PAEDIATRICS

A systematic review of tourniquet use in paediatric orthopaedic surgery: can we extrapolate from adult guidelines?

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- *Purpose:* Tourniquets are commonly used intraoperatively in orthopaedic surgery to control bleeding and improve visibility in the surgical field. Recent evidence has thrown into question the routine use of tourniquets in the adult population resulting in a British Orthopaedic Association standard for intraoperative use. This systematic review evaluates the evidence on the practice, benefits, and risks of the intraoperative use of tourniquets for trauma and elective orthopaedic surgery in the paediatric population.

- *Methods:* A prospectively registered systematic review was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (PROSPERO: CRD42022359048). A search of MEDLINE, Embase, the Cochrane Library and a Grey literature search was performed from their earliest record to 23 March 2023. Studies reporting tourniquet data in paediatric patients undergoing orthopaedic surgery were included. Data extracted included demographics, involved limb, trauma versus elective use, tourniquet use as primary or secondary measure, and tourniquet parameters and complications.

- *Results:* Thirty-nine studies were included. Tourniquet practices and information reporting varied considerably. Tourniquets were used uneventfully in the majority of patients with no specific benefits reported. Several physiological and biochemical changes as well as complications including nerve injury, compartment syndrome, skin burns, thrombosis, post-operative limb swelling, and pain were reported.

- *Conclusions:* Tourniquets are routinely used in both trauma and elective paediatric orthopaedic surgery with no high-quality research affirming benefits. Severe complications associated with their use are rare but do occur. High-quality studies addressing their benefits, the exact indication in children, and the safest way to use them in this population are necessary.

Keywords: pediatrics, orthopedics, tourniquets, intraoperative care

Introduction

Tourniquets have traditionally been used in orthopaedic surgery to control bleeding and increase visibility in the intraoperative surgical field (1, 2, 3, 4). An increasing body of evidence has grown regarding the potential risks associated with their use. This is somewhat foreseeable given their mechanism of

action: sustained circumferential pressure to occlude arterial flow resulting in reduced perfusion distal to the site of application. Laboratory research and studies in the adult population have shown that tourniquet use triggers changes in blood pressure and heart rate (5, 6), cerebral perfusion (7), coagulation (8, 9, 10), and core temperature (11). Local adverse effects include injury to muscle, blood vessels, nerves, and skin (2, 12, 13, 14, 15). Tourniquet use has also been associated with increased post-operative pain (16, 17, 18), longer length of hospital stay (16, 19), increased risk of wound infection and wound complications (19, 20), thromboembolic events (16, 18, 20), and compartment syndrome (16, 21). If not carefully sealed off, the accumulation of antiseptic surgical wash beneath the tourniquet during limb preparation can result in soft tissue damage and chemical burns (22).

Studies in the adult population have attempted to elucidate techniques for the safer use of tourniquets. Example of such methods include adjusting inflation pressures to the patient's systolic blood pressure (SBP) and limb occlusion pressure (LOP) (23, 24, 25) as well as choosing wider, contoured cuffs (26, 27, 28). Omitting the use of tourniquets altogether has gained momentum. Studies in adult arthroplasty surgery suggest tourniquets provide limited benefit in reducing operative time but are associated with surgical adverse events and a higher risk of complications (16, 20, 29). It is estimated that avoiding their use in knee arthroplasty could prevent nearly 2000 serious adverse events per year in the UK alone (29). Similarly, wide-awake local anaesthesia no tourniquet (WALANT) surgery for adult upper limb orthopaedic operations has been increasing in popularity and has shown good clinical results with reduced risk and cost (30, 31, 32, 33).

The existing evidence on tourniquet use in lower limb fracture fixation surgery in adults suggest that using a tourniquet may cause patients harm with limited benefit (34, 35).

Despite the growth in evidence from studies in adults, there is a significant paucity of literature with respect to the paediatric population. The British Orthopaedic Association (BOA) published a standard in 2021 (BOAST) regarding the safe use of intraoperative tourniquets, stating that 'tourniquets should only be used when clinically justified' (36). With respect to paediatric patients specifically, the only specification in this document states that patients younger than 16 years old should have tourniquets applied at a pressure of 50 mm Hg above limb occlusion pressure or 50–100 mm Hg above systolic blood pressure. This systematic review analyses the available evidence on the intraoperative use of tourniquets in paediatric orthopaedic trauma and elective surgery, aiming to evaluate the practices used, the benefits and reported complications in this population.

Methods

A systematic literature review was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Fig. 1). This was prospectively registered on the International Prospective Register of Systematic Reviews (PROSPERO), registration number (CRD42022359048).

