Surgical Hemostasis by Pneumatic Ankle Tourniquet During 3027 Podiatric Operations

A retrospective study was performed at the Denver Doctors Hospital in which 3818 surgical cases on the foot and/or ankle were reviewed over a 4-year period from July 1986 through May 1990. From the 3027 ankle tourniquet cases reviewed, it was determined that pneumatic ankle tourniquets are safe and effective in providing hemostasis during foot surgery. There were five postoperative complications noted with ankle cuffs, with post-tourniquet syndrome being the most common (three cases). Over the 4-year period, ankle tourniquets failed a total of 50 times, a 1.8% failure rate (0.25% failure rate in the last 17 months). The most common pressure setting used for ankle cuffs was 325 mm. Hg (400 mm. Hg for thigh cuffs). Tourniquet ischemia lasted from 4 to 139 min.; the most common duration of ischemia noted for ankle tourniquets was 30 to 60 min. (60 to 90 min. for thigh tourniquets). A review of the potential complications associated with tourniquets, as well as safeguards, recommendations, and contraindications are presented.

Richard Derner, DPM, FACFAS[1,2]
John Buckholz, DPM, FACFAS[2]

Historically, the use of a pneumatic tourniquet is common practice in surgery on the extremities. The application was first described in 1904 by Harvey Cushing (1). Its function, to provide a bloodless field, is now an essential feature for performing precise, highly technical operative procedures. Pneumatic tourniquets, when applied correctly and used properly, can provide an excellent method of hemostasis.

The application of distally placed pneumatic tourniquets on the lower extremity has been a controversial topic for many years. Throughout the literature, opinions concerning the efficacy and safety of distally placed pneumatic tourniquets have been freely stated, but little or no concrete evidence offered to substantiate these claims. In 1962, Klenerman stated, "Distally placed tourniquets, such as those around the ankle are unsafe because of lack of soft tissues, and are best avoided" (2). In 1973, Sanders wrote that he felt the tourniquet should be applied to the limb which is of maximum circumference, in which the area is well-padded with periosseous muscle (3). He recognized the importance to limit ischemia but added that in his opinion, "safety overrules convenience." Sanders further stated "tourniquets should never be applied distal to the knee or elbow." He theorized that "the circumference of the distal part of the limb is too small, and the nerves are too vulnerable to localized high pressures for a tourniquet to be applied there" (3).

An editorial in the 1973 *Canadian Medical Association Journal* (4), as well as Stewart (5), emphasized the need to protect the nerves and vessels by muscle bulk in order to avoid compression against bone. According to Stewart, "The correct site in the upper limb is around the arm and in the lower limb, around the upper thigh." These authors all propose the need for pneumatic tourniquets to be placed above well-padded tissues in order to protect vital structures. Unfortunately, no documented scientific evidence has been demonstrated to confirm these statements.

There are also theoretical arguments regarding the potential harm in the distally applied cuff. For example, fracture of the thin fibula, compared with the larger tibia, may occur with overinflation or poor positioning of the tourniquet. Rupture of the distal tibiofibular syndesmosis also may result from poor tourniquet application. In addition, the leakage of arterial blood flow by a perforating vessel (*i.e.*, perforating peroneal artery) can result in poor hemostasis and thus failure of the distally placed pneumatic tourniquet.

In contrast, several authors have advocated the use of ankle tourniquets in foot surgery. Mullick performed a study on 74 patients, 106 feet, using an arm-sized tourniquet placed on "the lowermost part of the tibia"

From the Department of Podiatric Surgery, Doctors Hospital, Denver, Colorado.
[1] Address correspondence to: 1718 Financial Loop, Lake Ridge, VA 22192.
[2] Diplomate, American Board of Podiatric Surgery.
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(6). Periods of ischemia lasted up to 75 min. Mullick concluded the low-leg tourniquet is safe, satisfactory, and avoids unnecessary ischemia.

In 1981, Chu *et al.* performed sensorimotor evaluations on 40 patients, using the pneumatic ankle tourniquet (7). Their results demonstrated that the effects on nerve function during tourniquet application were secondary to ischemia and anoxia, rather than to mechanical compression. With these findings, Chu *et al.* felt that the ankle tourniquet may be as effective and less traumatic than tourniquet application on the thigh. With these two very different viewpoints in mind, it is the goal of this article to use a retrospective study to demonstrate scientifically the efficacy and safety of the distal-placed (ankle) pneumatic tourniquet.

Complications of Tourniquets

Prior to applying a pneumatic tourniquet, the surgeon must be fully aware of the potential hazards associated with its use. Many articles have been dedicated to this subject alone. The complications of tourniquets can be divided into three categories: first, the effect of ischemia on cellular metabolism; second, sequelae produced by the effects of pressure, compression, or constriction; and third, problems associated with burns from tourniquet use.

Ischemic Effects

Muscle is considered to be the most vulnerable tissue when subjected to ischemia (8). The length of time a muscle is exposed to ischemia is directly proportional to the amount of muscle disruption which takes place. Therefore, it seems obvious that limiting the amount of tourniquet-induced ischemia a patient undergoes will indeed decrease the number of all complications produced by the tourniquet, including those involving muscle tissue.

Sapega *et al.* suggested two distinct forms of ischemia-induced muscle injury: a primary and a secondary injury (9). A primary muscle injury is considered to be an acute injury to the cell and related to the immediate metabolic insult. Such common findings as focal myofibril degeneration and cell necrosis occur with approximately 2 to 3 hr. of ischemia.

If the tissue damage from the primary injury to the muscle is severe, secondary muscle injury results. Microvascular congestion and autolysis of muscle, for example, do not present immediately with tourniquet ischemia, but develop slowly after tourniquet release and, therefore, are considered secondary forms of muscle injury. Prolonged use of a pneumatic tourniquet can produce myoglobinurea, a product of muscle breakdown, within the urine (10).

Tourniquet ischemia may also produce post-tourniquet syndrome, or post-ischemic hand syndrome, a term coined by Brunner (11). This complication presents with a nonpitting edema of the extremity, stiffness, pallor, weakness of muscles without paralysis, and sensations of numbness without true anesthesia (9, 11, 12). Most of these symptoms disappear within 1 week of surgery, but the edema may last a month or more postoperatively.

Sapega, as well as Brunner, felt the incidence of post-tourniquet syndrome increased with operations in which the tourniquet was inflated for a long period of time and no "breathing period" was used (9, 11). Muscle, being the most sensitive tissue to ischemia, is severely affected in this syndrome. This prolonged ischemia not only results in muscle cell deterioration, calcium ion disturbances, cell and mitochondrial damage, but also subsequent edema and postoperative muscle weakness (14–22).

