

## Factors Affecting Forearm Compartment Pressures in Children with Supracondylar Fractures of the Humerus

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**Summary:** This study evaluated forearm compartment pressures in 29 children with supracondylar humerus fractures. Pressures were measured before and after reduction in the dorsal, superficial volar, and deep volar compartments at the proximal 1/6th and proximal 1/3rd forearm. Pressures in the deep volar compartment were significantly elevated compared with pressures in other compartments. There were also significantly higher pressures closer to the elbow within each compartment. Fracture reduction did not have a consistent immediate effect on pressures. The effect of elbow flexion on post-reduction

pressures was also evaluated; flexion beyond 90° produced significant pressure elevation. We conclude that forearm pressures after supracondylar fracture are greatest in the deep volar compartment and closer to the fracture site. Pressures greater than 30 mm Hg may exist without clinical evidence of compartment syndrome. To avoid unnecessary elevation of pressures, elbows should not be immobilized in >90° of flexion after these injuries. **Key Words:** Compartment syndrome—Forearm compartment pressure—Pressure measurement—Supracondylar humerus fractures.

Supracondylar fracture of the humerus is a common injury in children, comprising 3%–18% of all pediatric fractures and 60% of pediatric fractures about the elbow (3,11,22). It is an injury associated with a number of well-known complications (9), one of the most feared being compartment syndrome of the forearm. First described by Volkmann in the 19th century (32), forearm compartment syndrome is a constellation of signs and symptoms related to increased pressures within the closed fascial spaces of the forearm, leading to vascular compromise and tissue ischemia, which may ultimately result in myonecrosis. The incidence of compartment syndrome following pediatric supracondylar humerus fracture may be estimated from the literature to be 1 to 3 per 1000 fractures (2,31,35).

The pathophysiology by which increased compartment pressures lead to muscle ischemia is debated, but is likely through a combination of arterial spasm, small vessel collapse, and increased venous pressure (23). The classic clinical signs of compartment syndrome are well known, and include the “6 Ps” – pain (especially with passive motion), and later, paralysis, pulselessness, par-

esthesia, pallor, and poikilothermia (19,21,34). Unfortunately, these signs are not always reliable, and compartment syndrome may remain undetected until permanent damage has occurred (1,19,26,34).

In attempts to detect elevated compartment pressures and allow intervention before irreversible ischemia and necrosis occur, a number of authors have studied techniques and applications of direct intracompartmental pressure monitoring. Although most studies agree that pressure measurements are a useful indicator of risk of compartment syndrome in the forearm and at other sites, authors disagree on criteria such as measurement technique and significant threshold values (6,14,19,20,25,26,33). Currently, pressure monitoring is considered to be indicated when compartment syndrome is suspected clinically. A pressure greater than 30 mm Hg or within 20–30 mm Hg of diastolic blood pressure is then reported to be indication for fasciotomy (6,19,21,24,25,34). The usefulness of compartment pressure monitoring is confounded, however, by studies that have demonstrated large variations in pressure over small distances in the limb (28), and depending on limb position (7,27) as well as distance from the fracture site (8).

The purpose of our study was to describe variations in forearm compartment pressure after Type II and Type III pediatric supracondylar humerus fracture, and to identify factors that affect pressure measurements. Specifically, we were interested in the effect of measurement location, including which compartment was measured, as well as distance from the elbow. We also investigated the effects that delays in presentation after injury might have on

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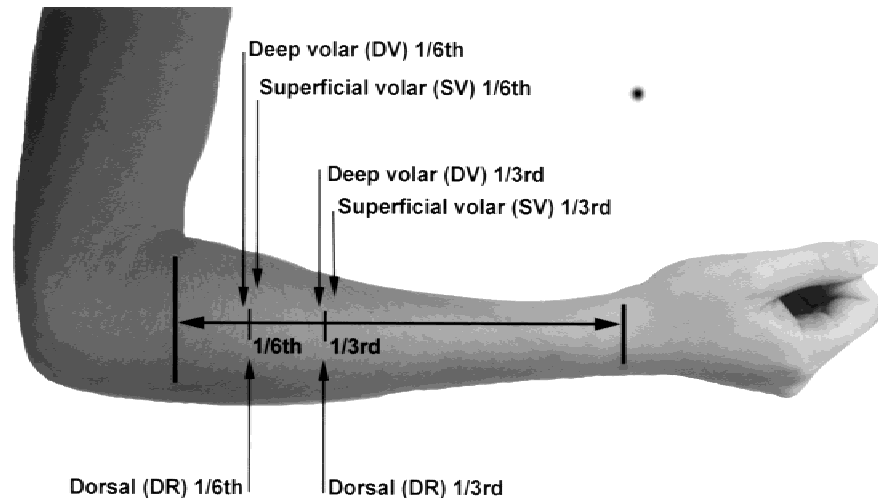


FIG. 1. Location of compartment pressure measurements.

pressures, and the immediate effects of fracture reduction. We compared pressures after Type II and Type III fractures, and after closed versus open reduction. Finally, we examined the effect of elbow position on post-reduction pressure. From our results, we provide guidelines regarding the role and interpretation of pressure measurements in the evaluation of forearm compartment syndrome after supracondylar humerus fracture.

### MATERIALS AND METHODS

Twenty-nine patients with a total of 29 Type II or Type III supracondylar humerus fractures were studied. All patients were seen at the Children's Hospital of Buffalo, NY between June 1997 and January 1999 and treated by authors D.A. or R.S. Included were 11 males and 18 females, with an average age of 7.2 years (standard deviation [SD], 2.8 years; range, 1.8–15.5 years). There were five Type II (17%) and 24 Type III fractures

(83%); all were closed injuries. Fracture type was assessed using Gartland classification (5) and only isolated Type II and Type III fractures were included. All but one fracture appeared radiographically to have occurred in an extension-type mechanism. The elapsed length of time between injury and operation averaged 8.1 hours, with a range of 2.5–25 hours. The appearance of the limb, including the presence of ecchymosis, edema, vascular injury, or neurologic impairment was noted.

