



# Clinical utilization of arterial occlusion pressure estimation method in lower limb surgery: effectiveness of tourniquet pressures

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**Objective:** The effectiveness of the arterial occlusion pressure (AOP) estimation method to set tourniquet inflation pressures was assessed in patients undergoing lower limb surgery.

**Methods:** One hundred ninety-eight operations were performed in 224 lower extremities of 193 patients. Tourniquet inflation pressures were set using the AOP estimation formula and adding 20 mmHg of safety margin to AOP value. Primary outcome measures were the amount of tourniquet pressure and its effectiveness. The quality of the surgical field and complications were assessed by the surgical team in a blinded fashion. Secondary measures included the time required to set the tourniquet pressure and complications.

**Results:** The initial and maximal tourniquet pressures used were  $168.4 \pm 14.5$  and  $173.3 \pm 15.6$  mmHg, respectively. The performance of the tourniquets was assessed as “excellent” and “good” in all stages of the procedure in 97.76% of cases. The time required to measure AOP and set the tourniquet cuff pressure was  $19.0 \pm 2.6$  sec. No complications occurred during or after surgery until discharge.

**Conclusion:** Clinical utilization of the AOP estimation formula is a practical and effective way of setting tourniquet pressures for lower limb surgery. Its usage allows achievement of a bloodless field with inflation pressures lower than those previously recommended in the literature for lower limb tourniquets.

**Keywords:** Arterial occlusion pressure; estimation method; inflation pressure; lower extremity; pneumatic tourniquet.

**Level of Evidence:** Level IV, Therapeutic study.

Pneumatic tourniquets are widely used to reduce blood loss and to ensure optimal operating conditions during extremity surgery.<sup>[1,2]</sup> However, compression of the tissues under a tourniquet is associated with soft tissue damage involving the skin, vessels, muscles, and

most importantly, nerves.<sup>[3-9]</sup> Therefore, the “minimal tourniquet inflation pressure” necessary to provide a bloodless field has been suggested to minimize the risk of complications from excessive inflation pressure.<sup>[10-18]</sup>

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Arterial occlusion pressure (AOP) is the lowest pneumatic tourniquet inflation pressure required to stop the arterial blood flow into the limb, and its usage has been shown to be useful in optimizing tourniquet cuff pressures.<sup>[19-24]</sup> The AOP estimation method is based on systolic blood pressure (SBP) and tissue padding coefficient (KTP) values ( $AOP = [SBP + 10] / KTP$ ) according to extremity circumferences.<sup>[25]</sup> Using this method in tourniquet pressure settings, the bloodless field was achieved at  $169.7 \pm 7.9$  mmHg in total knee arthroplasty (TKA) patients under hypotensive general anesthesia.<sup>[26]</sup> However, we were unable to find a study which investigated utilization of the AOP estimation method in tourniquet pressure settings in patients undergoing different lower extremity surgeries under normotensive anesthesia.

The aims of the present study were to apply the AOP estimation method to determine minimal tourniquet inflation pressures and to investigate its usefulness and effectiveness in adult patients scheduled for various lower extremity surgeries under normotensive anesthesia.

## Patients and methods

This study was approved by the Institutional Review Board and Ethics Committee, and written informed consent was obtained from the participants. Patients

undergoing lower extremity surgery with pneumatic tourniquet were selected for inclusion in the study. One hundred ninety-eight operations were performed in 224 lower extremities of 193 patients. The surgical procedures were TKA (unilateral and bilateral), revision TKA, open reduction and internal fixation for fractures, removal of internal fixation material, hallux valgus surgery, arthroscopic knee and ankle surgery, removal of a benign soft tissue mass, bunionectomy, Morton neuroma surgery, Achilles tendon repair, and arthrodesis of the ankle. Regional (spinal, combined spinal and epidural) anesthesia was administered in 208 cases, and general anesthesia was administered in 16 cases (Table 1). Age, gender, height, weight, body mass index, extremity circumference of the patients, and surgical procedures were recorded.