Search strategy and data extraction

The following electronic databases were searched from their earliest record to 23 March 2023: MEDLINE, Embase, and the Cochrane Library. A grey literature search was performed using referenced work in included studies and Google Scholar. Conference proceedings from the British Orthopaedic Association (BOA), European Paediatric Orthopaedic Society (EPOS), British Society for Children's Orthopaedic Surgery (BSCOS), and European Federation of National Associations of Orthopaedics and Traumatology (EFORT) were also searched. The search terms may be found in Appendix 1 (see the section on supplementary materials given at the end of this article).

The search was not limited by journal type or level of evidence. The data were collected using Covidence as a systematic review management software tool (©Covidence Systematic Review Software, Veritas Health Innovation, Melbourne, Australia). Two reviewers (VP, CB) determined study eligibility and any conflicts were resolved by a senior author.
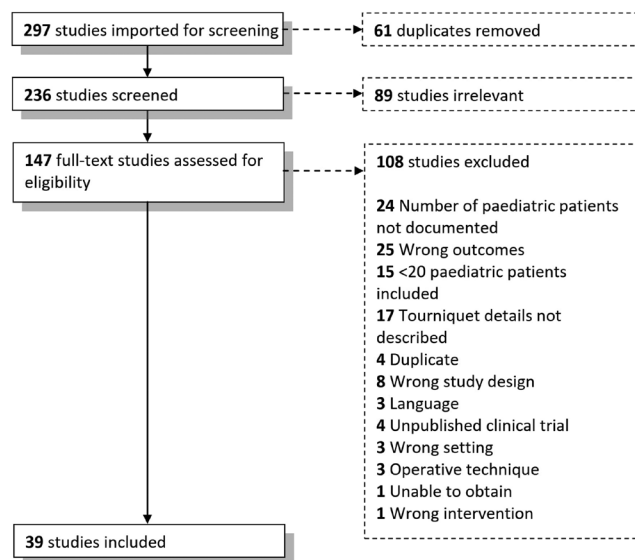

Figure 1

PRISMA chart for the study collection process.

Study eligibility

All studies reporting tourniquet data in paediatric patients (defined as under 18 years old) undergoing orthopaedic surgery were screened. Studies with more than 20 paediatric patients published in English, French or with available translations were included. Where complications and adverse outcomes occurred, there was no lower limit on patient number and all papers were included. Studies including adult populations were included only when the paediatric data were separate and explicitly documented. The PRISMA for the study collection process is outlined in Fig. 1.

Bias assessment

Bias assessment was conducted separately by two authors (VP, CB). The RoB 2 bias assessment method was used for randomised studies (37). ROBINS-I was used for cohort studies, case–control studies and non-randomised experimental studies (38). The method outlined by Murad *et al.* was used for case series and retrospective reviews (39). The results of the bias assessment for each included study are shown in Table 1. The bias assessment is reported in Appendix 2.

Results

The initial literature search identified 297 articles. Thirty-nine studies met the eligibility criteria and were included for data extraction and analysis.

The majority of the studies reported on the general paediatric orthopaedic population. Three studies investigated tourniquet use in specific patient sub-populations: two were in osteogenesis imperfecta (40, 41) and one was in sickle cell disease (SCD) (42). Table 1 summarises data regarding study type, number of patients, limb involved, trauma versus elective use, tourniquet use as primary or secondary outcome, and risk of bias. Most of the studies ($n = 22$) reported tourniquet use in the lower limb with 17 studies reporting upper limb or both. Eight studies reported use in trauma cases and 22 in elective cases, three articles did not specify the setting, and the remaining papers were written with respect to both elective and trauma patients. Bias assessment showed 9 out of 39 studies were at low risk of bias, 13 out of 39 moderate, and 17 out of 39 at high risk (Table 1, Appendix 2).

Tourniquet practices and parameters are specified in Table 2. Most reported studies used pneumatic tourniquets and three used Esmarch bandage or similar technology.

Complications were uncommon but clinically significant, ranging from debilitating to life threatening. Table 3 summarises the reported complications.

Physiological effects

Four studies reported that tourniquet use in children triggers intraoperative physiological and biochemical changes. Bloch *et al.* 1992 and 1997 (43, 44) reported that use of a tourniquet caused an increase in core body temperature, which persisted until the time of tourniquet deflation and was more significant when bilateral lower limb application took place. The authors concluded this may be secondary to decreased effective heat loss from the skin of the limb distal to the tourniquet, thus trapping metabolic heat in the central compartment. They suggested this should be taken into consideration when warming is applied intraoperatively to avoid hyperthermia.