Forearm compartment pressures were recorded under sterile conditions using a standard anesthesia arterial line monitor and pressure transducer attached to a 16-gauge intravenous needle. (An 18-gauge needle was used for smaller patients.) Immediately after induction of general anesthesia, and before any fracture manipulation, compartment pressures were measured in the superficial volar (SV), deep volar (DV), and dorsal (DR) forearm compartments. Within each compartment, the following locations were used: (1) 1/3 the distance from antecubital

TABLE 1. Summary of compartment pressures

Compartment	Distance from elbow crease	Before or after reduction	Fractures		
			Type II (n = 5)	Type III (n = 24)	All (n = 29)
Superficial volar	1/3	Before	7.3 ± 2.5	12.9 ± 7.5	12.1 ± 7.3
Superficial volar	1/3	After	10.5 ± 1.0	14.8 ± 10.1	14.2 ± 9.4
Superficial volar	1/6	Before	15.0 ± 15.5	24.1 ± 15.6	22.8 ± 15.5
Superficial volar	1/6	After	12.8 ± 6.6	22.0 ± 13.0	20.7 ± 12.6
Deep volar	1/3	Before	8.3 ± 2.9	19.7 ± 7.7	18.1 ± 8.2
Deep volar	1/3	After	9.3 ± 3.0	19.7 ± 10.5	18.2 ± 10.5
Deep volar	1/6	Before	20.7 ± 16.8	34.9 ± 19.4	32.9 ± 19.3
Deep volar	1/6	After	17.6 ± 11.8	27.8 ± 13.5	26.0 ± 13.6
Dorsal	1/3	Before	5.3 ± 6.1	15.0 ± 10.2	13.6 ± 10.2
Dorsal	1/3	After	7.4 ± 7.0	15.1 ± 9.0	13.8 ± 9.1
Dorsal	1/6	Before	6.0 ± 5.3	25.7 ± 12.3	22.9 ± 13.5
Dorsal	1/6	After	9.6 ± 6.2	21.1 ± 11.4	19.0 ± 11.5
Deep volar	1/3	After*	9.3 ± 3.0	20.2 ± 9.9	18.4 ± 9.9
Deep volar	1/3	After†	14.0 ± 4.7	21.9 ± 8.4	20.6 ± 8.4
Deep volar	1/3	After‡	15.5 ± 6.8	24.4 ± 11.2	23.0 ± 11.0
Deep volar	1/3	After§	43.0 ± 2.2	59.8 ± 30.6	57.1 ± 28.6

Elbow flexion: \*0°, †40°, ‡90°, §120°.

Data (mm Hg) shown as mean ± standard deviation.

crease to wrist crease and (2) 1/6 the distance from antecubital crease to wrist crease. This resulted in a total of 4 volar measurements (SV 1/3, SV 1/6, DV 1/3, and DV 1/6) and 2 dorsal measurements (DR 1/3 and DR 1/6) (Fig. 1). All pressures were measured in the approximate midline of the extremity following previously described techniques to avoid neurovascular structures (13).

The majority of fractures (76%) were then treated with closed reduction and percutaneous fixation; seven (24%) underwent open reduction after inadequate results of the closed procedure. All fractures were fixed using crossed medial and lateral Kirschner wires. After surgery, with the patient still under anesthesia, all pressure measurements were repeated. In addition to the previous six measurements, three additional post-reduction pressures were measured. All were taken in the DV 1/3 location, with the elbow in 40°, 90°, and 120° of flexion. (All other pre-reduction and post-reduction pressures were recorded with the elbow in full extension.)

Seven variables with potential effects on compartment pressure were analyzed as follows: (1) elapsed time from injury; (2) fracture type (II versus III); (3) compartment (SV versus DV versus DR); (4) distance from elbow crease (1/3 vs. 1/6); (5) reduction (pre-reduction vs. post-reduction); (6) reduction method (closed versus open); and (7) post-reduction flexion (0° vs. 40° vs. 90° vs. 120°). A multifactorial analysis of variance (ANOVA) was performed to assess any statistical interactions oc-

curing between these variables. No significant interactions were found except for the effects of reduction (pre-versus post-reduction) and distance from elbow crease (1/3 vs. 1/6) ( $P < 0.05$ ). Accordingly, all other variables were assessed individually.

The effect of elapsed time from injury to operation was analyzed using correlation matrices and Fisher  $r$  to  $z$  conversion. Two-sided paired  $t$  tests were used to assess the effects of distance from elbow crease, compartment, and reduction. Due to the interaction of reduction and distance from elbow crease, we analyzed reduction at each distance separately. Fracture type and reduction method were analyzed with single factor ANOVA and Fisher projected least significant difference (PLSD) post hoc testing. The effect of elbow flexion on post-reduction pressure was calculated using a repeated measures ANOVA with Fisher PLSD. For all statistical measures, a significance level of  $P < 0.05$  was used.

## RESULTS

Mean overall pressures at each location are provided in Table 1. The greatest pre-reduction pressures were recorded in the DV 1/6 location (mean =  $32.9 \pm 19.3$  mm Hg). The greatest post-reduction pressures were also found in this location ( $26.0 \pm 13.6$  mm Hg). The lowest pre-reduction readings were in the SV 1/3 location ( $12.1 \pm 7.3$  mm Hg), whereas the lowest post-reduction