In the operating room, following standard monitoring, patients received general, spinal, epidural, or combined spinal and epidural anesthesia, according to indications. In all patients, the thigh circumference was measured 20 cm proximal to the superior pole of the patella and recorded, with the knee extended by a tape measure. The tourniquet cuff was placed around the thigh, with the distal edge 15 cm proximal to the proximal pole of the patella. Standard pneumatic tourniquet with an 11-cm cuff was applied by a physician. To determine the appropriate tourniquet inflation pressure, the

**Table 1.** Surgical procedures, exsanguination methods, and types of anesthesia.

	Number of cases (n=198)	
	n	%
Surgical procedures		
Unilateral total knee arthroplasty	97	48.9
Bilateral total knee arthroplasty	26	13.1
Revision total knee arthroplasty	6	3.03
Open reduction and internal fixation	20	10.1
Removal of internal fixation	5	2.52
Arthroscopic knee surgery	24	12.1
Arthroscopic ankle surgery	2	1.01
Achilles tendon repair	2	1.01
Hallux valgus surgery	7	3.53
Arthrodesis	5	0.25
Morton neuroma surgery	1	0.50
Resection of benign soft tissue tumor	2	1.01
Bunionectomy	1	0.50
Exsanguination method		
Elevation for 3 min	83	41.9
Esmarch bandage	115	58.8
Anesthesia		
Regional anesthesia (spinal, combined epidural and spinal)	182	91.9
General anesthesia	16	8.08

AOP estimation formula ( $AOP = [SBP + 10] / K_{TP}$ ) was used. The calculation was made using initial SBP and tissue padding coefficient values from a list, according to limb circumferences of the patient (Table 2). After calculation of AOP, tourniquet pressures were determined by adding a safety margin of 20 mmHg to AOP values (tourniquet pressure =  $AOP + 20$  mmHg). The time required for the measurement of extremity circumference and calculation process was recorded.

After exsanguination with an Esmarch bandage or elevation of the limb for 3 minutes, the tourniquet cuff was inflated to the proper determined setting. The tourniquet pressure was manually raised 10 mmHg in response to each 10 mmHg-increment increase in SBP, which was measured at 5 minute intervals throughout the tourniquet period. Primary outcome measures (SBP, AOP, tourniquet pressures, initial SBP, initial tourniquet pressure, maximal SBP, maximal tourniquet pressure, tourniquet time) were recorded.

Secondary outcome measures included quality of

**Table 2.** Tissue padding coefficients based on limb circumferences.<sup>[25]</sup>

Extremity circumferences (cm)	Estimated $K_{TP}$
20	0.91
21	0.90
22	0.89
23	0.88
24	0.87
25	0.86
26 to 27	0.85
28	0.84
29	0.83
30 to 31	0.82
32 to 33	0.81
34	0.80
35 to 36	0.79
37 to 38	0.78
39 to 40	0.77
41 to 43	0.76
44 to 45	0.75
46 to 48	0.74
49 to 51	0.73
52 to 54	0.72
55 to 57	0.71
58 to 60	0.70
61 to 64	0.69
65 to 68	0.68
69 to 73	0.67
74 to 75	0.66

$K_{TP}$ : Tissue padding coefficient.

operative field, complications, surgeon's awareness of tourniquet pressure, and surgeon's rating of tourniquet performance (excellent: no blood in the surgical field; good: some blood in the surgical field but no interference with surgery; fair: blood in the surgical field but no significant interference with surgery; poor: blood in the surgical field obscures the view) at the beginning, middle, and end of the surgical procedure. All patients were examined after surgery every day during hospital stay for signs of any complications such as skin damage, nerve palsies, or vascular occlusion by a blind investigator.

All data and resulting outcomes were analyzed with the aid of descriptive statistics using SPSS software (version 15.0, SPSS Inc., Chicago, IL, USA).