It has also been recognized that compartment syndrome can occur with the use of pneumatic tourniquets (23–25). Compartment syndrome can be defined as an increase in pressure within a confined osseofascial space. The resultant vicious cycle of edema and ischemia, if uninterrupted, may lead to necrosis of muscle and the development of deforming contractures of the affected part (23).

Ischemia and edema must be present for compartment syndrome to ensue. Ischemia results from the external pressure produced by the tourniquet upon the different compartments. The production of edema distal to the tourniquet is directly related to the duration of ischemia. Edema must be produced in a significant quantity to initiate the vicious cycle that produces compartment syndrome.

The edema is a sequela of an alteration in the permeability in muscle capillary membranes. This causes an increase in fluid and intracompartmental pressure. The increase in edema may result from repeated episodes of inflation and deflation, which do not allow full recovery of the ischemic tissues.

Ischemia produced by the pneumatic tourniquet also produces an environment which an be detrimental to patients with sickle cell disease and sickle cell trait. This red blood cell disorder in combination with the decrease in pH, leading to acidosis, circulatory stasis, and low oxygen concentration, can precipitate a sickling of the red blood cell, resulting in a vaso-occlusive crisis, as well as other sickle cell manifestations (26, 27). The patient with sickle cell disease (homozygous form) as opposed to sickle cell trait (heterozygous form) is more sensitive to a lower oxygen tension, and would consequently be more prone to sickling of the red blood cell. Theoretically, the patient with the sickle cell disease would be more prone to complications than the sickle cell trait patient (28).

Systemic reactions observed from tourniquet ischemia are relatively rare. Noncardiac circulatory overload, which is defined as an increase in blood volume secondary to excess salt and water retention, excess blood or fluid administration, acute glomerulonephritis, oliguria, or anuria, has occurred in relation to the use of pneumatic tourniquets. Using bilateral thigh tourniquets, Maurer *et al.* noted a phenomenon similar to the Bainbridge reflex (29). This reflex is defined as a sudden rise in heart rate with the rapid induction of blood or saline into anesthetized animals (circulatory overload). To avoid this phenomenon, the authors suggested limiting the time of bilateral thigh cuffs and switching to ankle tourniquets to complete the procedures.

Pressure/Compression/Constriction Effects

The most common complication associated with pressure or compression is tourniquet paralysis syndrome. This term was first used by Moldaver (30) in 1954, but dates back approximately 100 years prior. Since the advent of the pneumatic tourniquet, the incidence of tourniquet paralysis syndrome has decreased significantly and is today almost nonexistent. The term tourniquet paralysis syndrome can be defined as an abnormality in the function of peripheral nerves distal to the site of the tourniquet application. This results in the loss of motor function, touch sensation, vibration and position sense and the inability to discern light pressure. The ability to determine warm and cold sensations, pain, and sympathetic function are not lost during the paralysis syndrome (30–33).

The symptoms of tourniquet paralysis syndrome may last from a few days to 3 to 5 months. The duration is related to the severity of the injury. Those few cases that last longer demonstrate muscle atrophy, in addition to the symptoms previously mentioned (34, 35).

The etiology of tourniquet paralysis syndrome, which at present seems to be excessive pressure on the affected nerve, was once thought to be ischemia (36–42). Ochoa *et al.* demonstrated and proved that the damage to nerve fibers was a result of applied pressure and was not secondary to ischemia (43). With the aid of an electron microscope, it was shown that the primary lesion caused by compression of the large myelinated fibers was a displacement of the node of Ranvier from its normal position. The nodes of Ranvier were displaced away from the cuff and toward the uncompressed tissue.

Additionally, cases of tourniquet paralysis syndrome resulting from the use of tourniquets with faulty gauges have also been documented. For example, Flatt studied 1500 cases and noted only two complications (44). Both complications were diagnosed as tourniquet paralysis syndrome and were secondary to faulty gauges. Hamilton and Sokoll (45) and Prevoznik (46) warned of this problem as well, and they suggested the routine examination and recalibration of the tourniquet pressure gauges.

Pneumatic tourniquets have also been considered a cause of deep vein thrombosis. However, knowing the multifactorial etiology of deep vein thrombosis, namely, disruption in normal blood flow, an aberration in the coagulation process, and changes in the vascular endothelium, it is difficult to suggest, demonstrate, or prove that this postoperative complication resulted from tourniquet ischemia (47). Studies have also been performed that describe a possible decrease in the incidence of deep vein thrombosis and an increase in post-tourniquet bleeding in patients on whom a tourniquet was applied (48–52). At the present time, there is no scientific evidence that tourniquets increase the incidence of deep vein thrombosis (47, 53).

On the other hand, if a patient has a history of deep vein thrombosis, one must be cognizant of the potentially fatal sequela of pulmonary embolism which can occur with tourniquet use. More precisely, the Esmarch[3] bandage can cause (and has caused) this rare but disastrous complication (54–60). According to McClaren and Rorabeck, the Esmarch bandage can produce pressures in excess of 1000 mm. Hg directly under the tourniquet (58). Middleton noted a pressure of 710 mm. Hg was obtained with only six turns of the Esmarch bandage (59). Furthermore, Hofmann and Wyatt pointed out both the Esmarch bandage and the pneumatic tourniquet create a pressure gradient that results in the initiation of a sudden increase in the velocity of the venous blood flow capable of disturbing a preexisting thrombus (57).

Vascular complications associated with the pneumatic tourniquet are rare but have been related to compression by a tourniquet. Although not widely recognized, arterial spasms and acute arterial occlusion can occur with use of the tourniquet (2, 49, 61, 62). Klenerman noted arterial spasms result secondary to long periods of tourniquet ischemia, leading to poor control of the muscular layer surrounding the blood vessels (2). Clinically, one sees a white, cold digit(s) which can last for several minutes or possibly longer. However, an arterial occlusion is usually caused secondary to the disruption of atheromatous plaque at or distal to the tourniquet site. This is a medical emergency and could possibly result in the loss of the part affected.

Lastly, tourniquet compression can produce a muscle rupture secondary to its constriction (63). A muscle rupture was diagnosed in the lower extremity in a young athlete undergoing foot surgery. A tourniquet was

[3] Davol Inc., Providence, RI.

placed around the thigh of the patient and the medial hamstring subsequently ruptured upon inflation of the tourniquet.

Tourniquet-Related Burns

The burning of skin beneath the site of a pneumatic tourniquet is considered to be a very rare complication. Several authors have briefly mentioned this phenomenon (64–67). Some have correlated this problem to the use of tourniquets with children (67). The condition was thought to be "caused by spirit solutions seeping beneath tourniquets and being held tightly against the rather delicate skin of the children" (67). Dickinson and Bailey thought that the burns resulted from the use of a povidone-iodine skin preparation which contained 70% alcohol (65).