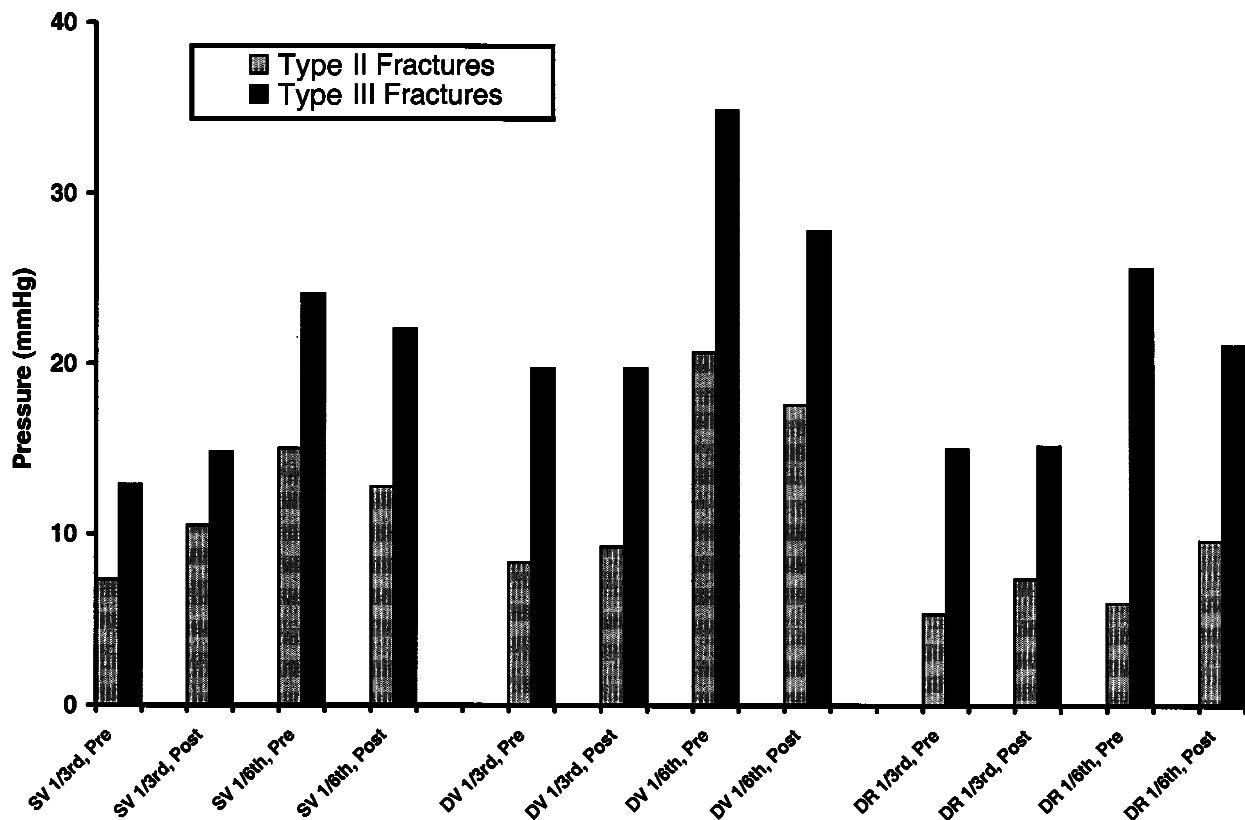


FIG. 2. Mean pressures for Type II and Type III fractures. DR, dorsal; DV, deep volar; Pre, pre-reduction; Post, post-reduction; SV, superficial volar.

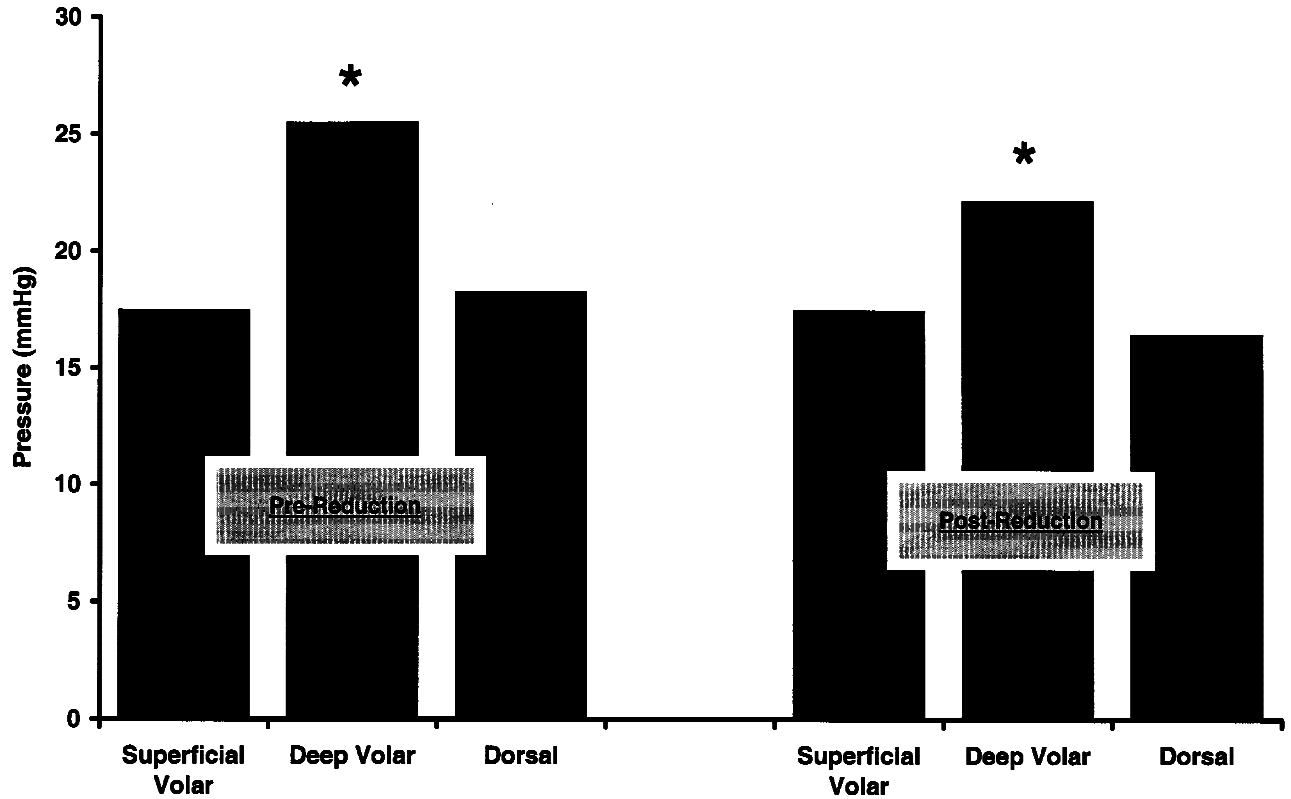


FIG. 3. Effect of compartment on pre- and post-reduction pressures. \* $P < 0.05$ : deep volar compartment differed significantly from both superficial volar and dorsal. Superficial volar and dorsal did not differ significantly from each other.