## Results

Patient characteristics are summarized in Table 3. The time required to measure AOP and set the tourniquet cuff pressure was  $19.0 \pm 2.6$  sec, and the average estimated AOP of the patients was  $148.7 \pm 16.5$  mmHg. Mean initial and maximal tourniquet pressures utilized were  $168.4 \pm 14.5$  and  $173.3 \pm 15.6$  mmHg, respectively (Table 4).

**Table 3.** Patient demographics.

Parameter	Value
	Mean $\pm$ SD
Age (years)	64.2 $\pm$ 14.3
Gender (Female/Male)	159/39
Height (cm)	162.9 $\pm$ 8.0
Weight (kg)	79.4 $\pm$ 13.2
Body mass index (kg/m <sup>2</sup> )	29.9 $\pm$ 5.1
Limb circumference (cm)	51.1 $\pm$ 6.9

SD: Standard deviation.

**Table 4.** Systolic blood pressures, tourniquet pressures, and tourniquet times (Mean $\pm$ SD).

Parameter	Value
	Mean $\pm$ SD
Time to estimate AOP and set the cuff pressure (sec)	19.0 $\pm$ 2.6
Estimated AOP (mmHg)	148.7 $\pm$ 16.5
Initial SBP (mmHg)	98.7 $\pm$ 9.6
Initial tourniquet pressure (mmHg)	169.5 $\pm$ 14.8
Maximal SBP (mmHg)	103.5 $\pm$ 10.4
Maximal tourniquet pressure (mmHg)	174.2 $\pm$ 15.8
Tourniquet time (minute)	77.6 $\pm$ 22.4

AOP: Arterial occlusion pressure; SBP: Systolic blood pressure; SD: Standard deviation.

**Table 5.** Surgeon's opinion regarding performance of the tourniquets at various stages of surgery.

Surgeon's opinion	Stage of surgery					
	Initial		Middle		End	
	n	%	n	%	n	%
Excellent	213	95.08	217	96.89	222	99.10
Good	6	2.678	3	1.339	0	0
Fair	3	1.339	2	0.892	0	0
Poor	2	0.892	2	0.892	2	0.892

The performance of the tourniquets was assessed as "excellent" and "good" in all stages of the procedure in 219 cases (97.76%). Three (1.33%) and 2 (0.89%) patients were rated as "fair" at the beginning and in the middle of the procedure. Two patients were rated as "poor" at the beginning of the procedure. Air leak from the tourniquet cuff was detected, and the operations of these patients were completed without tourniquet use. These patients rated as "poor" in the middle and at the end of the surgical procedure (Table 5).

No complications such as damage to skin, vessels, nerves, or compartment syndrome was observed during or after surgery until discharge.

## Discussion

The use of a pneumatic tourniquet may be associated with local complications including limb paralysis, damage to nerves, muscles, vessels, and skin, as well as other injuries such as compartment syndrome, especially in diabetic patients.<sup>[1-5]</sup> Clinical and experimental studies show that nerve conduction abnormalities and muscle dysfunctions occur after tourniquet application in more than 70% of lower extremity surgeries and are correlated with impaired postoperative function and delayed recovery. Moreover, it has been suggested that incidence of these abnormalities, which have been attributed to length of ischemia period as well as excessive inflation pressures, are underreported.<sup>[6]</sup> As a goal, the tourniquet should be used at the minimal pressure and for the least time possible.<sup>[7]</sup>

Literature review shows that there is a lack of standard practice or consensus among orthopedic surgeons regarding optimal inflation pressures, which contributes to the use of unnecessarily high tourniquet pressures in lower limb surgeries.<sup>[8]</sup> Furthermore, a significant percentage of orthopedic surgeons routinely apply fixed pressures of 250–300 mmHg in lower extremity surgery based on experiences and accept these pressures as safe, in spite of reported adverse effects of high tourniquet pressures.<sup>[9]</sup>