The tourniquet burns appear to be related to the concentration of alcohol or spirit within the skin preparations and, quite possibly, to the texture of the patients' skin. High concentrations of alcohol or spirit in skin preparations are present for their bactericidal activity as well as for their effectiveness as a degreasing agent, allowing the increased penetration of the povidone-iodine (65). Fortunately, most preparations used today are equally as effective and do not contain large concentrations of alcohol or spirit.

Materials and Methods

From July 1986 through May 1990, 3027 pneumatic ankle tourniquets were used on 2729 patients undergoing foot and/or ankle surgery. These surgical procedures were all performed at one institution, the Denver Doctors Hospital. The medical records of all lower-extremity surgical cases involving a pneumatic tourniquet were examined. The following data were obtained from these charts: tourniquet placement (ankle or midthigh), tourniquet sterility (sterile *versus* nonsterile), pressure of the tourniquet, duration of inflation (in minutes), site of the tourniquet (right, left, or bilateral), type of padding used under the tourniquet, whether there was an episode of deflation followed by reinflation during the operation, time interval between this deflation and reinflation, surgical procedure performed, age and sex of the patient, type of anesthesia administered (local with intravenous sedation, general, or spinal), whether tourniquet failure occurred, and name of the physician involved with the surgery.

The sterile pneumatic tourniquets were used one time only and never resterilized. The tourniquet was applied on the extremity after the surgical scrub was performed. A 4-inch sterile bandage roll was used for padding underneath the sterile tourniquets. Cast padding (nonribbed) was applied under the nonsterile tourniquets.

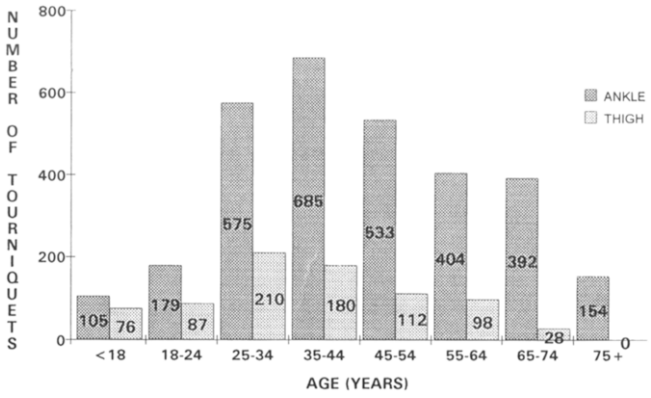

Figure 1. Distribution of surgical procedures performed related to the different age groups and tourniquet placement (ankle *versus* thigh). Note the procedures performed over the age of 75 (all ankle cuffs).

Failure of the pneumatic tourniquet was defined as an inability to achieve hemostasis at a pressure setting at least 100 mm. Hg above the patient's systolic blood pressure.

Once these results were calculated, all of the physicians were contacted and they completed a detailed questionnaire. This questionnaire described the potential complications associated with the tourniquet (*i.e.*, tourniquet paralysis syndrome, compartment syndrome, burns, etc.). Each physician was given a list of his/her patients broken down into the years of the study (1986 to 1990). The charts of the patients involved in the study were reviewed by each physician, and the results of all complications were tabulated.

Results

A total of 3115 patient charts were reviewed from July 1986 through May 1990. From this, 3818 extremities using either an ankle or thigh tourniquet were evaluated. Of the 3115 patients, 2364 were female and 751 were male, a 3.1:1 female-to-male ratio. Age ranged from 2 years to 91 years (Fig. 1). Tourniquets were used on 2037 right extremities and on 1781 left extremities. Seven hundred ninety-one thigh tourniquets were used on 685 patients. This resulted in 107 bilateral operations and 577 unilateral operations. Ankle tourniquet cases totaled 3027, including 596 bilateral operations and 2431 unilateral operations. Two thousand seven hundred fifty-five tourniquets were sterile and 272 were nonsterile reusable tourniquets. Figure 2 provides the numbers of ankle and thigh tourniquets applied from July 1986 through May 1990.

The pneumatic ankle tourniquet pressure setting averaged 310.52 mm. Hg. The pressure setting used most often for the ankle tourniquet was 325 mm. Hg (1297 times). Thigh tourniquet pressure averaged 398.39 mm.

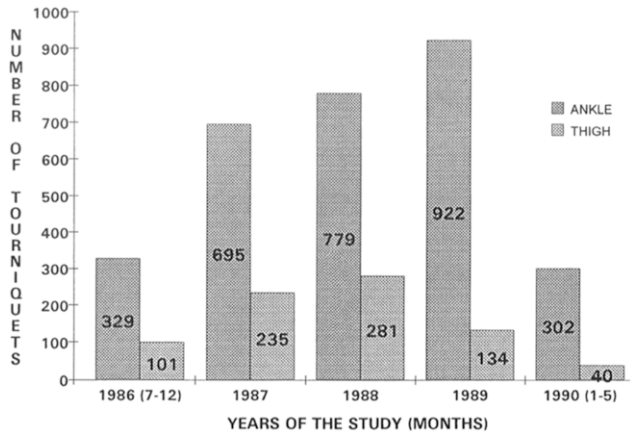

Figure 2. Number of ankle *versus* thigh tourniquets applied from July 1986 through May 1990.

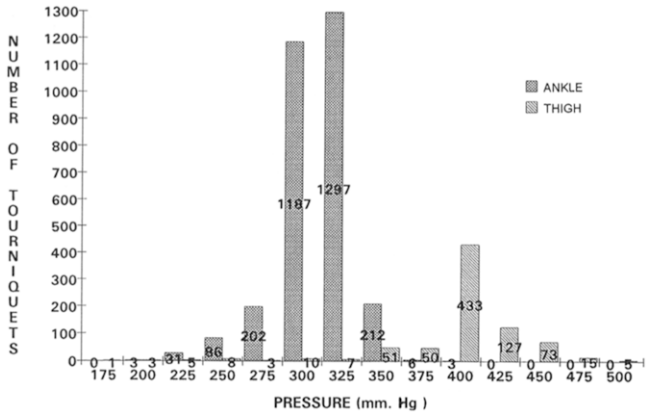

Figure 3. Range of pressure used for both the ankle and thigh tourniquets.

Hg and was most commonly set at 400 mm. Hg (433 times). The ankle tourniquet ranged between 200 and 400 mm. Hg and the thigh tourniquet ranged from 175 to 500 mm. Hg (Fig. 3).

The duration of ankle tourniquet ischemia extended from as short as 4 min. to as long as 139 min. The ischemic episode for thigh tourniquets ranged from 10 min. to 136 min. Ankle tourniquet ischemia most often lasted between 30 and 60 min., and the most common time period for the thigh tourniquet was between 60 and 90 min. Figure 4 demonstrates the duration of ischemia in 15-min. increments for both the ankle and thigh tourniquets.