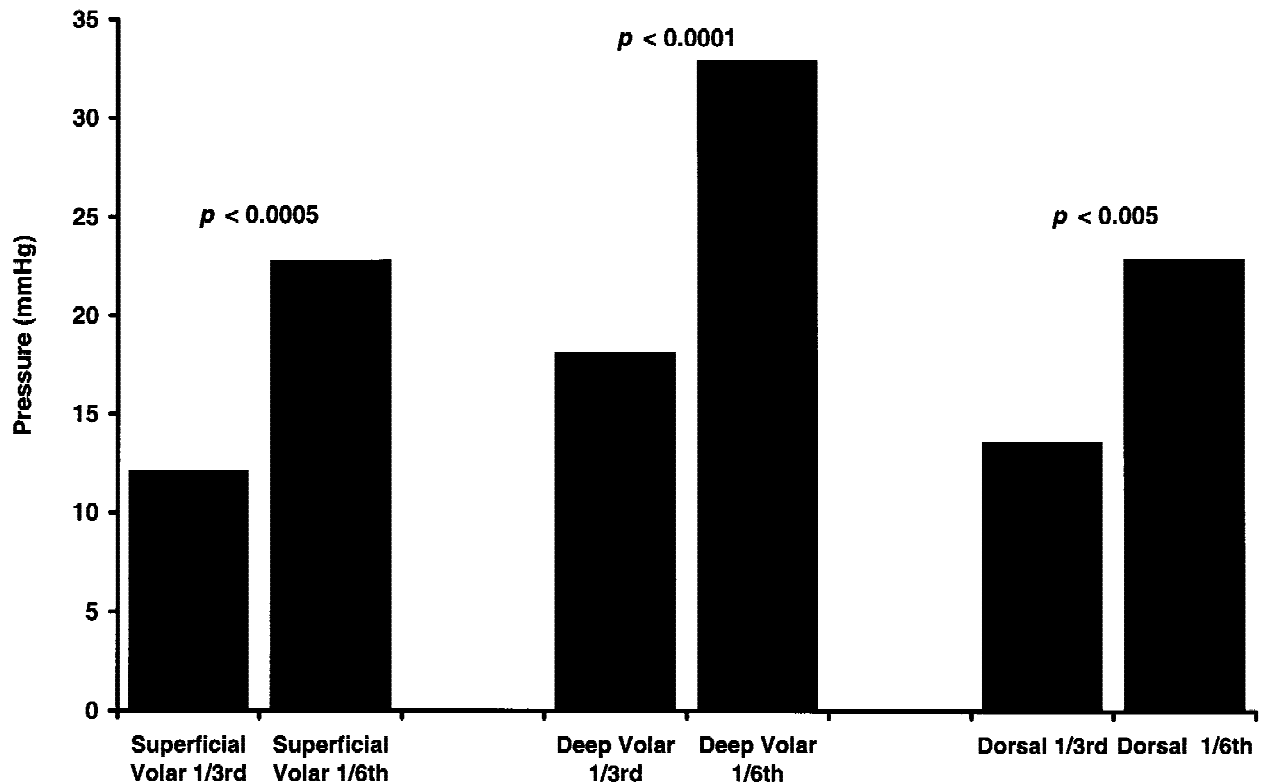


FIG. 4. Effect of distance from elbow crease on pre-reduction pressures.

pressures were in the SV 1/3 location ( $14.2 \pm 9.4$  mm Hg) and in the DR 1/3 ( $13.8 \pm 9.1$  mm Hg) location.

#### Effect of elapsed time from injury

Correlations of elapsed time with the mean pressure in each location were all negative, with  $r$  values ranging from  $-0.093$  to  $-0.56$ ; however, none approached statistical significance ( $P > 0.05$  for all). There was also no significant correlation between elapsed time and maximum pre-reduction pressure ( $r = -0.222$ ;  $P > 0.05$ ).

#### Effect of fracture type

Figure 2 compares pressures after Type II fractures and after Type III fractures at each location. Pressures after Type II fractures followed similar trends to those after Type III fractures in all analyses, although at each location, Type II fractures exhibited pressures 5–19 mm Hg lower than the corresponding Type III fracture values. Many of these differences approached but did not reach statistical significance. However, because there were no interactions between fracture type and other variables, we were able to group and compare all pressures occurring after Type II fractures with all after Type III fractures. This resulted in a highly significant difference, with the average pressure after Type II fracture 10.1 mm Hg lower than that after Type III fracture ( $P < 0.0001$ ).

#### Effect of compartment

Significantly higher pressures were recorded in the DV compartment when compared with the SV ( $P < 0.05$ )

or DR ( $P < 0.05$ ) compartments. The SV and DR compartments did not differ when compared directly ( $P > 0.05$ ). These relationships were consistent before and after reduction (Fig. 3). Prior to reduction, the average DV pressure was 8.0 mm Hg greater than the average SV pressure and 7.2 mm Hg greater than the average DR pressure. After reduction, these differences were 4.7 mm Hg and 5.7 mm Hg, respectively.

#### Effect of distance from elbow crease

Overall, the effect of distance from the elbow crease (1/3 versus 1/6) was highly significant ( $P < 0.0001$ ). Prior to reduction, pressures measured at the 1/6 distance were 11.6 mm Hg greater, on average, than pressures at the 1/3 distance. Post-reduction, pressures measured at the 1/6 distance were 6.8 mm Hg greater. Data are shown for each individual compartment in Figures 4 (pre-reduction) and 5 (post-reduction). Within every compartment, before and after reduction, pressures were higher when measured closer to the elbow crease.

#### Effect of reduction

Because of the statistical interaction between the effect of reduction and distance from the elbow crease, the effect of reduction was analyzed at each distance separately. Reduction did not significantly alter pressures at the 1/3 distance ( $P > 0.05$ ), but did lower pressure at the 1/6 distance by 4.3 mm Hg on average ( $P = 0.001$ ) (Fig. 6).