Lynn *et al.* reported an increase in serum lactate, potassium, base deficit, and $PaCO_2$, as well as a decrease in blood pH in the systemic circulation upon tourniquet deflation. This created a mixed respiratory and metabolic acidosis independent of patient size (45). The metabolic acidosis generally took longer than 10 min to resolve. In this study, tourniquet pressure threshold was 275 mm Hg. Findings in keeping with Lynn *et al.* were also reported in two studies by Goodarzi *et al.* (46, 47), in which inflation pressures were set to 75 mm Hg above the patient's SBP, in line with BOAST recommendations.

In these two studies, tourniquet use was associated with changes in blood pressure, pulse rate and temperature. Mean tourniquet time in the two studies was 100 min (range: 50–136) (47) and 90 min (range: 52–148) (46). Longer tourniquet time was associated with increased pulse rate, serum lactate levels, and end-tidal carbon dioxide (46, 47).

A case series by Misra *et al.* (48) looked at tourniquet pressures of 100 mm Hg and 50 mm Hg above SBP on two children for lower limb and upper limb tourniquets respectively. This is in accordance with the most recent BOAST guidelines (36). In both children, heart rate (HR) and blood pressure (BP) increased within 30 min of tourniquet inflation. Increasing the depth of anaesthesia had no effect, but when the tourniquet pressures were dropped to 50 mm Hg above SBP for the lower limb and 25 mm Hg above SBP for the upper limb, HR and BP returned to baseline.

Nerve injury

Seven studies reported nerve injury in paediatric patients undergoing orthopaedic surgery with the use of a tourniquet. In Schrock *et al.*, five of 42 paediatric patients incurred peroneal nerve palsies associated with tourniquet use whilst undergoing tibial derotation osteotomies (49). Mean tourniquet time was 57 min, but tourniquet pressures were not documented. The recovery of the palsies was also not documented. In a

Table 1 Study characteristics and risk of bias assessment.

Study	Study design	Tourniquet use*	Trauma/elective	Upper/lower limb	*N*	Bias
Reilly *et al.* (65)	RCT	Primary	Elective	Lower limb	21	Low
Tamai *et al.* (69)	RCS	Secondary	Both	Lower limb	100	High
Goodarzi *et al.* (47)	Experimental study	Primary	Elective	Lower limb	30	Low
Eidelman *et al.* (66)	Experimental study	Primary	Both	Both	43	High
Ida *et al.* (61)	Case report	Primary	Elective	Lower limb	1	High
Saw *et al.* (51)	Case report	Primary	Trauma	Lower limb	1	High
Goodarzi *et al.* (46)	Case–control study	Secondary	Not specified	Lower limb	40	Moderate
Bloch *et al.* (44)	Case–control study	Primary	Both	Lower limb	47	High
Ashraf *et al.* (68)	Case series	Secondary	Both	Lower limb	1002	Low
Lynn *et al.* (45)	Case series	Primary	Elective	Both	15	Low
Prakash *et al.* (73)	Case series	Secondary	Elective	Lower limb	75	Low
Tareco *et al.* (76)	Case series	Secondary	Elective	Lower limb	30	Low
Hanlon *et al.* (56)	Case series	Primary	Elective	Lower limb	28	Low
Tredwell *et al.* (55)	Case series	Primary	Elective	Both	2	Moderate
Lieberman *et al.* (64)	Case series	Primary	Not specified	Both	29	Moderate
Silver *et al.* (57)	Case series	Primary	Elective	Both	8	Moderate
Inan *et al.* (53)	Case series	Secondary	Elective	Lower limb	28	Moderate
Misra *et al.* (48)	Case series	Primary	Elective	Both	2	High
Hodgins *et al.* (58)	Case series	Primary	Elective	Lower limb	2	High
Dickinson *et al.* (59)	Case series	Primary	Elective	Upper limb	3	High
Kang *et al.* (67)	Case series	Primary	Elective	Upper limb	113	High
Murphy *et al.* (60)	Case series	Secondary	Elective	Lower limb	2783	High
Zampieri *et al.* (70)	Cohort study	Secondary	Elective	Lower Limb	57	High
Lindgren *et al.* (71)	Cohort study	Secondary	Trauma	Upper Limb	24	High
Hanna *et al.* (62)	Cohort study	Primary	Both	Lower limb	204	Low
Baghdadi *et al.* (77)	Cohort study	Secondary	Trauma	Upper limb	204	Low
Reinhardt *et al.* (78)	Cohort study	Secondary	Trauma	Upper limb	31	Moderate
Yalcinkaya *et al.* (54)	Cohort study	Secondary	Trauma	Upper limb	45	Moderate
Watts *et al.* (79)	Cohort study	Secondary	Trauma	Lower limb	31	Moderate
Cai *et al.* (80)	Cohort study	Secondary	Trauma	Upper limb	32	Moderate
Bloch *et al.* (43)	Cohort study	Primary	Elective	Lower limb	56	High
Jardaly *et al.* (52)	Cohort study	Secondary	Trauma	Lower limb	95	High
Oginni & Rufai (42)	Cohort study	Primary	Elective	Both	39	High
Ryan *et al.* (81)	RR	Secondary	Elective	Both	197	Moderate
Sullivan *et al.* (40)	RR	Secondary	Both	Both	37	Moderate
Vas *et al.* (63)	RR	Secondary	Elective	Lower limb	160	Moderate
Ross *et al.* (41)	RR	Primary	Not specified	Both	49	Moderate
Schrock *et al.* (49)	RR	Secondary	Elective	Lower limb	42	High
Slawski *et al.* (50)	RR	Secondary	Elective	Lower limb	255	High

