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Review Articles

Compartment Syndrome of the Foot: An Evidence-Based Review

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A R T I C L E I N F O

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A B S T R A C T

Compartment syndrome of the foot (CSF) is a surgical emergency, with high risk of morbidity and poor outcome, including persistent neurologic deficits or amputation. Uncertainty remains regarding surgical approaches, pressure monitoring values, and the extent of surgical treatment. This review provides a summary of the current knowledge and reports evidence-based diagnostic and therapeutic management options for CSF. Articles describing CSF were identified from MEDLINE, PubMed, and Cochrane databases up until February 2018. Experimental and original articles, systematic and nonsystematic reviews, case reports, and book chapters, independent of their level of evidence, were included. Crush injuries are the leading cause of CSF, but CSF can present after fractures of the tarsal or metatarsal bones and dislocations of the Lisfranc or Chopart joints. CSF is often associated with persistent neurologic deficits, claw toes, amputations, and skin healing problems. Diagnosis is made after accurate clinical evaluation combined with intracompartmental pressure monitoring. A threshold value of <20 mmHg difference between the diastolic blood pressure and the intracompartmental pressure is considered diagnostic. Management consists of surgery, whereby 2 dorsal incisions are combined with a medioplantar incision to the calcaneal compartment. The calcaneal compartment can serve as an "indicator compartment," as the highest-pressure values can regularly be measured within this compartment. Appropriately powered studies of CSF are necessary to further evaluate and compare diagnostic and therapeutic options.

Compartment syndromes (CSs) are a frequent consequence of trauma and represent a limb-threatening surgical emergency. Up to 6% of patients with foot injuries related to motorcycle accidents develop compartment syndrome of the foot (CSF) (1). This number is even higher in patients with a dislocation of the Chopart's joint (25%) or a Lisfranc injury (34%) (2). Exertional CSF has also been described (3,4). In both entities, a rising intracompartmental pressure causes damage to the muscles, nerves, or vessels (5). Patients suffering from high-speed trauma or who are multiply and severely injured are at high risk of developing a CS (6). In the foot, classically, a CS has been described as a consequence of crush injuries, which induce swelling and increase compartment pressure. Other causes of CSFs include toxic effects (for example, a snake bite) and inflammatory reactions (7).

The long-term effects of untreated CSs were described by Volkmann et al (8) more than 100 years ago; the permanent damage after an untreated CS is still known as "Volkmann contracture." At the beginning of the last century, Hildebrand (9) described the importance of intracompartmental pressure in this field.

Despite the serious consequences of CSF, there is only limited published evidence reporting the state of the art on this topic to guide diagnostic and therapeutic approaches to manage patients with CSF. The present work provides a structured overview guiding

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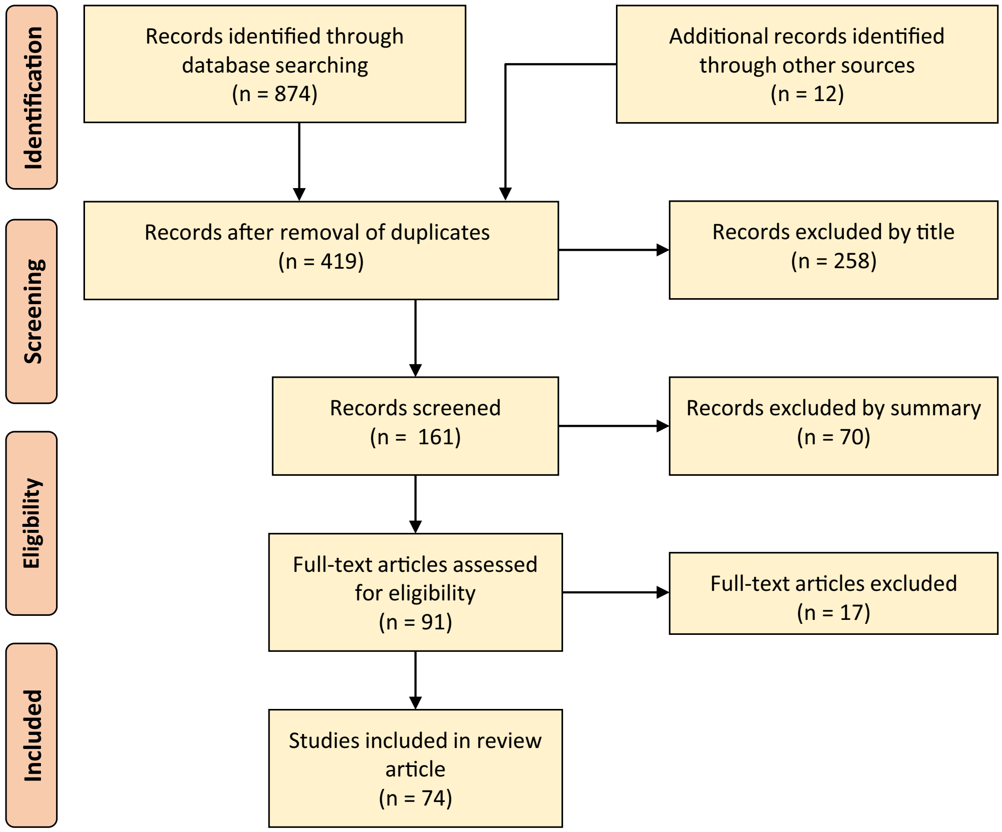