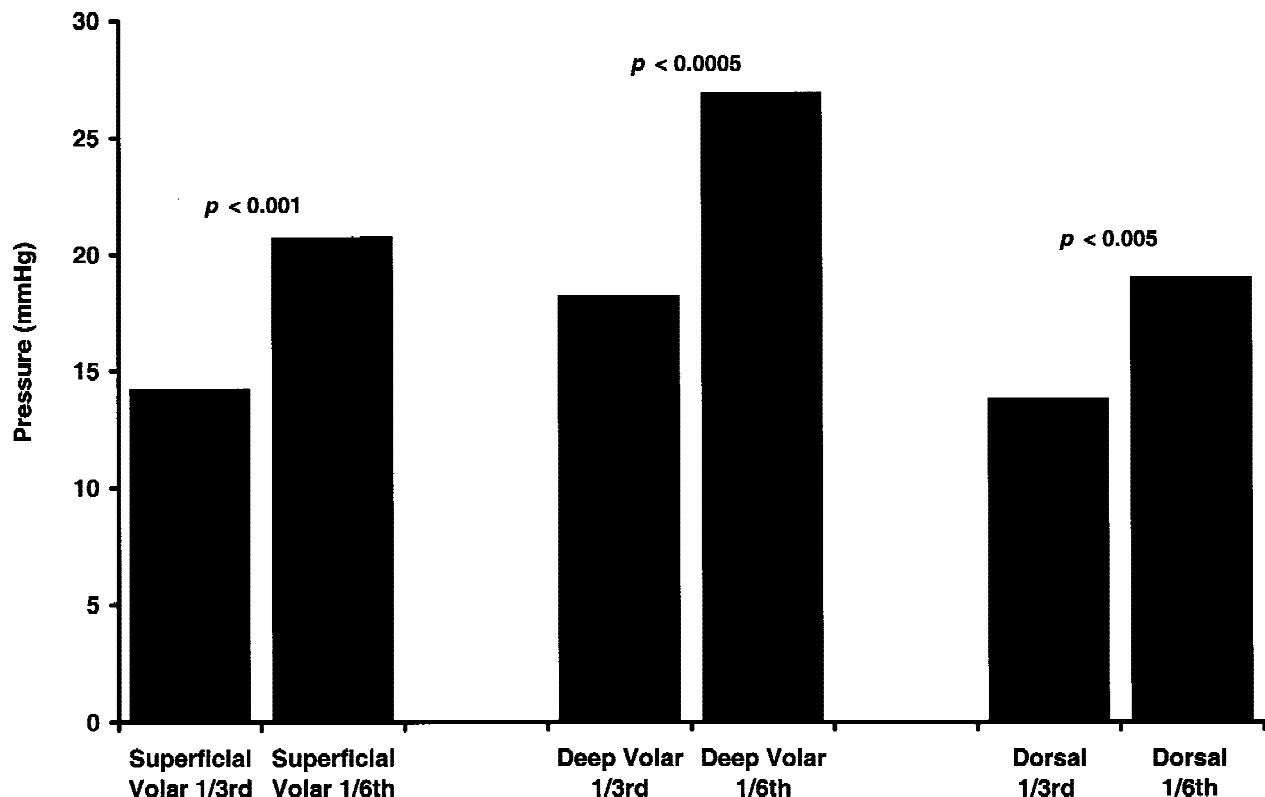


FIG. 5. Effect of distance from elbow crease on post-reduction pressures.

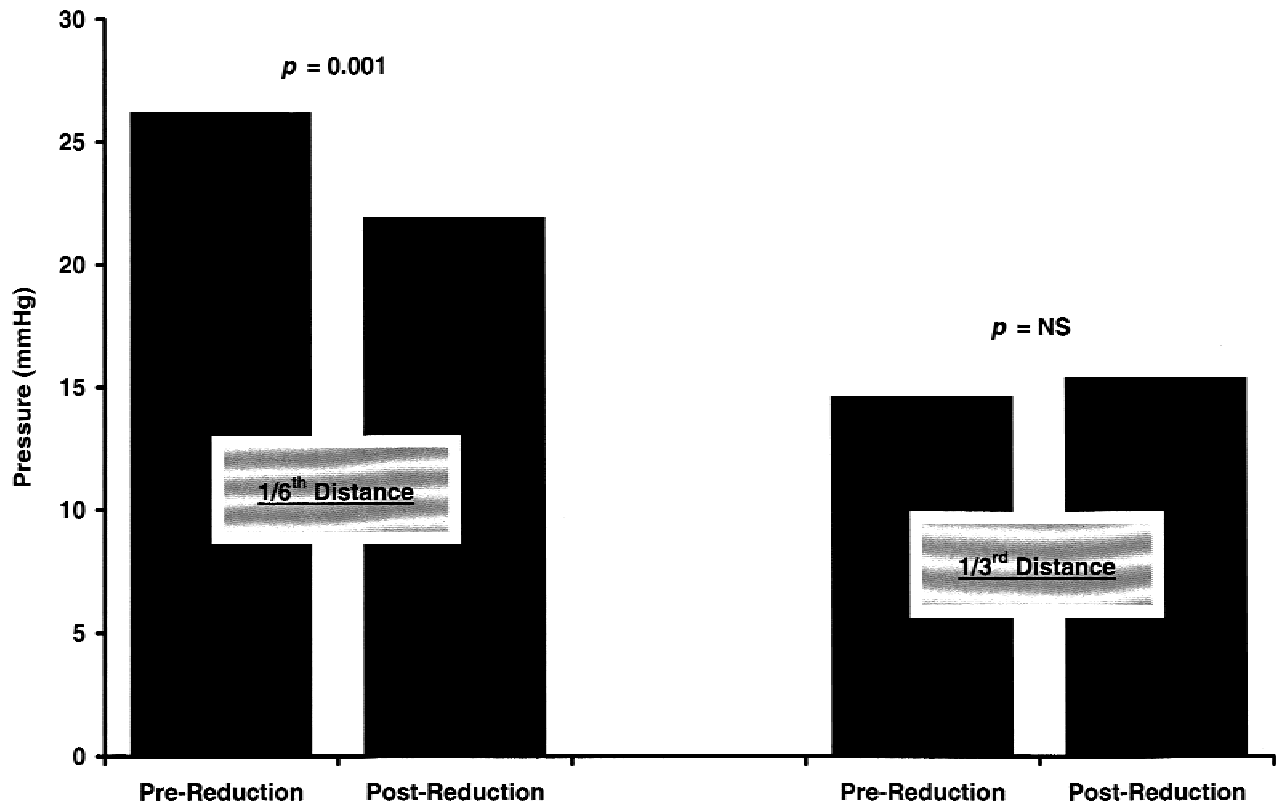


FIG. 6. Effect of reduction on pressure. NS, not significant.

#### Effect of reduction method

Open reduction resulted in greater overall post-reduction pressures than did closed reduction, with a mean pressure difference of 6.8 mm Hg ( $P < 0.0001$ ). When analyzed for each compartment individually (Fig. 7), the only significant difference was found in the DV compartment, with pressures after open reduction 9.2 mm Hg greater than those after closed reduction ( $P < 0.02$ ). Values in the SV compartment approached but did not reach significance (difference = 6.6 mm Hg;  $P < 0.08$ ).

#### Effect of flexion on post-reduction pressures

As measured at the DV 1/3 location, post-reduction pressures were significantly greater with the elbow in 120° of flexion when compared with 0°, 40°, and 90° ( $P < 0.0001$  for all comparisons), with the average pressure at 120° nearly 35 mm Hg greater than that at 90°. There were no significant differences between 0°, 40°, and 90° (Fig. 8).

#### Clinical observations

Seventeen fractures (59%) occurred in the left extremity and 12 (41%) in the right. Most (27 of 29) were caused by a fall, most commonly from gym or playground equipment (11 of 29). Two patients were injured by direct blows. No patient had clinical evidence of compartment syndrome at any time during his or her clinical course. Eleven patients exhibited evidence of neurovascular injury. A pulseless extremity was noted in one pa-

tient, another had a weak but dopplerable radial pulse. Seven patients exhibited signs of anterior interosseous nerve (AIN) dysfunction. In 4 patients, AIN weakness was associated with other neurovascular symptoms, including decreased radial nerve sensation (1 patient) and decreased median nerve sensation (3 patients). Isolated radial or median nerve symptoms also occurred in two patients. We could not correlate neurovascular status with compartment pressure, and all patients recovered full function.