*Tourniquet use as a primary or secondary outcome.
RCT, randomised controlled trial; RCS, retrospective comparative study; RR, retrospective review.

similar study of tibial osteotomies by Slawski *et al.* (50), 11 cases of peroneal nerve injury were reported. All had recovered by 6 months post-operatively. Mean tourniquet time was 91 min (range: 48–125), similarly tourniquet pressures were not reported. Saw *et al.* reported a case of a 15-year-old who underwent arthroscopic surgery for a tibial eminence fracture (51). The patient developed common peroneal nerve palsy that resolved within 1 week. The tourniquet time and pressure were 112 min and 250 mm Hg, respectively. The authors of these studies believed the aetiology of these nerve injuries to be caused by the tourniquet. Schrock *et al.* also suggested that injury via intra-operative retraction or displacement of osteotomy fragments may also have played a role (49).

Jardaly *et al.* compared the use of closed reduction internal fixation (CRIF) to open reduction internal fixation (ORIF) for the surgical management of tibial tubercle fractures (52). A tourniquet was used for ORIF but not in the CRIF technique. The mean tourniquet time was 50.6 min (range: 21–100), but pressure data were not reported. In the ORIF group, three patients had numbness post-operatively, one had a peroneal nerve palsy and one had to undergo fasciotomy. Tourniquet time and pressures for these patients were not documented. Of note, 42% of patients in this study were obese

Table 2 Tourniquet variables.

Study	Type of tourniquet	Mean (range) average tourniquet	
		Time, minutes	Pressure, mm Hg
Kang *et al.* (67)	Other: ARGYLE Penrose tubing	(30–109)	(177–192)
Eidelman *et al.* (66)	Other: S-MART	44 (15–75)	227 (190–260)
			246 (160-342)
Oginni & Rufai (42)	Esmarch bandage	31 (15–45)	–
Lynn *et al.* (45)	Pneumatic	58 (31–94)	248 (150–425)
		62 (2–26)	
Ross *et al.* (41)	Pneumatic	69 (10–120)	200 (180–300)
Goodarzi *et al.* (47)	Pneumatic	100 (50–140)	217 (200–250)
Goodarzi *et al.* (46)	Pneumatic	90.35 (55–132)	–
		90.05 (52–148)	
Hodgins *et al.* (58)	Pneumatic	85.5 (71–100)	225 (200–250)
Hanlon *et al.* (56)	Pneumatic	99 (45–160)	Not exceeding 250
Reilly *et al.* (65)	Pneumatic	91	300
		89	151 (145.6–156.4)
Lieberman *et al.* (64)	Pneumatic	54.5	175.8 (140–250)
Silver *et al.* (57)	Pneumatic	54.5	283.3 (250–300)
Ida *et al.* (61)	Pneumatic	23	250
		27	
Saw *et al.* (51)	Pneumatic	112	250
Sullivan *et al.* (40)	Pneumatic	80	250
Tredwell *et al.* (55)	Pneumatic	1	200
Misra *et al.* (48)	Pneumatic	60	(125–185)
Bloch *et al.* (44)	Pneumatic	103 (unilateral)	–
		115 (bilateral)	
Hanna *et al.* (62)	Pneumatic	75.91 (7–195)	–
Vas *et al.* (63)	Pneumatic	–	150
Bloch *et al.* (43)	Pneumatic	–	–
Dickinson *et al.* (59)	Pneumatic	–	–
Yalcinkaya *et al.* (54)	Pneumatic	–	–
Murphy *et al.* (60)	Not specified	66 (23–127)	–
Slawski *et al.* (50)	Not specified	91 (48–125)	–
Reinhardt *et al.* (78)	Not specified	89.5 (54–126)	–
		35.6 (0–100)	
Ashraf *et al.* (68)	Not specified	78.4 (11–264)	–
Watts *et al.* (79)	Not specified	76.1 (40–110)	–
		100.1 (60–135)	
Tamai *et al.* (69)	Not specified	104 (48–132)	–
Baghdadi *et al.* (77)	Not specified	53.1 (15–120)	–
		55 (25–100)	
Jardaly *et al.* (52)	Not specified	50.6 (21–100)	–
Ryan *et al.* (82)	Not specified	30.1 (1–118)	–
Tareco *et al.* (76)	Not specified	81.5	–
		58.4	
Cai *et al.* (80)	Not specified	37.7	–
		56.9	
Inan *et al.* (53)	Not specified	48	–
		60	
Prakash *et al.* (73)	Not specified	26	–
Schrock *et al.* (49)	Not specified	57	–
Zampieri *et al.* (70)	Not specified	62 (median)	–
		90.5 (median)	
Lindgren *et al.* (71)	Not specified	46	–
		92	