The initial inflation of the tourniquet followed by a deflation/reinflation episode took place 80 times for the ankle tourniquet (2.6%) and 19 times for the thigh cuff (2.4%). Fifty of these episodes were directly related to failure of the sterile ankle tourniquet. The need for a breathing period resulted in the remaining 49 episodes. The average breathing period used for the ankle cuff was 6.0 min. (32 extremities), and ranged from 1 to 26 min.

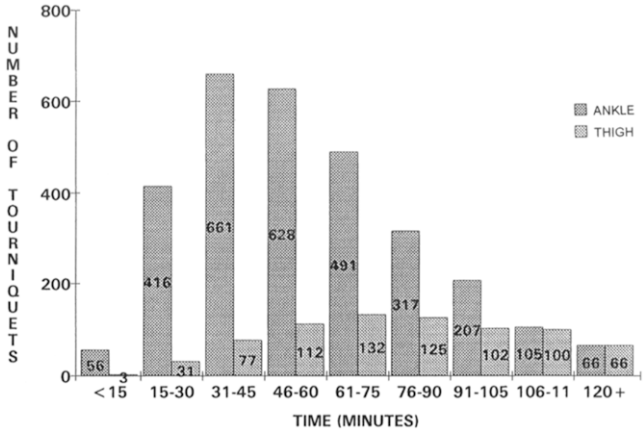

Figure 4. Duration of ischemia for the ankle and thigh tourniquets related to the different time increments.

The 17 thigh tourniquets averaged 20.5 min. for a breathing period and ranged from 1 to 70 min.

Local anesthesia, either alone or in combination with intravenous sedation, was used 2788 times with ankle tourniquets and only once with the thigh cuff. General anesthesia was administered 238 times in combination with the ankle tourniquet and 785 times with the thigh tourniquet. Spinal anesthesia was administered once with an ankle tourniquet and five times with thigh tourniquets.

As previously discussed, tourniquet failure was seen 50 times. This was associated only with the use of sterile pneumatic ankle tourniquets. However, in the last 2 years of the study, the Denver Doctors Hospital changed to a sterile tourniquet (the Zimmer[4] Banana Cuff) manufactured by a different company, and a significant improvement was seen, with a resultant drop in the number of failures (Fig. 5).

Of the 56 physicians accounting for all 3115 patients in this study, 45 were able to be contacted, resulting in a study of 3077 patients. From the 3027 extremities with an ankle tourniquet, 3008 were able to be evaluated. A total of five complications were noted. Three of the complications were diagnosed as post-tourniquet syndrome. In all of these cases, the symptoms of muscle weakness, pallor, nonpitting edema, stiffness, and sensations of numbness were transient and lasted less than 1 week postoperatively. No long-term sequelae were seen in this group of patients. One patient developed sickle-cell related problems postoperatively. Initially, a cold, exquisitely painful foot was noted, and this gradually resolved. The persisting edema, also seen initially, disappeared approximately 4 months afterward. Finally, a deep vein thrombosis was diagnosed in one case in which an ankle tourniquet was used. Several days after surgery,

[4] Zimmer Inc., P.O. Box 708, Warsaw, IN 46581-0708.

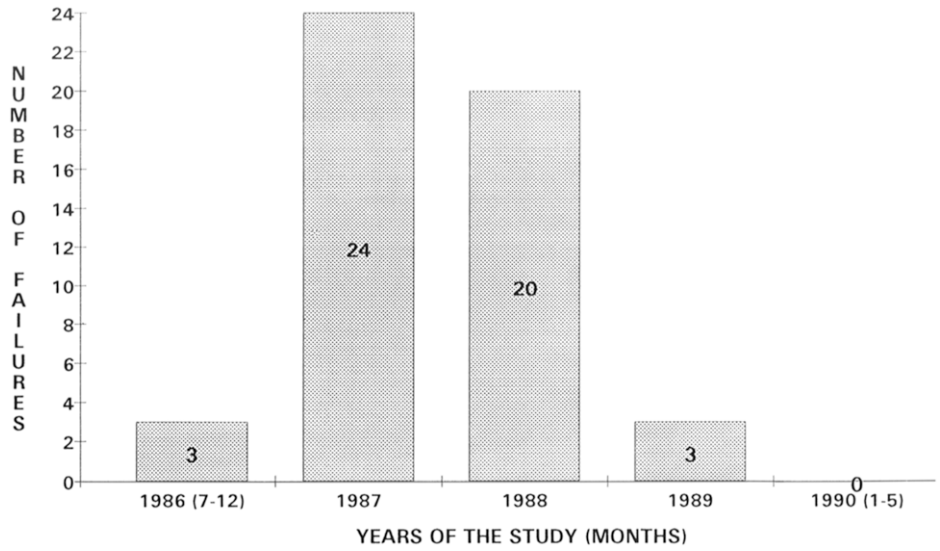

Figure 5. Demonstration of tourniquet failures related to the years of the study. Note the reduction of failures in 1989 and 1990. This is a direct result of proper fit and better design of the tourniquet.

the deep vein thrombosis was diagnosed. Aggressive treatment with urokinase was subsequently implemented.

Neither the ankle nor the thigh tourniquet produced any cases of tourniquet paralysis syndrome, compartment syndrome, muscle rupture, systemic complications, pulmonary embolism, or myoglobinurea in our series. The thigh tourniquet did produce three cases of post-tourniquet syndrome. These symptoms were also short-lived, with no long-term sequelae noted. A breathing period was utilized in one of the two cases involving the thigh tourniquet, resulting in post-tourniquet syndrome. Finally, it was noted that significantly long periods of tourniquet ischemia (2 hr. or more) resulted in all of the reported cases of post-tourniquet syndrome.

Discussion

For several years, foot surgeons have used pneumatic ankle tourniquets while performing foot and ankle surgery. Absence of documented proof of ankle cuff safety has led to this present study. Several articles have stated that distally placed cuffs are dangerous because they lack soft tissue coverage of the vital structures (2–5). This finding, however, has never been proven in a scientific manner, but rather has been argued theoretically. It is the finding of this study, by evidence of the small number of complications noted, that ankle tourniquets are a safe method of hemostasis for foot and ankle surgery.

If, for example, soft tissue coverage was crucial for ankle tourniquet safety, pressure-related complications would have occurred frequently. To the contrary, in fact, tourniquet paralysis syndrome did not occur once in this study. Other pressure-related complications (*i.e.*, deep vein thrombosis, vascular complications, and muscle rupture) were also very rare findings in this series of 3818 extremities reviewed.