#### DISCUSSION

In this study, we elaborate on the current literature describing compartment pressure measurement in pediatric patients with supracondylar humerus fractures. A number of studies have investigated the role of direct pressure recording in these patients; however, most included only patients with suspected compartment syndrome. We describe pressure characteristics in a series of patients with this fracture, especially as affected by location of measurement, delay from injury to reduction, and post-reduction arm position. This is similar to studies by Heckman et al. (8) and Triffitt et al. (30) characterizing compartment pressures in the leg after tibial fracture.

Our sample population is similar to that in previous studies of supracondylar humerus fractures. Age, gender distribution, side of fracture, mechanism of injury, and

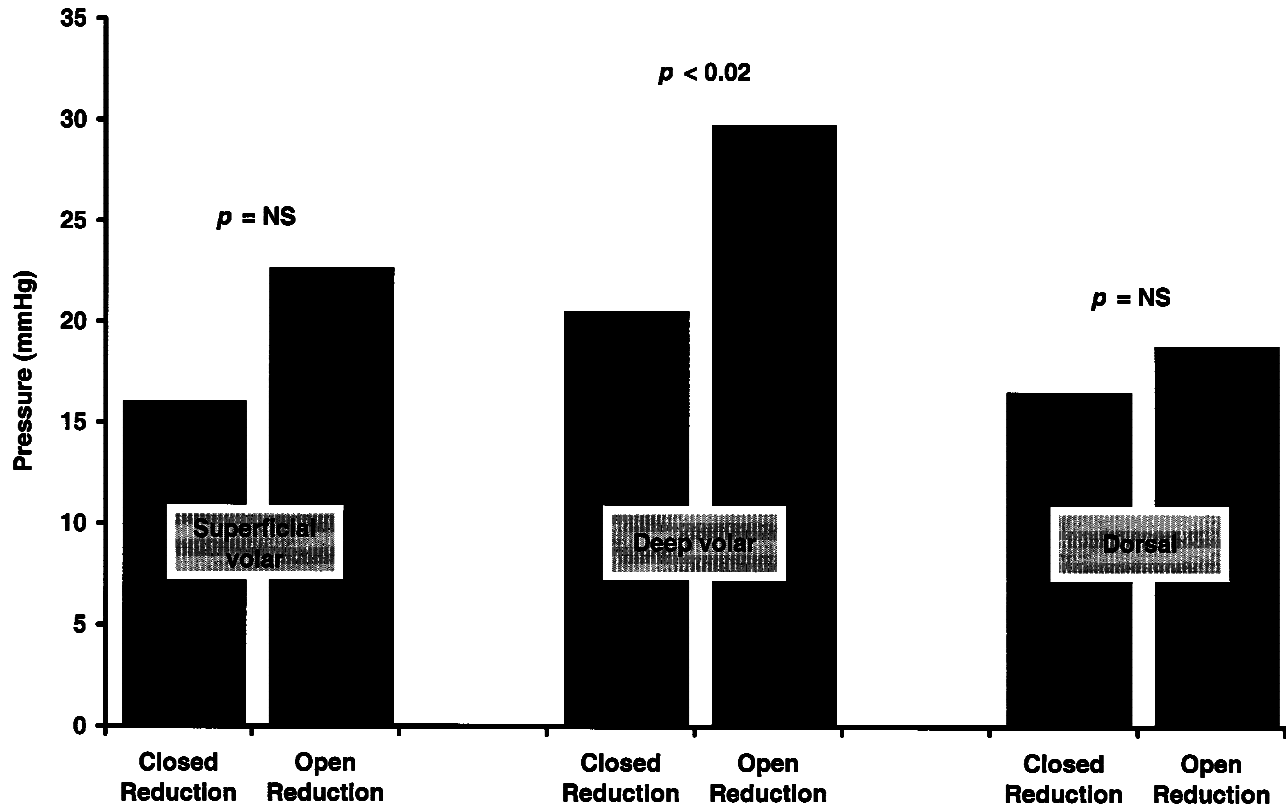


FIG. 7. Effect of closed versus open reduction on post-reduction pressures. NS, not significant.

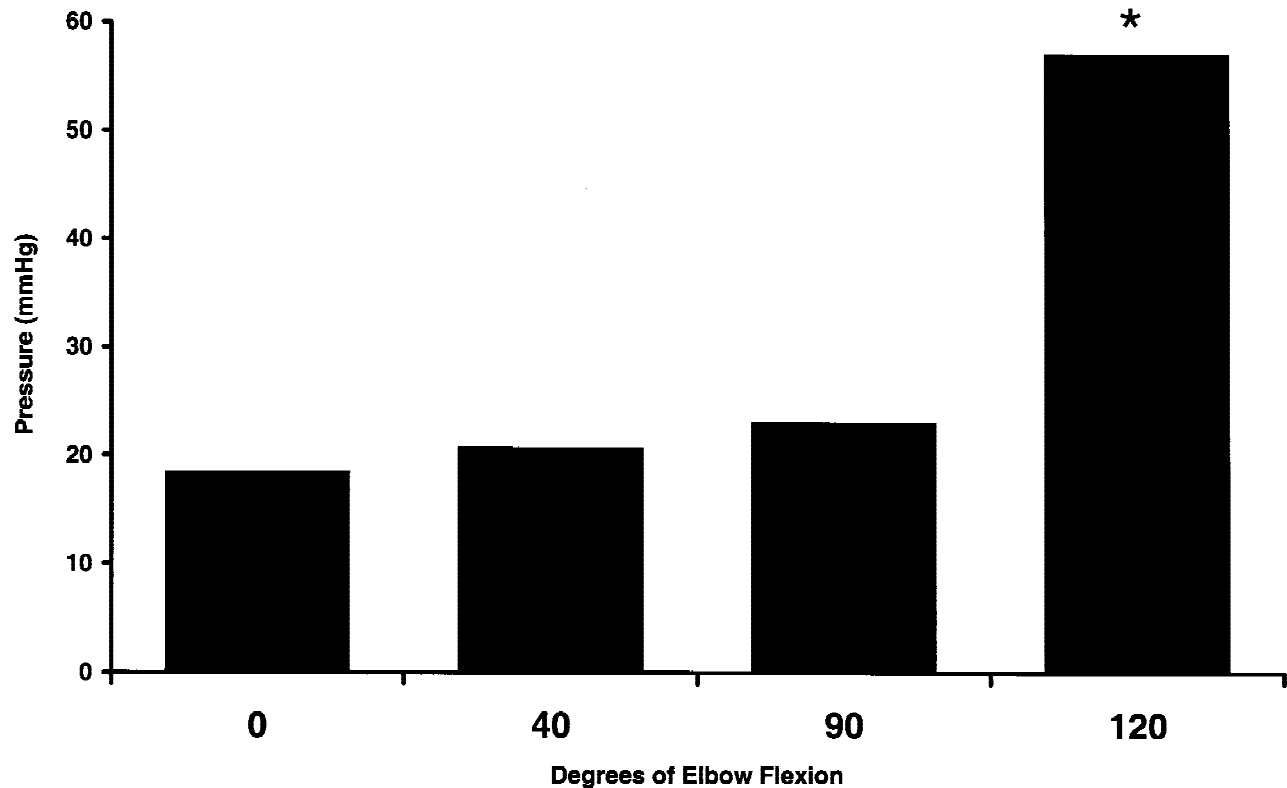
radiographic appearance (flexion versus extension) are all consistent with prior characterizations (3,4,11,18). We made our measurements using readily available, convenient, and easy to use anesthesia arterial pressure monitoring equipment. Although studies have suggested that this "simple-needle" technique results in greater pressure values than when using a side-ported needle or slit catheter (17,26), more recent studies have found comparable accuracy among all three methods (29,36).