Table 3 Complications.

Complication/ Study	Patients affected, *n*	Trend identified*
Alteration in physiological parameters†		
Bloch *et al* (43)		Increased CBT
Bloch *et al.* (44)		Increased CBT
Lynn *et al.* (45)		Mixed respiratory and metabolic acidosis
Goodarzi *et al.* (47)		Increased CBT, lactate, end-tidal CO_2
Goodarzi *et al.* (46)		Increased BP, HR, CBT
Misra *et al.* (48)		Increased BP and HR
Nerve Injury		
Schrock *et al.* (49)	5	
Slawski *et al.* (50)	11	
Saw *et al.* (51)	1	
Jardaly *et al.* (52)	4	
Yalcinkaya *et al.* (54)	1	
Inan *et al.* (53)	5	
Tredwell *et al.* (55)	15	
Compartment syndrome		
Jardaly *et al.* (52)	1	
Skin burns		
Hodgins *et al.* (58)	2	
Dickinson *et al.* (59)	3	
Thrombosis and Embolism		
Murphy *et al.* (60)	7	
Ida *et al.* (61)	1	
Pain		
Hanna *et al.* (62)		Increased pain and analgesia requirements
Vas *et al.* (63)	6	
Limb swelling		
Silver *et al.* (57)		Tourniquet use results in limb swelling

*Trends are identified over the study population rather than specific individuals; †parameters such as core body temperature (CBT), heart rate (HR), blood pressure (BP) or serum lactate and pH.

and a considerably larger number of patients underwent ORIF than CRIF (81 and 17, respectively).

Inan *et al.* investigated the occurrence of neurological complications after supracondylar extension femoral osteotomy in 28 patients with cerebral palsy and fixed flexion deformity of the knee (53). Nineteen patients had bilateral procedures with 48 procedures performed in total, of which 40 used a tourniquet. Five patients had neurological complications. No association was found between tourniquet inflation time and neurological complication rate. In this study, the authors suggested that neurological complications were secondary to operative technique, especially inadequate femoral shortening.

Yalcinkaya *et al.* investigated the surgical management of unstable forearm fractures in 45 children. They attributed one case of radial nerve palsy with wrist drop to the use of tourniquet (54). A tourniquet with a pneumatic cuff was used, but tourniquet time and pressure were not mentioned. In a survey by Tredwell *et al.*, of the 67 complications reported by 44 surgeons, 15 involved nerve injury (55).

Limb swelling and compartment syndrome

Jardaly *et al.* reported one case of post-operative compartment syndrome (52). Tourniquet time and pressure were not reported, but the maximal tourniquet inflation time in the study was 100 min. Hanlon *et al.* (54) measured compartment pressures in the central compartment of the foot after clubfoot surgery (56). In this study 16 of 39 operated feet had compartment pressures of a level that could trigger compartment syndrome with no correlation between compartment pressure recordings and tourniquet time.

Silver *et al.* found a 10% increase in limb volume after a pneumatic tourniquet was released. Swelling did not correlate with tourniquet pressure or time (57). The authors suggested that return of the exsanguinated blood and reactive hyperaemia secondary to ischaemia were responsible for this increase in limb volume. They recommend tourniquets are deflated prior to haemostasis and application of cylindrical bandaging to reduce the risk of compartment syndrome.