In addition to its safety, the pneumatic ankle tourniquet has been proven to be an effective means of providing hemostasis. The nonsterile ankle tourniquet was used 272 times without one failure. There were 2755 applications of sterile tourniquets with only 50 failures. This resulted in a failure rate of 1.8%. From January 1989 to May 1990, there was a total of 3 failures with 1223 sterile ankle tourniquets used, resulting in a reduced failure rate of 0.25% for that time. The reduction in failure with the sterile tourniquet was noted to be related directly to changing cuff manufacturers. The Zimmer Banana Cuff tourniquet gave more predictable hemostasis because of the technical improvements made over the devices initially used in the study.

Importantly, a larger sterile field is created, improving asepsis, with sterile pneumatic ankle tourniquets. Specifically, these devices can be employed when surgical procedures are performed on the rearfoot, where there is close proximity between the surgical site and the tourniquet. To date, there has been no study relating the number of infections with the sterile *versus* the unsterile tourniquet, but one would suspect that sterile ankle tourniquets could only decrease the number of potential infections. Therefore, if at all possible, sterile ankle tourniquets should be used when performing rearfoot surgery. Unfortunately, cost must be considered when a sterile tourniquet is selected. These devices can only be used once and must be discarded afterward.

Because this study involved a large number of physicians, results could not be standardized, leading to the

possibility of error and a higher incidence of complications than actually recorded. However, the large number of cases reviewed gives more than ample evidence regarding the safety and efficacy of ankle tourniquets. The data presented overshadow the large number of physicians questioned and the variability that can sometimes result.

In this series, the most common complication encountered was post-tourniquet syndrome (7 cases). The classic findings of stiffness, pallor, nonpitting edema, muscle weakness, and numbness were all initially present postoperatively, and all resolved within 1 week. Muscle weakness was most notable with the thigh tourniquet. These patients were unable to bear weight on the affected extremity until this symptom had disappeared. Fortunately, none of the patients in the study developed the severe muscle atrophy that can occur from post-tourniquet syndrome.

Post-tourniquet syndrome may have easily gone undiagnosed, and therefore under-reported because of the symptoms associated with this complication. For example, the finding of postoperative edema could have been caused by several factors. Poor tissue handling, poor patient compliance, hematoma, the nature of the procedure itself, and post-tourniquet syndrome might all demonstrate significant edema postoperatively. In addition, injections of local anesthesia are capable of producing the sensations of numbness that mimic post-tourniquet syndrome. This problem must be looked for closely or it may go unnoticed by the surgeon.

Since post-tourniquet syndrome is a result of ischemia and is not caused directly by excessive pressure of the tourniquet, the duration of tourniquet use should be minimized if at all possible. The tourniquet provides an unphysiologic atmosphere for all the involved tissues; therefore, no time is considered to be "safe." All preoperative skin markings, in addition to a determination for "true" local anesthesia (if applicable), should be made prior to elastic-wrap exsanguination and pneumatic tourniquet inflation.

The duration of tourniquet ischemia has varied according to the literature, and no specific time limit has been determined. A time period as short as 30 min. and as long as 3 hr. has been proposed (9, 11, 16, 19, 44, 53, 54, 68–75). In 1951, Brunner wrote that 1 hr. of ischemia was safe for healthy adults (11). Wilgis, using 50 patients, wrote that 2 hr. should be used as an upper limit for tourniquet ischemia, and that more time would result in muscle fatigue (19). He also stated the tourniquet should be deflated for 15 to 20 min. for every 2 hr. inflated.

In more recent studies, 3 hr. of tourniquet ischemia was proposed as being "safe." Santavirta *et al.* determined, using rabbits, that a tourniquet time up to 3 hr. induced only sublethal damage to skeletal muscle (74). Using rhesus monkeys, Patterson *et al.* also felt that 3 hr. was close to the upper limit for which a muscle can resist the tourniquet (16, 73). They also demonstrated that the muscle directly under the tourniquet underwent more severe changes than muscle distal to the cuff.

With respect to reinflation, Sapega *et al.* (9) and Newman (68) both used NMR spectroscopy to study the intracellular events of muscle tissue in relation to tourniquet time. Newman questioned the use of venous blood results as an accurate measure for cell activity. According to his findings, the 10-min. breathing period prevented the depletion of adenosine triphosphate within the cells and, therefore, was able to provide enough chemical energy for the metabolic demands to be met.

Sapega *et al.* (9) used canine limbs for their experimental work. They felt this gave results closer to those of humans. In their study, they discovered that if a tourniquet time of 3 hr. is needed, it was best to inflate first for 1½ hr. and deflate for 5 min. (the breathing period) and finally reinflate for another 1½ hr.

One fact remains apparent when reviewing these studies, namely, the inability to determine the point at which human tissue is not going to return to its preischemic condition. Brunner pointed out that some patients may demonstrate a high degree of tolerance to ischemia (11). If this is true, the time limit for tourniquet use may vary from individual-to-individual not only species-to-species.

It is the present authors' experience that 2 hr. as an upper time limit for the lower extremity has resulted in very few complications. Problems have arisen, however, with use of a "breathing period." Therefore, one should try to avoid a number of inflation, deflation, or breathing period episodes, if possible. If avoidance of these episodes is not possible, the deflation of the pneumatic cuff at the 2 hr. interval and reinflation after 10 min. is recommended. This second ischemic period should not last more than 1 hr. In conjunction with this procedure, placement of the tourniquet on the ankle will limit the amount of ischemia and potential postoperative sequelae. This should prevent post-tourniquet syndrome and the other well-recognized manifestations associated with prolonged tourniquet use.

Sickle cell manifestations were also experienced by one patient during the tourniquet study. This problem could have resulted in more serious loss to the patient than the relatively mild symptoms encountered. Although studies by Martin *et al.* (26) and Stein and Urbaniak (76) do not suggest an increased risk of complications with tourniquets in sickle cell patients, it is possible for such a problem to arise. It seems the risk for the sickle cell patient is unknown regarding the development of symptoms during a surgical procedure involv-

ing a tourniquet. Surgery itself may produce situations that place patients with sickle cell at a higher risk. Therefore, it is the authors' opinion that until a device is produced to determine the exact susceptibility of the sickle cell patient, a tourniquet should be avoided, and the surgery should be performed in a wet manner.

Lastly, in this series, one patient developed a deep vein thrombosis postoperatively. As explained earlier, it is very difficult to correlate deep vein thrombosis with the use of tourniquets. In addition, the patient involved had a history significant for tobacco use and was taking oral contraceptives, two significant risk factors for deep vein thrombosis. These two factors, in combination with the elements causing deep vein thrombosis, made it difficult to correlate this case of deep vein thrombosis with tourniquet use.

