Erdős <i>et al</i> ¹⁰	5 (<12 y) 1 (15–18 y)	NA	Pedestrians struck	NA	NA	Majority of study focused towards lower limb compartment syndrome	30%–50% (range 30–60 mmHg)	1	2.5–99.0 h	Skin grafting 3	Temporary closure with epigastric synthetic skin substitute	NA	NA	NA	NA	4.2% permanent contractures /epiphysiolysis of distal radius
Grottkau <i>et al</i> ²	20	NA	Pedestrians struck	Open: 9 Closed: 11 RR 2.2 for open	NA	FA fractures (74%) SC (15%) carpal/metacarpal (11%) comatose (14%)	NA	40% went undiagnosed initially, one patient diagnosed after 4 d of injury	Six hands no fasciotomy	NA	NA	NA	NA	NA	NA	NA
Kanj <i>et al</i> ¹⁵	23	6 or follow-up to complete recovery	Fractures (57%), fall from height/crush injury/hand intravenous infiltrates 4/23	Five no fracture cases, NA data about open/close injury	Pain (83%), swelling (65%), paralysis (22%–26%), pulseless (9%)	NA	17/23 >30 mmHg	3/23	32.8 h (3.7–158.0)	NA	NA	NA	NA	NA	Excellent/fair/poor	4% poor outcome (one had sensory deficit; one both motor and sensory deficits), 4 had stiffness with no FA rotations
Prasam <i>et al</i> ³	14	22 (NA)	Long bone fracture	58% iatrogenic, intravenous infiltration, gunshot, road traffic injury	Obtunded sensorium (83%) difficult in examination	Zone 2/3 of Foucher: 14/6	NA	2	9.4 h (2–24)	Contracture release/skin grafting (6.7 mon)	NA	NA	NA	NA	NA	58% normal outcome; three amputation
McQueen <i>et al</i> ¹⁶	23	NA	Distal radius (15), FA (13 mixed with adults)	Pedestrian injury, crush 59 patients (36%) and of the distal radius in 16 (9.8%)	Injury to the soft tissues without a fracture occurred in 38 patients (23.2%)	SC humerus (40%), FA fractures (40%)	15	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mubarak and Carroll ⁶	21	NA	Motorcycle spokes wheel	RTA/injury (70%), closed fracture 2/24 have intravenous infiltrate	Pain (76%) mixed with other 5 Ps. Paralysis (100%)	SC humerus (20%) FA, distal radius, proximal forearm (80%)	20	12 patients (both upper and lower limbs)	44 h (5–192)	SC: 2/24 with brachial artery repair; redo K wire: 2 (mean 5 d)	SC: 2 FA: 2 (brachial artery repair)	NA	NA	NA	NA	SC: 7/9 severe deformity, FA: 7/10 severe
Our study	24	67.3 (59–80)	Tight oil bandage (29%)	RTA/injury (70%), closed fracture 2/24 have intravenous infiltrate	Pain (76%) mixed with other 5 Ps. Paralysis (100%)	SC humerus (20%) FA, distal radius, proximal forearm (80%)	9	15 patients	44 h (5–192)	SC: 2/24 with brachial artery repair; redo K wire: 2 (mean 5 d)	3 delayed closure (mean 5 d)	Radial motor 12; sensory 24wk, median motor 10.3; sensory 13 wk (mean 5 d)	Radial 6; median (87%) 7.5 ulnar 8.5 mon (5–10)	S4: 21 (87%) S3: 13 6.9 mm	Full	Elbow stiffness, stiff claw hand, osteomyelitis humerus, non-union SC

Compartmental pressure: pressure was considered to be increased if it was either greater than 30 mmHg or if the DP was less than 30 mmHg. DP: difference between the diastolic blood pressure and the intracompartmental pressure; FA: forearm; K: wire, Kirschner wire; NA: not available; 2PD, 2-point discrimination; 5 Ps: pain, paresthesia, pallor, pulselessness and paralysis; RR, relative risk of 2.2 for developing a compartment syndrome in the forearm for an open fracture versus a closed fracture; RTA: road traffic accident; SC: supracondylar.

not impossible. The onset of motor and sensory paralysis as in our cases sequel to tight oil bandage; the recovery pattern of median and ulnar nerve at a mean of 8.0 and 8.5 months rules out neuropraxia/axonotmesis type of injury. Again, for a rational explanation, the different pattern of neuromuscular recovery needs a large prospective study containing in vitro models, in vivo nerve injury models, molecular expressions and neuromuscular junction studies. It is logical to understand that ischemia induces markedly elevated ICP, which gets decompressed by fasciotomy and allows the nerve and muscle to regenerate back in their due course of time.

CONCLUSIONS

Surgical decompression in acute compartment syndrome involving the upper limb in children allows the recirculation of blood and muscle and nerve fibers to regenerate definitely to produce excellent proximodistal sensory recovery and full functional motor recovery irrespective of various contemporary factors. Early surgical decompression produces excellent functional results.

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