Efforts have been made to optimize the tourniquet inflation pressures in lower limb surgery, and the concept of "minimal inflation pressure" has been constantly redefined for decades.<sup>[8-26]</sup> Regardless of SBP or limb circumference, Pauers et al. used a standard pressure of 250 mmHg and reported that an adequately bloodless field was achieved in all cases.<sup>[10]</sup> Several studies investigated the soft tissue pressure distribution under a tourniquet cuff with limbs of human cadavers and dogs.<sup>[11-14]</sup> These studies showed that tissue pressures are consistently lower than tourniquet pressures, which are inversely correlated with the circumference of the limb. Additionally, these studies demonstrated that the main factors affecting optimal tourniquet pressures include the girth of the limb and SBP of the patient, suggesting that a tissue pressure above the SBP of the patient is adequate to stop blood flow to the limb.<sup>[11-14]</sup> However, the patient's SBP may rise during surgery, and conventional tourniquet systems, which remain on the initial setting pressure throughout the procedure, cannot respond to these hemodynamic changes. In these cases, the inflation pressure should be adjusted manually in order to prevent leakage from an increase in SBP or to prevent unnecessarily high inflation pressures following a decrease in SBP. Because these steps require additional monitoring by the staff, it has been suggested that a fixed safety margin of 100–150 mmHg should be added to the patient's initial SBP.<sup>[15]</sup> Using this method, Estersohn et al. and Newman et al. achieved surgical hemostasis at tourniquet pressures of 210 mmHg and 252.2±22.8 mmHg, respectively, in lower limb surgery. The high inflation pressures in their studies may be attributed to the SBP of their patients and the extent of the safety margin (90–125 mmHg) which was applied.<sup>[16,17]</sup>

AOP is the minimal pneumatic tourniquet inflation pressure required to stop arterial blood flow into a limb and is determined by slow cuff inflation to pulse cessation with diagnostic equipment such as a Doppler flowmeter or pulse oximeter.<sup>[18-20]</sup> Previous studies showed that AOP is strongly correlated with SBP and limb girth, and it is recommended to add a safety margin

to AOP in consideration of hemodynamic fluctuations during surgery. Using this method, Klenerman and Hullahs suggested using twice the SBP value as the tourniquet pressure setting.<sup>[18]</sup> Reid et al. used a safety margin of 75 mmHg and reported that a bloodless field was provided at pressures of  $231.0 \pm 26.5$  mmHg for lower extremity surgery.<sup>[19]</sup> The current guidelines of the Association of Perioperative Registered Nurses recommend that a safety margin of 40 mmHg should be added for AOP below 130 mmHg, 60 mmHg for AOP between 131 mmHg and 190 mmHg, and 80 mmHg for AOP above 190 mmHg for adults.<sup>[20]</sup>

Since the AOP determination method requires additional monitoring, an automated tourniquet system was developed to measure AOP and set tourniquet pressure. Using this system, Younger et al. found that 87.5% of patients had “excellent” or “good” operative field with a mean tourniquet pressure of  $198.5 \pm 20.2$  mmHg in lower limb surgery.<sup>[21]</sup> Their mean tourniquet pressures were higher than our results, which may be explained by the addition of a safety margin of 40–80 mmHg to AOP, in accordance with the Association of Perioperative Registered Nurses’ recommendations.

Several studies have suggested using wider tourniquet cuffs, as they transmit a greater percentage of the applied tourniquet pressure to deeper tissues and allow arterial closure at lower pressures.<sup>[22]</sup> Although wider cuffs stop the arterial flow with lower inflation pressures, Mittal et al. found that wider cuffs impair nerve conduction more severely than narrower cuffs.<sup>[23]</sup> Moreover, in a prospective randomized study with 14 healthy volunteers, Kovar et al. found no differences between narrow and wide tourniquets.<sup>[24]</sup> Since the tissue padding coefficients were determined using 11-cm wide tourniquet cuffs in the AOP estimation formula, we applied the same size cuff to all our patients in this study.<sup>[25]</sup>