Tourniquet Safeguards

Due to the potential complications associated with tourniquets, several recommendations are presented. First, the pneumatic ankle tourniquet used today for the adult should be approximately 4 inches in width and 18 to 22 inches in length. This provides adequate surface area underneath the tourniquet to evenly distribute pressure produced by the cuff. For proper fit, the tourniquet should overlap 6 to 8 inches. This overlapping of the tourniquet, as with a blood pressure cuff, produces a more accurate reading of the pressure gauge, subsequently reducing the number of failures. For example, pediatric tourniquets were routinely used in our study in 1987 and 1988, resulting in a high number of failures (Fig. 5). In addition, the conical shape of the distal lower extremity usually necessitates a gentle curve to the cuff to enhance proper fit of the tourniquet.

Second, placement of the tourniquet at the ankle should be immediately proximal to the malleoli. Initially, padding is applied without wrinkles 4 to 6 layers thick distal to the malleoli, and 6 to 8 inches proximal. To potentiate soft tissue coverage, the tourniquet's distal edge should be at or immediately proximal to the most prominent points of the medial and lateral malleolus.

To enhance visualization, exsanguination of the extremity must be performed prior to ankle tourniquet inflation. This is accomplished either by elevation of extremity for 3 min. at 60 degrees or by the use of an Ace[5] wrap applied from distal to proximal (sterile Ace wraps are used when sterile tourniquets are applied). The Esmarch bandage is not recommended for this purpose. The type of pressure applied by the Esmarch bandage may not only damage skin, nerve, or muscle but, as Mullick pointed out, can cause a harmful shearing force which may possibly dislodge a thrombus (54). It has resulted not only in pulmonary embolism, but also the splitting of skin and damage to deeper structures (54). The authors have found a sterile Ace wrap to be an excellent means of exsanguination, whether it be for the ankle or thigh tourniquet. So far, this has not been shown to cause any unwanted effects such as those of the Esmarch bandage.

It is recommended that the duration of ischemia produced by the ankle tourniquet not exceed 2 hr. This 2-hr. time restriction is based on reviewing the large number of surgical cases, within and around the 2 hr. time limit, and noting very few complications. Although 3 hr. of tourniquet ischemia has been suggested (71–73), it is the authors' opinion that further research and data should be obtained before considering this length of time as "safe" for tourniquet ischemia.

It is better, on the other hand, to extend the ischemic episode by 5 to 10 min. past 2 hr. than to deflate the tourniquet and reinflate after a breathing period. Again, a breathing period is best avoided. If necessitated, the breathing period should last no less than 10 min., and reinflation of the tourniquet should not exceed 60 min.

Ankle tourniquet pressure is the next parameter to be mentioned. Several authors have suggested the addition of 70 to 100 mm. Hg to the patient's systolic blood pressure as the proper setting for a pneumatic tourniquet (76). A particular study also used a Doppler stethoscope to determine adequate ankle tourniquet pressure, and determined the maximum safe tourniquet pressure was 250 mm. Hg (77). This information, however, should be tempered with the results of the present study demonstrating an average safe ankle tourniquet pressure setting of 310 mm. Hg.

All papers on this subject propose the use of as little pressure as possible to achieve hemostasis. Although this statement is true, more than just the patient's systolic blood pressure should be considered for proper tourniquet pressure setting. The circumference of the extremity, quantity of soft tissue present, quality of the skin and soft tissue, age of the patient, type of tourniquet (ankle, thigh, sterile, unsterile), fit of the tourniquet, type and quantity of padding used, and systolic blood pressure of the patient must all be examined before determining the correct ankle (or thigh) tourniquet pressure. Therefore, the setting of ankle tourniquet pressure is patient-specific, and should be at least 100 mm. Hg above the patient's systolic blood pressure. While the present study had an average tourniquet pressure of 310 mm. Hg, this is not a specific recommendation but one hospital's considered norm. It is also recommended that no tourniquet pressure setting exceed 500 mm. Hg.

Lastly, there are several contraindications to ankle tourniquet application. The tourniquet should be

[5] Becton Dickinson and Co., Franklin Lakes, NJ 07417-1883.

avoided in patients with poor circulation or vasculitis. Trauma to these vessels by the tourniquet may cause permanent arterial occlusion or the embolization of atherosclerotic plaques. A history of deep vein thrombosis and/or pulmonary embolism also contraindicates tourniquet use. The application of a cuff on a patient with a history of deep vein thrombosis or pulmonary embolism may result in the shearing-off of a clot, causing a potentially fatal pulmonary embolism. Patients who test positive for or have a family history of sickle cell anemia should also avoid tourniquets. This complication could result in potentially severe irreversible sequelae.

Finally, a tourniquet should be placed upon the extremity in a position to create as little ischemia as possible. The best location for the tourniquet is based on the type of procedure to be performed and not the type of anesthesia utilized. For example, a thigh tourniquet is not necessary for bunion surgery on a patient who has opted for general anesthesia, and is best avoided. On the other hand, ankle tourniquets cannot be employed when repairing a ruptured Achilles tendon or for major tendon transfers and therefore, the thigh tourniquet is the only option.

Conclusions

It has been proven that pneumatic ankle tourniquets are safe and effective for foot and ankle surgery. A 2-hr. time limit is suggested for all tourniquets. It is better, though, to exceed 2 hr. by 5 to 10 min. than to use a breathing period. A breathing period, if used, should be 10 min. long, and the second reinflation should not exceed 60 min.

A pressure of at least 100 mm. Hg above the patient's systolic blood pressure should be used. The pressure setting should be individualized and based on the following: quantity and quality of soft tissue present, patient age, type of tourniquet, tourniquet fit and type of padding used, and the patient's systolic blood pressure. The ankle tourniquet is based placed immediately proximal to the medial and lateral malleolus. Padding should always be used, and should be kept wrinkle-free when applied.

The foot should be exsanguinated prior to tourniquet inflation. An Esmarch bandage should be avoided, and a less constrictive Ace wrap is optimal. Post-tourniquet syndrome was the most common complication, with seven total cases observed. Fortunately, none of these cases developed long-term sequelae.

The pneumatic tourniquet should not be used in patients with poor circulation, severe vasospastic disease or sickle cell anemia. In addition, the tourniquet should be avoided in patients with a history of deep vein thrombosis or pulmonary embolism. The use of a tourniquet should be individualized for the procedure to be performed. The ankle tourniquet should be used if at all possible, and the thigh cuff reserved for operations in which use of the ankle tourniquet is not practical.