Overall, we found a number of compartment pressures with average values near or greater than 20 mm Hg (Table 1). This is in contrast to a recent study of forearm pressures after pediatric supracondylar fracture, which found average pre- and post-reduction pressures of less than 10 mm Hg with the elbow in full extension (27). Others, though, have demonstrated pressures greater than 30 mm Hg commonly occurring after other traumatic injuries with no adverse sequelae (15,30). The large standard deviations associated with our values do reflect the large pressure variations amongst individuals with this injury. However, despite frequently elevated pressures, no patient exhibited signs or symptoms of compartment syndrome at any time. Such findings discourage the use of absolute pressure thresholds, no matter how great, as indicators of impending compartment syndrome, and support the concept that in the absence of clinical indications, elevated compartment pressures alone are not sufficient indication for fasciotomy (24,26,30).

Before and after reduction, the greatest pressures were

found in the DV compartment (Fig. 3), and within each compartment, pressures were greatest closer to the fracture (Figs. 4, 5). Intuitively, one would expect the greatest pressures to occur closest to fracture-associated inflammation and edema. Increased muscle mass may also contribute to the greater pressures in the proximal forearm (28). Our results are consistent with prior studies directly correlating leg compartment pressures with proximity to tibia fracture (8) and finding significant variations in pressure over small distances within a single compartment in the normal limb (28), all indicating that pressure does not necessarily equilibrate throughout a compartment. As it is commonly recommended that the highest recorded pressure serve in the decision regarding intervention (8,34), pressures close to the elbow in the DV compartment should be measured in patients in whom compartment syndrome is a clinical concern. Our study also reinforces that if fasciotomy is deemed necessary, adequate decompression of deep volar musculature is mandatory.

We were unable to document any relationship between pressure and the length of time elapsing between injury and reduction. Accordingly, in terms of preventing pressure increases in the typical patient, fracture reduction may not be an emergent requirement. However, the act of reduction itself did have a small beneficial effect on pressures in the more proximal forearm (Fig. 6), regardless of the length of time prior to reduction. Reduction appeared to have no significant effect on pressures in the



**FIG. 8.** Effect of elbow flexion on post-reduction pressure. \*Pressures at 120° differed from all other positions with  $P < 0.0001$ ; there were no significant differences among 0°, 40°, and 90°. All pressures measured in deep volar 1/3<sup>rd</sup> position.

more distal locations. While both closed and open reduction decreased proximal forearm pressures, this effect was greater after closed reduction. That is, when compared with closed reduction, open reduction was associated with greater post-reduction pressures, especially in the DV compartment (Fig. 7). Rather than act as a “pressure release,” open procedures may cause increased inflammation and edema secondary to additional tissue trauma and decreased compartment volume when incisions are closed. Furthermore, open procedures occurred after one or more failed closed reductions, which also increase tissue disruption. It is likely that overall greater tissue trauma underlies the greater pressures found in Type III versus Type II fractures, as well (Fig. 2).

In our series, the single factor responsible for the greatest elevations in post-reduction pressure was arm position. We found no significant increases at the DV 1/3 location with the elbow at 0°, 40°, or 90° of flexion. It was not until the arm was flexed to 120° that marked pressure increases were seen (Fig. 8). This indicates that the “threshold position” for increased forearm pressures occurs between 90° and 120° of elbow flexion. A recent study of supracondylar humerus fractures described ablation of the radial pulse at 120° of elbow flexion (12); another described increases in pressure occurring at only 90°, and recommended avoidance of any significant flexion for prolonged periods of immobilization (27). Based on our findings, arms may be safely immobilized in up to, but not more than, 90° of flexion. Because hyperflex-

ion up to 120° is historically recommended (and often necessary) to maintain reduction in un-pinned Type II fractures (16), pinning these fractures may be preferred to obviate the need to immobilize the extremity in this position (10,22,35).

This study is limited by a number of factors. It would be useful to measure baseline compartment pressures in the uninjured arms of these patients. Seiler et al. (28) describe significant pressure differences that exist over short distances in the normal forearm, with slightly greater pressures occurring more proximally. Comparison of pressures in the injured and uninjured limbs might allow more accurate analysis of true pressure variation caused by fracture. It would also be worthwhile to compare pressures in dominant and non-dominant injured limbs. If muscle mass plays a significant role in compartment pressure, it is possible that dominant extremities would exhibit greater pressures. Compartment pressures may also be differentially affected by extension-type and flexion-type injuries. The relative rarity of the latter made it impossible to compare the two in our study. Finally, an analysis of blood pressure, including mean arterial pressure, at the time of compartment pressure measurement would be useful. Increasing evidence points to the importance of the perfusion gradient between arterial pressure and compartment pressure in the development of compartment syndrome (7,33,34). Unfortunately, for most of our patients, a retrospective review of patient records did not reveal exact arterial pressures at the time of compartment pressure measurement.



In summary, this study presents a number of clinically useful guidelines. For patients with supracondylar humerus fractures in whom elevated compartment pressures are suspected, forearm pressures closest to the fracture site should be most closely monitored, as this is where peak pressures occur. In addition, DV pressures must be monitored, as pressures in this compartment are nearly always greater than those in the SV or DR compartments. Elapsed time after injury does not appear to affect pressures, in that a longer delay between injury and presentation was not associated with increased pressures. Finally, post-surgical pressures do not rise significantly until the forearm is flexed more than 90°, indicating that arms may be safely immobilized in up to 90° of flexion after fracture fixation. Greater suspicion for increased compartment pressure and possible compartment syndrome should be maintained after Type III fractures and after open reduction. Even in these patients, however, elevated pressures may occur without any sign or risk of compartment syndrome. Accordingly, decisions regarding fasciotomy should not be based solely on pressure values, but on the combination of pressure measurements and clinical evaluation.