SBP is a manageable factor in tourniquet pressure optimization. Thus, SBP of the patients should be kept as low as possible and maintained throughout surgery. In our previous studies, we used the controlled hypotension and minimal inflation pressure technique, which provided a bloodless field in all patients, with a mean tourniquet pressure of  $169.7 \pm 7.9$  mmHg for lower extremity surgeries and  $118.2 \pm 7.2$  mmHg for upper extremity surgeries, values significantly lower than those previously reported and recommended in the literature.<sup>[26,27]</sup> Those studies showed that anesthetic management is of critical importance in preventing intraoperative hemodynamic fluctuations and allows use of minimal inflation pressures at all times during the surgery. In our study, the surgical team was satisfied with the perfor-

mance of the tourniquet in 97.75% of cases, with mean initial and maximal tourniquet pressures of  $168.4 \pm 14.5$  and  $173.3 \pm 15.6$  mmHg, respectively. One of the main factors that allowed for lower inflation pressures in our study was the utilization of the AOP estimation method, which provided quick and accurate results. Another factor was our safety margin of 20 mmHg, which is lower than recommendations in the literature. Finally, the anesthetic management allowed for hemodynamic stability. Regional (spinal, combined spinal epidural) or general anesthesia was administered in 92.8% and 7.2% of cases, respectively, and maximal SBP of the patients was only 4.8% higher compared with initial SBP values ( $103.5 \pm 10.4$  vs  $98.7 \pm 9.6$ , respectively). In 3 patients, the surgical team rated the surgical field as “fair” at the start of the operation. Two of those patients were rated as “fair,” and 1 of them was rated as “excellent” in the middle of the operation. The surgeon observed that the amount of blood did not adversely affect the quality or duration of the surgical procedures. Since the presence of blood in the surgical area lasted for 4–7 minutes and disappeared spontaneously, inadequate exsanguination is thought to be the probable cause in these cases. Moreover, these 3 patients were operated for bone fracture repair. Thus, another possible reason is that the blood came from the hematoma at the fracture site. Two patients were rated as “poor” at the start of operation by the surgeon. In both cases, a significant amount of blood obscured the view of the surgical field. The tourniquet cuffs under the surgical drapes were checked and found to be non-inflated. Operations of these patients were performed without tourniquet. After the operations, the tourniquet cuffs were found to be damaged, and this was recorded as equipment failure.

Recently, a new adaptive pneumatic tourniquet system which automatically adjusts tourniquet inflation pressure in synchrony with the patient’s SBP has been developed. Using these new adaptive systems, Ishii, et al. obtained excellent bloodless field in nearly all patients undergoing foot and ankle surgeries.<sup>[28,29]</sup> Nevertheless, the mean maximal tourniquet inflation pressures were  $233 \pm 18$  and  $235 \pm 27$  mmHg in Ishii’s studies, which are higher than our results.<sup>[28,29]</sup> The main reasons of these high inflation pressures were the additional pressure of 100 mmHg added to SBP, the SBP changes during the surgical procedures, and the mean maximal change of  $28 \pm 13$  and  $33 \pm 22$  mmHg in SPB during tourniquet periods. Moreover, the blood pressure measurement was set to cycle automatically with 2.5 min intervals in their tourniquet system.<sup>[28,29]</sup> Since nerve injuries due to automatic blood pressure monitors have been reported with

even 3 min intervals, the extremity in which the non-invasive blood pressure measurements are performed might also be a risk factor.<sup>[30]</sup>

In conclusion, clinical utilization of the AOP estimation method allows rapid and accurate estimation for optimizing tourniquet inflation pressure settings. The bloodless surgical field was maintained with lower inflation pressures than those recommended in the current literature for lower limb surgery. Maintenance of hemodynamic stability is paramount, regardless of the method utilized to achieve it, and the practice of using a high safety margin leading to high inflation pressures should be replaced with evidence-based levels in order to avoid subjecting the patient to unnecessary complications of pneumatic tourniquet application.

**Conflicts of Interest:** No conflicts declared.

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