Fig. 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) flow diagram of literature review (10).

clinicians to formulate diagnostic and treatment plans in patients with CSF.

Materials and Methods

A comprehensive search of the English and German language literature was conducted (C.L., V.S.) using the MEDLINE, PubMed, and Cochrane databases. The search was performed in February 2018 without date limits to identify studies that reported on CSF. Different combinations of the terms "compartment syndrome," "foot," "compartment pressure," "anatomic compartments," "ankle," "fascial spaces," and "fasciotomy" were used. We included experimental and original articles, systematic and nonsystematic reviews, case reports, and book chapters, independent of their level of evidence. Therefore, 2 independent reviewers (C.L., V.S.) screened all titles and abstracts for eligibility. Disagreements were resolved by consensus after discussion between the 2 reviewers. The reference lists from the included articles were also reviewed by hand (Fig. 1).

Results and Discussion

Anatomic Considerations

The number of compartments of the foot and their spatial distribution is still debated, leading to confusion and heterogeneity in interpreting existing studies and formulating treatment recommendations. Hence, there is a need for a clear-cut anatomic definition.

In 1990, Manoli and Weber (5) described 9 anatomic compartments within the foot. For that study, the authors injected gelatin into cadaver specimens and then further processed and analyzed them under cryopreservation. The compartments were labelled according to their location as medial compartment, lateral compartment, superficial compartment, adductor compartment, calcaneus compartment, and 4 interosseous lodges. Although a conclusive agreement regarding the exact classification is still pending, the Manoli and Weber classification is presently in routine clinical practice (Table 1) (5).

Pathophysiology and Etiology

Two major factors characterize the described pathology: limited space (implied by the term "compartment") and increase of intracompartmental pressure. Rise of pressure can develop from either an increase of the intracompartmental components (e.g., muscle swelling) or a decrease of the compartment volume. The rise of pressure within the compartment can exceed capillary hydrostatic pressure, causing vascular stasis and therefore inducing a shift toward anaerobic metabolism of skeletal muscles. Oxygen debt within the skeletal muscles can then induce increased capillary permeability and initiate inflammatory cascades (15).

Another common cause of increased intracompartmental pressure is bleeding, as seen in vascular damage after surgical procedures or in fractures. Special attention should be paid to patients suffering from coagulopathies or those under strict anticoagulation, as bleeding might occur without any apparent trauma (4). Furthermore, extravascular presence of blood causes additional tissue injury by various biochemical and cellular processes aggravating tissue ischemia (16). Less frequent causes of an increase in pressure are burns, intoxication, toxic reactions, or intensive exercise (3,4). Decrease of the compartmental volume was initially described by Volkmann et al (8), and is seen when casts, bandages, and splints are too tight and when limbs are trapped from a crush injury or even when incorrectly positioned during surgery.