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## REFERENCES

- Bae DS, Kadiyala RK, Waters PM. Acute compartment syndrome in children: contemporary diagnosis, treatment, and outcome. *J Pediatr Orthop* 2001;21:680–88.
- Blakemore LC, Cooperman DR, Thompson GH, et al. Compartment syndrome in ipsilateral humerus and forearm fractures in children. *Clin Orthop* 2000;376:32–8.
- Cheng JCY, Ng BKW, Ying SY, et al. A 10-year study of the changes in the pattern and treatment of 6,493 fractures. *J Pediatr Orthop* 1999;19:344–50.
- Copley LA, Dormans JP, Davidson RS. Vascular injuries and their sequelae in pediatric supracondylar humerus fractures: toward a goal of prevention. *J Pediatr Orthop* 1996;16:99–103.
- Gartland JJ. Management of supracondylar fractures of the humerus in children. *Surg Gynecol Obstet* 1959;109:145–54.
- Gelberman RH, Garfin SR, Hergenroeder PT, et al. Compartment syndromes of the forearm: diagnosis and treatment. *Clin Orthop* 1981;161:252–61.
- Hargens AR, Mubarak SJ. Current concepts in the pathophysiology, evaluation, and diagnosis of compartment syndrome. *Hand Clin* 1998;14:371–83.
- Heckman MM, Whitesides TE Jr., Grewe SR, et al. Compartment pressures in association with closed tibial fractures: the relationship between tissue pressure, compartment, and the distance from the site of the fracture. *J Bone Joint Surg [Am]* 1994;76:1285–92.
- Jacobs RL. Supracondylar fracture of the humerus in children. *Illinois Med J* 1967;132:696–701.
- Kadiyala RK, Waters PM. Upper extremity pediatric compartment syndromes. *Hand Clin* 1998;14:467–75.
- Lins RE, Simovitch RW, Waters PM. Pediatric elbow trauma. *Orthop Clin North Am* 1999;30:119–32.
- Mapes RC, Hennrikus WL. The effect of elbow position on the radial pulse measured by Doppler ultrasonography after surgical treatment of supracondylar elbow fractures in children. *J Pediatr Orthop* 1998;18:441–4.
- McCarthy DM, Sotereanos DG, Towers JD, et al. A cadaveric and radiologic assessment of catheter placement for the measurement of forearm compartment pressures. *Clin Orthop* 1995;312:266–70.
- McDougall CG, Johnston GH. A new technique of catheter placement for measurement of forearm compartment pressures. *J Trauma* 1991;31:1404–7.
- McQueen MM, Christie J, Court-Brown CM. Compartment pressures after intramedullary nailing of the tibia. *J Bone Joint Surg [Br]* 1990;72:395–97.
- Millis MB, Singer JJ, Hall JE. Supracondylar fracture of the humerus in children – further experience with a study in orthopaedic decision-making. *Clin Orthop* 1984;188:90–97.
- Minkowitz B, Busch MT. Supracondylar humerus fractures. Current trends and controversies. *Ortho Clin North Am* 1994;25:581–94.
- Moed BR, Thorderson PK. Measurement of intracompartmental pressure: a comparison of the slit catheter, side-port needle, and simple needle. *J Bone Joint Surg [Am]* 1993;75A:231–5.
- Mubarak SJ, Hargens AR, Owen CA, et al. The wick catheter technique for measurement of intramuscular pressure: a new research and clinical tool. *J Bone Joint Surg [Am]* 1976;58A:1016–20.
- Mubarak SJ, Hargens AR. Acute compartment syndromes. *Surg Clin North Am* 1983;63:539–65.
- Naidu SH, Heppenstall RB. Compartment syndrome of the forearm and hand. *Hand Clin* 1994;10:13–27.
- Otsuka NY, Kasser JR. Supracondylar fractures of the humerus in children. *J Am Acad Orthop Surg* 1997;5:19–26.
- Pelligrini VD Jr., Reid JS, Evarts CM. Complications: compartment syndromes. In: Rockwood CA Jr., Green DP, Bucholz RW, Heckman JD eds. *Fractures in adults*. Philadelphia: Lippincott-Raven Publishers, 1996:487–492.
- Rorabeck CH, Castle GSP, Hardie R, et al. Compartmental pressure measurements: an experimental investigation using the slit catheter. *J Trauma* 1981;21:446–9.
- Rorabeck CH. The treatment of compartment syndromes of the leg. *J Bone Joint Surg [Br]* 1984;66B:93–7.
- Royle SG. The role of tissue pressure recording in forearm fractures in children. *Injury* 1992;23:549–52.
- Schrader WC, Riley PM, Weiner DS. Volar forearm compartment pressure measurements in pediatric supracondylar humerus fractures. Pediatric Orthopaedic Society of North America 1998 Annual Meeting, Cleveland, Ohio, May 7, 1998 (Paper No. 2).
- Seiler JG III, Womack S, De L'Aune WR, et al. Intracompartmental pressures in the normal forearm. *J Orthop Trauma* 1993;7:414–16.
- Smith MD. Tips of the trade: #19. An intraoperative technique for measuring compartmental pressures. *Orthop Rev* 1989;18:1316–8.
- Triffitt PD, Konig D, Harper WM, et al. Compartment pressures after closed tibial shaft fracture. *J Bone Joint Surg [Br]* 1992;74B:195–8.
- van Egmond DB, Tavenier D, Meeuwis JD. Anatomical and functional results after treatment of dislocated supracondylar fractures of the humerus in children. *Neth J Surg* 1985;37:45–9.
- Volkman R. Die ischaemischen muskellahmungen und kontraktionen. *Zentralbl Chir* 1888;8:801.
- Whitesides TE Jr, Haney TC, Morimoto K, et al. Tissue pressure measurement as a determinant for the need of fasciotomy. *Clin Orthop* 1975;113:43–51.
- Whitesides TE Jr, Heckman MM. Acute compartment syndrome: update on diagnosis and treatment. *J Amer Acad Orthop Surg* 1996;4:209–18.
- Wilkins KE. Supracondylar fractures of the distal humerus. In: Rockwood CA Jr., Wilkins KE, Beaty JH, eds. *Fractures in children*. Philadelphia: Lippincott, Williams, and Wilkins Publishers, 1996:669–752.
- Wilson SC, Vrahas MS, Berson L, et al. A simple method to measure compartment pressures using an intravenous catheter. *Orthopedics* 1997;20:403–6.