Skin burns

Two case series reported on chemical skin burns caused by pooling of antiseptic skin preparation underneath the tourniquet. Hodgins *et al.* reported two children who developed partial thickness chemical burns (58). Chlorhexidine gluconate 2% in 70% isopropyl alcohol was used for prepping the limbs. One case had a 10 × 15 cm deep partial-thickness burn on the posterior thigh that healed over the course of 4 weeks with silver-based dressings. The second case incurred a burn of 4 × 3 cm also on the posterior thigh, which again was managed conservatively. In the first and more severe case, no shut-off was used to isolate the tourniquet and the padding under the tourniquet had become soaked with antiseptic. Tourniquet pressures were 250 mm Hg and 200 mm Hg, and both children had tourniquets inflated for longer than one hour (100 min and 71 min). Dickinson *et al.* also reported on three children who incurred partial thickness chemical burns under tourniquets (59). Povidone–iodine with 70% alcohol content was used for prepping in this study. Tourniquet times and pressures, as well as the use of a shut-off were not documented. In the survey reported in Tredwell *et al.* the most reported complication was skin damage (21/67), whereas muscle injury accounted for eight of the 67 reported complications (55).

Thrombosis and embolism

Murphy *et al.* investigated the risk of thromboembolism after knee arthroscopy in 2,783 adolescents (60). Seven patients had symptomatic lower limb deep vein thromboses (DVT), which were subsequently confirmed on ultrasound. The average tourniquet time was 66 min (range: 23–127). In three of the seven patients, tourniquet time was longer than 60 min. One patient was subsequently diagnosed with factor V Leiden deficiency. There was no statistical analysis assessing the relationship between tourniquet time and venous thromboembolism (VTE) risk. Tourniquet data for the patients who did not have a VTE were not reported.

Ida *et al.* reported the case of a 5-year-old child who underwent reduction of hip dislocation and Achilles tendon lengthening to treat neurogenic hip dislocation and clubfoot (61). The child was reported to incur fat embolism syndrome triggered by the deflation of the tourniquet. The tourniquet had been applied at a pressure of 250 mm Hg for 23 min on the left lower limb and 27 min on the right lower limb.

Pain

Hanna *et al.* included 204 children who underwent lower limb orthopaedic surgery. Tourniquet use was associated with increased pain levels and post-operative analgesia requirements (62). Mean tourniquet time was 75.9 min (range: 7–195), but tourniquet pressures were not reported. This study also found that tourniquet use was associated with shorter operating time, reduced blood loss, and no increase in infection rates.

Vas *et al.* investigated the benefit of a three-in-one block in conjunction with a continuous sciatic block for intraoperative pain caused by the tourniquet in 160 children (63). They proposed that a sciatic block does not anaesthetise the area affected by the tourniquet entirely and this justified additional anaesthetic measures. The tourniquet was set to a predefined pressure of 150 mm Hg with no tourniquet times documented. The three-in-one block was mostly successful, but six children still had increased heart rates and upper body movement triggered by the painful stimulus of tourniquet inflation, which was managed with boluses of ketamine and propofol.

Sub-population studies

Sullivan *et al.* (40) and Ross *et al.* (41) investigated the incidence of fractures from tourniquet use in patients with osteogenesis imperfecta. Sullivan *et al.* included 37 patients (mean age = 10, s.d. = 4.8) with tourniquet pressure 250 mm Hg. Ross *et al.* included 49 patients (median age: 7.9, range: 0.2–17.7) and median tourniquet pressure was 200 mm Hg (range: 180–300). Neither study reported any iatrogenic fractures secondary to tourniquet use.

Oginni & Rufai investigated the incidence of complications with the use of tourniquets for sequestration surgery in 18 children and one adult with SCD and 20 controls (42). Mean tourniquet time was 31 min in the SCD group and 33 min in the control group. Three cases of extremity swelling were reported in both the SCD and the control group.

Tourniquet technique

Two studies investigated the concept of LOP instead of standardised pressures or pressures determined based on SBP. In Lieberman *et al.* operations were successfully performed using 50 mm Hg above LOP. Mean tourniquet pressures of 173.4 mm Hg and 176.7 mm Hg were used in the upper and lower limb respectively, significantly lower pressures than the commonly used 250 mm Hg and 300 mm Hg (64).

The concept of LOP was also used by Reilly *et al.* who demonstrated significantly reduced inflation pressures could safely be used for arthroscopic knee surgery (65). In this randomised controlled study, paediatric patients undergoing primary arthroscopic elective anterior cruciate ligament (ACL) repair were randomised between a standardised pressure of 300 mm Hg and individualised LOP. Operative time was equivalent in the two groups, but average tourniquet pressure was 151 mm Hg in the LOP compared to 300 mm Hg in the standardised group. A wider contour cuff achieved effective blood flow occlusion at lower inflation pressures. Haemostasis was adequate in both the LOP and standardised inflation pressure groups, with no difference in quality of the surgical field on analysis of visual analogue scale scores. No complications were reported.