The pathophysiology of CS, which shows parallels with ischemia-reperfusion injury, is complex and based on key points such as perfusion disorder, capillary leak, endothelial dysfunction related to

Table 1
Foot compartments according to various anatomic studies (4,11)

	Kamel and Sakla (12), 1961	Manoli and Weber (5), 1990	Seidel (13), 2001	Faymonville et al (14), 2012; Schöffl (4), 2012
Number of compartments	3 (+ 3 subcompartments)	9	5	6
Compartments and related muscles	Medial compartment: Abductor hallucis muscle	Medial compartment: Abductor hallucis muscle Flexor hallucis brevis muscle	Medial compartment: Abductor hallucis muscle	Medial compartment: Abductor hallucis muscle
	Lateral compartment: Abductor digiti minimi muscle Flexor digiti minimi brevis muscle	Lateral compartment: Abductor digiti minimi muscle Flexor digiti minimi brevis muscle	Lateral compartment: Abductor digiti minimi muscle Flexor digiti minimi brevis muscle	Lateral compartment: Flexor digiti minimi brevis muscle
	Intermediate compartment: Superficial layer: Flexor digitorum brevis muscle Flexor digitorum longus muscle Lumbrical muscles Middle layer: Flexor hallucis brevis muscle Flexor hallucis longus muscle Adductor hallucis muscle Deep layer (= interosseous compartment): Interosseous muscles	Superficial compartment: Flexor digitorum longus muscle Flexor digitorum brevis muscle	Superficial central compartment: Flexor digitorum brevis muscle Tendons of flexor digitorum longus muscle Tendons of lumbrical muscles	Dorsal compartment: Anterior tibial muscle Extensor digitorum longus muscle Extensor halluces longus muscle
		Adductor compartment: Adductor hallucis muscle	Deep rear foot compartment: Quadratus plantae muscle Tendon of flexor digitorum longus muscle Tendon of flexor hallucis longus muscle	Superficial central compartment: Flexor digitorum brevis muscle Tendons of flexor digitorum longus muscle Tendons of lumbrical muscles
		Calcaneus compartment: Quadratus plantae muscle	Deep forefoot compartment: Interossei muscles Adductor hallucis muscle Flexor hallucis brevis muscle	Deep forefoot compartment: Adductor hallucis muscle Flexor hallucis brevis muscle Interosseous muscles
		4 interosseous compartments: Interosseous muscles	–	Deep hind foot compartment: Quadratus plantae muscle Flexor hallucis longus muscle Flexor digitorum longus muscle
Atypical muscles of the foot	Quadratus plantae muscle	Flexor hallucis longus muscle	–	–

complement activation, accumulation of free radicals, systemic inflammatory response syndrome, and apoptosis and necrosis (4,6,17–19).

According to the law of Hagen-Poiseuille, a change of vessel radius leads to a 4-fold change in local perfusion. With the increase of tissue pressure, the venous pressure rises, which leads to a decrease of the arteriovenous gradient (6). That situation is further impaired if the patient is hemodynamically unstable and in hypotonic conditions. In combination with high blood viscosity, this decreased arteriovenous gradient causes insufficient circulation in the affected regions. In 1896, Starling (20) described the capillary leak syndrome as a fluid exchange between plasma and tissue caused by changes in the hydrostatic pressure and the protein-osmotic forces. Capillary leak then causes the formation of a so-called interstitial and intracellular third space (6). Additionally, toxic metabolic products accumulate in ischemic regions, and free radicals and an activated complement system cause further endothelial dysfunction. The traumatized tissue can also react with a local inflammatory reaction and accumulation of leukocytes, leading to systemic inflammatory response syndrome (4).

Exertional Compartment Syndrome

Exertional compartment syndrome (ECS) can occur when repetitive muscle contraction causes exertional ischemia and swelling and induces a pressure rise within the compartment. Patients suffering from ECS characteristically complain about increased pain during training, with resolution of symptoms with cessation of exercise (4,21).

Compartment of the Foot: Mechanisms

The possible mechanisms leading to a CSF are described heterogeneously, but several injury mechanisms are known to carry a high-risk potential including: high-velocity accidents, fractures of the tarsal or metatarsal bones, dislocations of the Lisfranc or the Chopart joints, and crush injuries (22–25). Crush injuries are often described as the leading cause of CSF (28%), followed by falls from a considerable height and car accidents (26% each) (26). The literature reports motorcycle and bicycle accidents at 7.5% and 2.5%, respectively, and other injury mechanisms such as train accidents, gunshot wounds, or sports injuries at <5% each (4,26–31).