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References

1. Cushing, H. Pneumatic tourniquets: with special reference to their use in craniotomies. Med. News 84:577, 1904.
2. Klenerman, L. The tourniquet in surgery. J. Bone Joint Surg. 44B:937, 1962.
3. Sanders, R. The tourniquet, instrument or weapon? Hand 5:119–123, 1973.
4. Editorial: The tourniquet, instrument or weapon? Can. Med. Assoc. J. 109:827, 1973.
5. Steward, J. D. M. Tourniquets, ch. 5. In *Traction and Orthopedic Appliances*, pp. 181–189, Churchill Livingstone, Edinburgh, 1975.
6. Mullick, S. Low leg tourniquet. West Indian Med. J. 26:182–186, 1977.
7. Chu, J., Fox, I., Jassan, M. Pneumatic ankle tourniquet: clinical and electrophysiologic study. Arch. Phys. Med. Rehabil. 62:570–575, 1981.
8. Klenerman, L. Tourniquet paralysis. J. Bone Joint Surg. 65B:374–375, 1983.
9. Sapega, A. A., Heppenstall, R. B., Chance, B., Park, Y. S., Sokolow, D. Optimizing tourniquet application and release times in extremity surgery. J. Bone Joint Surg. 67A:303–314, 1985.
10. Williams, J. E., Tucker, D. B., Read, J. M. Rhabdomyolysis-myoglobinurea: consequences of prolonged tourniquet. J. Foot Surg. 22:52–56, 1983.
11. Brunner, J. M. Safety factors in the use of the pneumatic tourniquet for hemostasis in surgery of the hand. J. Bone Joint Surg. 33A:221–224, 1951.
12. Klenerman, L., Crawley, J., Lowe, A. Hyperemia and swelling of the limb upon release of a tourniquet. Acta. Orthop. Scand. 53:209–213, 1982.
13. Haljamae, H., Enger, E. Human skeletal muscle energy metabolism during and after complete tourniquet ischemia. Ann. Surg. 182:9–14, 1975.
14. Dahlback, L. O., Rais, O. Morphologic changes in striated muscle following ischemia. Acta. Chir. Scand. 131:430–440, 1966.
15. Harmon, J. W. A histological study of skeletal muscle in acute ischemia. Am. J. Pathol. 23:551–565, 1947.
16. Patterson, S., Klenerman, L., Biswas, M., Rhodes, A. The effect of pneumatic tourniquets on skeletal muscle physiology. Acta. Orthop. Scand. 52:171–175, 1981.
17. Santavirta, S., Luoma, A., Arstila, A. U. Ultrastructural changes in striated muscle after experimental tourniquet ischaemia and short reflow. Eur. Surg. Res. 10:415–424, 1978.
18. Solonen, K. A., Hjelt, L. Morphological changes in striated muscle during ischaemia. Acta. Orthop. Scand. 39:13–19, 1968.
19. Wilgis, E. F. Observations of the effects of tourniquet ischemia. J. Bone Joint Surg. 53A:1343–1346, 1971.
20. Farber, J. L., Chien, K. R., Mittnacht, S. The pathogenesis of irreversible cell injury in ischemia. Am. J. Pathol. 102:271–281, 1981.