Eidelman *et al.* and Kang *et al.* explored different forms of elastic tourniquets. In Eidelman *et al.*, 51 procedures in 43 patients were carried out using the S-MART tourniquet, which consists of an elastic ring, stockinet sleeve, and pull straps (66). Two sizes of S-MART tourniquet were used depending on limb circumference. The smaller system provided a pressure of 227 ± 37 mm Hg (mean ± s.d.) and the larger one 246 ± 86 mm Hg (mean ± s.d.). The authors reported good visibility in the surgical field without complications. In Kang *et al.* the ARGYLE elastic band tourniquet was used in young children needing upper limb surgery (67). This consisted of a 3.2 cm by 30 cm ARGYLE Penrose tubing. The tourniquet circumference was 70% of the arm circumference of the child and the tourniquet pressure range was 171–182 mm Hg. Visibility in the surgical field was reported as adequate and no complications reported.

When considering local impact of tourniquet use on skin, Tredwell *et al.* (55) explored the practices of paediatric orthopaedic surgeons in the USA and Canada. They looked at several aspects of tourniquet use including the degree of skin wrinkling caused by different models of tourniquets as well as the effect

of the use of padding. When considering tourniquet pressure they found an equal share of surgeons select pressures based on either a standard pressure, a pressure based on age, extremity and size, or an inflation pressure based on SBP (either 100 mmHg above SBP, or doubling SBP). They found padding reduced both peak depth and number of wrinkles compared to using the cuffs without padding. The study reported one case where bilateral lower limb tourniquets were used, but the tourniquet on the primary leg was inadvertently left inflated when the contralateral leg was being operated on, with catastrophic consequence. The child later underwent limb amputation for the severe ischaemic injury suffered. The authors suggested tourniquets should be removed once they are no longer needed to prevent this type of error.

Infection

Ashraf *et al.* investigated complications from knee arthroscopy in children (68). A total of 1002 children were included. Mean age was 15.4 years (range: 4–17). A tourniquet was used in 643 surgeries with a mean tourniquet time of 78.4 min (range: 11–264). Tourniquet pressures were not reported. Longer tourniquet times (>114 min) were associated with increased risk of major complications ($P < 0.001$), including septic arthritis, wound complication requiring repeat closure, arthrofibrosis requiring manipulation under anaesthesia, and revision surgery.

No complications

Nine studies reported tourniquet use without any complications. Tourniquet use was defined; however, this was not the primary outcome of these studies. These studies investigated complications following peripheral nerve blocks (69), surgical fixations for recurrent patellar dislocation (70), and forearm re-fractures after surgical fixation (71).

Discussion

Tourniquets are commonly used in orthopaedic operations, with recognised benefits as well as risks. To guide safe practice, a new set of BOAST guidelines was published in October 2021 (36). This systematic review evaluated the available evidence regarding the use of tourniquets in orthopaedic surgery in the paediatric population.

Tourniquets were used uneventfully in the majority of patients, including patients with osteogenesis imperfecta (40, 41).

However, evidence of potential negative effects and complications of tourniquet use were found in the paediatric population reviewed. These include changes in physiological parameters such as blood pressure, heart rate, and core temperature, as well as biochemical changes triggering a state of mixed respiratory and metabolic acidosis (43, 44, 45, 46, 47). These changes can be explained by redistribution of blood flow, localised pressure damage and the state of limb ischaemia, resulting in skeletal muscle reverting to anaerobic respiration and lactate production (72). Apart from the suggestion that aggressive warming should be avoided in paediatric patients undergoing surgery with a tourniquet (43, 44), these studies do not discuss the clinical significance of the findings and whether they require a change in practice. Of note, in Bloch 1992, the patients in the control group underwent non-orthopaedic operations. It may be questioned whether specific aspects of orthopaedic surgery, such as drilling into bone, may trigger hyperthermia irrespective of tourniquet use. Furthermore, both studies by Bloch focused exclusively on lower limb surgery and did not report on tourniquet pressures. With regard to the serum changes detected in the study by Lynn *et al.* these occurred in the context of a tourniquet pressure threshold of 275 mm Hg, which is higher than recommended in the most recent BOAST guidelines (36). Higher tourniquet pressures may cause more significant tissue damage and cell breakdown underneath the tourniquet with release of intracellular contents and activation of the inflammatory response. One could argue this may have influenced the metabolic changes observed by Lynn *et al.* (45). However, the two studies by Goodarzi *et al.* (46, 47), which were performed in the context of inflation pressures of 75 mm Hg above the patient's SBP, in line with BOAST recommendations, supported the findings by Lynn *et al.*, providing evidence that these metabolic changes occur even when lower inflation pressures are used.