21. Strock, P. E., Majno, G. Vascular responses to experimental tourniquet ischemia. Surg. Gynecol. Obstet. 129:309–318, 1969.
22. Strock, P. E., Majno. G. Microvascular changes in acutely ischemic rat muscle. Surg. Gynecol. Obstet. 129:1213–1224, 1969.
23. Greene, T., Louis, D. S. Compartment syndrome of the arm - a complication of the pneumatic tourniquet. J. Bone Joint Surg. 65A:270–273, 1983.
24. Heppenstall, R. B., Scott, R., Sapega, A., Park, Y. S., Chance, B. A comparative study of the tolerance of skeletal muscle to ischemia. J. Bone Joint Surg. 68A:820–827, 1986.
25. Luk, K. D. K., Pun, W. K. Unrecognized compartment syndrome in a patient with tourniquet palsy. J. Bone Joint Surg. 69B:97–99, 1987.
26. Martin, W. J., Green, D. R., Dougherty, N., Morgan, D., O'Heir, D., Zarro, M. Tourniquet use in sickle cell disease patients. J. A. P. M. A. 74:291–294, 1984.
27. Willinsky, J. S., Lepow, R. Sickle cell trait and use of the pneumatic tourniquet. J. A. P. M. A. 74:38–41, 1984.
28. Harris, J. Studies on the destruction of red blood cell: the biophysics and biology of sickle cell disease. Arch. Intern. Med. 97:164–167, 1956.
29. Maurer, N. H., Voegeli, P. T., Jr., Sorkin, B. S. Non-cardiac circulatory overload secondary to pneumatic thigh tourniquets. J. A. P. M. A. 73:589–592, 1983.
30. Moldaver, J. Tourniquet paralysis syndrome. Arch. Surg. 68:136–144, 1954.
31. Aho, K., Kianta, M., Varpanen, E. Pneumatic tourniquet paralysis. J. Bone Joint Surg. 65B:441–443, 1983.
32. Eckhoff, N. L. Tourniquet paralysis. Lancet 2:343–345, 1931.
33. Mukherjee, D. J. Tourniquet paralysis. J. Indian Med. Assoc. 69:130–132, 1977.
34. Rudge, P. Tourniquet paralysis with prolonged conduction block. J. Bone Joint Surg. 56B:716–720, 1974.
35. Trojaborg, W. Prolonged conduction block with axonal degeneration. J. Neurol. Neurosurg. Psychiatry 40:50–57, 1977.
36. Lewis, T., Pickering, G. W., Rothschild, P. Centripetal paralysis arising out of arrested bloodflow to the limb, including notes on a form of tingling. Heart 16:1–32, 1931.
37. Denney-Brown, D., Brenner, C. Paralysis of nerve induced direct pressure and by tourniquet. Arch. Neurol. Psychiatry 51:1–26, 1944.
38. Bentley, F. H., Schlapp, W. The effects of pressure conduction in peripheral nerve. J. Physiol. 102:72–82, 1943.
39. Speigel, I. J., Lewin, P. Tourniquet paralysis. J. A. M. A. 129:432–435, 1945.
40. Martin, F. R., Paletta, F. X. Tourniquet paralysis. A primary vascular phenomenon. South. Med. J. 59:951–953, 1966.
41. Nathan, P. W. Ischaemic and post-ischaemic numbness and paraesthesiae. J. Neurol. Neurosurg. Psychiatry 21:12–23, 1958.
42. Fowler, T. J., Danta, G., Gilliatt, R. W. Recovery of nerve conduction after a pneumatic tourniquet: observations on the hindlimb of a baboon. J. Neurol. Neurosurg. Psychiatry 35:638–647, 1972.
43. Ochoa, J., Fowler, T. J., Gilliatt, R. W. Anatomical changes in peripheral nerves compressed by a pneumatic tourniquet. J. Anat. 113:433–455, 1972.
44. Flatt, A. E. Tourniquet time in hand surgery. Arch. Surg. 104:190–192, 1972.
45. Hamilton, W. K., Sokoll, M. D. Tourniquet paralysis. J. A. M. A. 199:625, 1967.
46. Prevoznik, S. J. Injury from use of pneumatic tourniquets. Anesthesiology 32:177, 1970.
47. Angus, P., Nakielny, R., Goodrum, D. T. The pneumatic tourniquet and deep venous thrombosis. J. Bone Joint Surg. 65B:336–339, 1983.
48. Fahmy, N. R., Patel, D. G. Hemostatic changes and postoperative deep vein thrombosis associated with use of a pneumatic tourniquet. J. Bone Joint Surg. 63A:461–465, 1981.
49. Nakahara, M., Sakahashi, H. Effect of application of a tourniquet on bleeding factors in dogs. J. Bone Joint Surg. 49A:1345–1351, 1967.
50. Robinson, A. J., Holcroft, J. W., Olcott, C. N., Blaisdell, W. Pulmonary and coagulation changes in tourniquet shock. J. Surg. Res. 19:65–70, 1975.
51. Miller, S. H., Eyster, E., Saleem, A., Gottlieb, L., Buck, D., Graham, W. P. Intravascular coagulation and fibrinolysis within primate extremities during tourniquet ischemia. Ann. Surg. 190: 227–230, 1979.
52. Rutherford, R. B., West, L., Hardaway, R. M. Coagulation changes during experimental hemorrhagic shock. Ann. Surg. 164: 203–214, 1966.
53. Love, B. R. The tourniquet. Aust. N. Z. J. Surg. 48:66–70, 1978.
54. Mullick, S. The tourniquet in operations upon the extremities. Surg. Gynecol. Obstet. 146:821–826, 1978.
55. Austin, M. The Esmarch bandage and pulmonary embolism. J. Bone Joint Surg. 45B:384–385, 1963.
56. Estrera, A. S., King, R. P., Platt, M. R. Massive pulmonary embolism: a complication of the technique of tourniquet ischemia. J. Trauma 22:60–62, 1982.
57. Hofmann, A., Wyatt, R. W. B. Fatal pulmonary embolism following tourniquet inflation. J. Bone Joint Surg. 67A:633–634, 1985.
58. McClaren, A. C., Rorabeck, C. H. The pressure distribution under tourniquets. J. Bone Joint Surg. 67A:433–438, 1985.
59. Middleton, R. W. D. Tourniquet paralysis. J. Bone Joint Surg. 55B:432, 1973.
60. Pollard, B. J., Lovelock, H. A., Jones, R. M. Fatal pulmonary embolism secondary to limb exsanguination. Anesthesiology 58: 373–374, 1983.
61. Giannestras, N. J., Cranley, J. J., Lentz, M. Occlusion of the tibial artery after a foot operation under tourniquet. J. Bone Joint Surg. 59A:682–683, 1977.
62. Williams, T. A., Baerg, R. H., Beal, W. S. Acute arterial occlusion secondary to the use of a pneumatic thigh tourniquet. J. A. P. M. A. 76:464–465, 1986.
63. Logel, R. J. Rupture of the long tendon of the biceps brachii muscle. Clin. Orthop. 121:217–221, 1976.
64. Handely, R. C. Chemical burns beneath tourniquets. Br. Med. J. 298:254, 1989.
65. Dickinson, J. C., Bailey, B. N. Chemical burns beneath tourniquets. Br. Med. J. 297:1513, 1988.
66. Evans, D. M. Tourniquets. J. Med. Def. Union 1:22, 1985.
67. Anonymous: Tourniquets and theatre safeguards. J. Med. Def. Union 1:2, 1985.
68. Newman, R. J. Metabolic effects of tourniquet ischaemia studied by nuclear magnetic resonance spectroscopy. J. Bone Joint Surg. 66B:434–440, 1984.
69. Chiu, D., Wang, H. H., Blumenthal, M. R. Creatine phosphokinase release as a measure of tourniquet effect on skeletal muscle. Arch. Surg. 111:71–74, 1976.
70. Arenson, D., Weil, L. S. The uses and abuses of tourniquets in foot surgery. J. A. P. A. 66:854–862, 1976.
71. Klenerman, L. Tourniquet time–how long? Hand 12:231–234, 1980.
72. Paletta, F. X., William, V., Ship, A. G. Prolonged tourniquet ischaemia of extremities. J. Bone Joint Surg. 42A:945–950, 1960.

73. Patterson, S., Klenerman, L. The effect of pneumatic tourniquets on the ultrastructure of skeletal muscle. J. Bone Joint Surg. 61B:178–183, 1979.
74. Santavirta, S., Hockerstedt, K., Linden, H. Pneumatic tourniquet and limb blood flow. Acta. Orthop. Scand. 49:565–570, 1978.
75. Santavirta, S., Hockerstedt, K., Nirnikoski, J. Effect of pneumatic tourniquet on muscle oxygen tension. Acta. Orthop. Scand. 49: 415–419, 1978.
76. Stein, R. E., Urbaniak, J. Use of the tourniquet during surgery in patients with sickle cell hemoglobinopathies. Clin. Orthop. 151: 231–233, 1980.
77. Diamond, E., Sherman, M., Lenet, M. A quantitative method of determining the pneumatic ankle tourniquet setting. J. Foot Surg. 24:330–334, 1985.

Additional References

Altman, M. I. Use of the pneumatic tourniquet for hemostasis in foot surgery. J. Foot Surg. 8:25–27, 1969.

Cohen, R. S., Kaplan, E. G. Use of the pneumatic tourniquet. J. Foot Surg. 18:96–99, 1979.

Estersohn, H. S., Sourifman, H. A. The minimum effective midthigh tourniquet pressure. J. Foot Surg. 21:281–284, 1982.

Fox, I. M. Mandracchia, V., Jassen, M., Chu, J. The pneumatic tourniquet in extremity surgery. J. A. P. A. 71:237–242, 1981.

Griffiths, J. C., Sankarankutty, M. Bone marrow pressure changes under an inflatable tourniquet. Hand 15:3–8, 1983.

Haber, J. H. The use of tourniquets in podiatric surgery - a review. J. Foot Surg. 17:109–111, 1978.

Jacobs, E., Feldman, M., Block, B. The use of pressure tourniquets in ambulatory foot surgery. J. Foot Surg. 12:26–32, 1973.

Klenerman, L., Crawley, J. Limb blood flow in the presence of a tourniquet. Acta. Orthop. Scand. 48:291–295, 1977.

Klenerman, L., Hulands, G. H. Tourniquet pressures for the lower limb. J. Bone Joint Surg. 61B:124–128, 1979.

Thomassen, E. H. An improved method for application of the pneumatic tourniquet on extremities. Clin. Orthop. 103:99–100, 1974.