Seven studies reported nerve injury (49, 50, 51, 52, 53, 54, 55) and other anecdotal adverse events reported are increased risk of thrombotic events (60), fat embolism (61), compartment syndrome (52), and chemical skin burns (58, 59). Notably, in the study by Murphy *et al.* (60) only patients who were symptomatic for DVT were scanned so the incidence of DVT may have been underreported. Skin burns occur when there is pooling of disinfectant under the tourniquet. This is an example of a tourniquet associated adverse event that is entirely preventable through the correct application of a shut-off. Similar to the evidence from the adult population (16), tourniquet use is associated with increased post-operative pain and analgesia (62), which can prolong hospital stay and interfere with rehabilitation.

The study by Oginni & Rufai (42) investigated tourniquet use in patients with SCD. In the SCD group, one child developed mild jaundice post-operatively; however, this may also have been secondary to the stress of surgery rather than tourniquet use. The authors concluded that using a tourniquet in SCD carries risk, though they provided limited evidence for this.

BOAST guidelines state specific recommendations on tourniquet inflation time and pressures (36). This review found that tourniquet inflation times were generally better reported than inflation pressures. Details on tourniquet time were reported in 88% of the included studies, with only 41% providing information on the inflation pressures used (Table 1). Three studies reported a correlation between tourniquet time and potential risk: Ashraf *et al.* which identified a correlation between major complications and tourniquet times >114 min (68) and the two studies by Goodarzi *et al.* where longer tourniquet time was associated with increased pulse rate, serum lactate levels, and end-tidal carbon dioxide (46, 47).

In terms of inflation pressures, a variation in the settings used was identified: 50 mm Hg above LOP (64), or values above SBP of 75 mm Hg (45), 100 mm Hg (73), and 275 mm Hg (45). Misra *et al.* showed that HR and BP returned to baseline when pressures of 50 mm Hg above SBP for the lower limb and 25 mm Hg above SBP for the upper limb were used (48).

Tourniquet time is in most cases dependent on surgical time, which is affected by type and complexity of the operation being performed. Tourniquet inflation pressure, on the other hand, is often set independently at the beginning of the operation. Studies have shown that direct pressure, especially at the cuff edge interface, can cause damage to surrounding tissues and lead to muscle and nerve injury. Yates *et al.* showed that peripheral nerve injury secondary to tourniquet use is the consequence of both mechanical pressure and ischaemia, conduction abnormalities being disproportionately severe at the tourniquet border zones (74). Ochoa *et al.* demonstrated that pressure from the tourniquet could result in displacement of the nodes of Ranvier and axonal demyelination (75). Using LOP as a reference seems to result in lower pressures than the standard 250 and 300 mm Hg being used whilst providing adequate visibility of the surgical field (64, 65). The timing for measurement of LOP with regard to general anaesthesia and how changes in SBP may affect LOP intraoperatively are variables which have not been accounted for. Another consideration highlighted by Liebermann *et al.* is inadequate fitting of the tourniquet to the limbs of younger children which invites further consideration (64).

Despite the primary goals for the intraoperative use of tourniquets being to improve visibility of the surgical field and decreased blood loss, no study directly assessed quality of the surgical field with and without the use of a tourniquet and only one study reported on the difference in blood loss (62) which was not clinically significant. The routine use of tourniquet in both elective and fracture fixation is not evidence based, in terms of benefits as well as potential complications.

Conclusions

Although tourniquets continue to be commonly used in paediatric orthopaedic surgery, the evidence regarding the current practice is insufficient, as is the reporting of perceived benefit versus complications. There is a lack of high-quality studies investigating the use of tourniquets in paediatric orthopaedics but significant complications have anecdotally been reported and specific examples are easily preventable. Further research is required to elucidate their exact indication in children and the safest, most effective way to use them.

Recommendations

Based on the findings of this review, the authors make the following recommendations:

- The necessity for tourniquet use needs to be assessed on a case-by-case basis.

- When a tourniquet is used, documentation including specific parameters should be an integral part of the operation notes.

- Tourniquets should be of the correct size, applied over a layer of padding and appropriately shut off. Pooling of disinfectant is to be avoided and, if occurs, should be promptly rectified to minimise the risk of burns.

- The use of tourniquets in the context of bilateral limb surgery needs additional caution. Clinicians should consider the removal of the tourniquet from the limb once surgery on that side is completed to avoid the potentially catastrophic effects of a tourniquet that is inadvertently left inflated.

- The anaesthetic team need to be mindful of the physiological responses to tourniquet use, including the risk of hyperthermia and acidosis.

- When using a tourniquet, post-operative monitoring of pain, swelling, and signs of compartment syndrome should be adhered to.

- There is a need for a large-scale high-quality study to clarify best practice and quantify the risks and benefits of tourniquet use in the paediatric population.

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VP, CB, AB, CH and YG declare that they have no conflicts of interest concerning this article. AT receives payment for educational activities

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