Regarding the location of bony injuries leading to a CSF, fractures of the calcaneus carry the highest risk of CSF (23%), followed by Lisfranc fractures (21%) and metatarsal or phalangeal fractures (18%) (26). Richter et al (2) noted a CSF in 25% of all Chopart dislocations and ≤34% of all Lisfranc dislocations. In addition, several recent reports highlight the risk of CSF after ankle sprains (32,33), open reduction and internal fixation of ankle fractures (34), and injection therapies of other foot disorders (35). Barshes et al (36) also highlighted the risk of CSF after urgent revascularization for acute limb ischemia. Toney et al (37) described non-necrotizing streptococcal cellulitis causing CSF in a patient positive for HIV.

Exertional CSFs have been described in soldiers (38), triathletes (39), ballet dancers (40), runners (3,41), basketball players, and other athletes (42–46). Recently, a case report was published of a CSF in a 15-year-old physically inactive female after school sports (47). Other reports have described spontaneous unexplained pressure rise in the foot compartments causing a CSF (4,48).

Diagnostic Approach

Medical history of a CS is a major risk factor for the development of a recurrent CS. Early recognition of an imminent CS remains the most important step. Clinical symptoms include red flags for CS: pain, paranesthesia, pallor, paresis, and pain with stretch (49,50). Cascio et al (51) mentioned more symptoms in 2005 when they described pallor, tension, sensory deficit, and motor deficit as core physical examinations and history findings. However, pain is the leading symptom of a CS, showing the highest sensitivity of all clinical parameters, although specificity is relatively low (17,50,52).

In contrast to other injuries or pathologies, immobilization of the affected limb combined with analgesic therapy does not lead to pain reduction (50). In the advanced stages, sensory or motor deficiency in the affected extremity can occur, and the skin may show slight reddening and overheating (52). Special consideration needs to be given to children with injuries of the foot; CSs remain commonly undiagnosed, given inconclusive radiographic findings owing to skeletal immaturity and the patients' inability to verbalize the symptoms (Fig. 2) (4,53).

Measuring Techniques

Intracompartmental pressure measurement is considered the gold standard in clinical practice. However, there is only little evidence validating the intracompartmental measurement techniques (25).

Noninvasive electronic stimulation is a potential diagnostic technique that should allow to differentiate between ischemic paranesthesia and nerve lesion but is not useful for daily clinical practice (17). Contrast-enhanced ultrasound imaging is a noninvasive functional imaging technique; alterations in microperfusion related to increased intracompartmental pressure can be visualized and quantified although gas-filled microbubbles. However, the existing studies are still laboratory-based or deal with animal models (54–56). Being a continuous and noninvasive monitoring technique for acute CS, near-infrared spectroscopy is promising, although validation studies are pending (57).

Invasive pressure measurement is an effective way to measure intracompartmental pressure by introducing a cannula into the muscle compartment; the cannula is connected to a manometer with a syringe (Figs. 2 and 3) (59). The investigator can then build up pressure with the syringe and measure the force required to overcome the compartmental resistance (equal to intracompartmental pressure). A device developed by Awbrey et al (60) is currently distributed by Stryker Orthopaedics (Mahwah, NJ); a cannula is connected to a small monitor that directly delivers pressure values when a saline-filled syringe is attached and pressed. This is an easy and quick testing tool that also provides continuous pressure monitoring when using a special catheter (e.g., in patients on intensive care units, and in exertional CS). In addition to these techniques, other devices such as cerebral pressure catheters or piezoelectrical probes have been described as potential measuring devices (61,62).

A meta-analysis showed that in 64% of all analyzed studies, surgical indication was based on pressure measurements only, and that ~31% of all surgical interventions were based on pressure measurements and clinical diagnosis (26). Only 5% of all interventions were based on clinical examination alone (4).

Pressure Values

Normally, intracompartment pressures are <8 mmHg (63). Surgical intervention is indicated in cases of elevated overall pressure or when

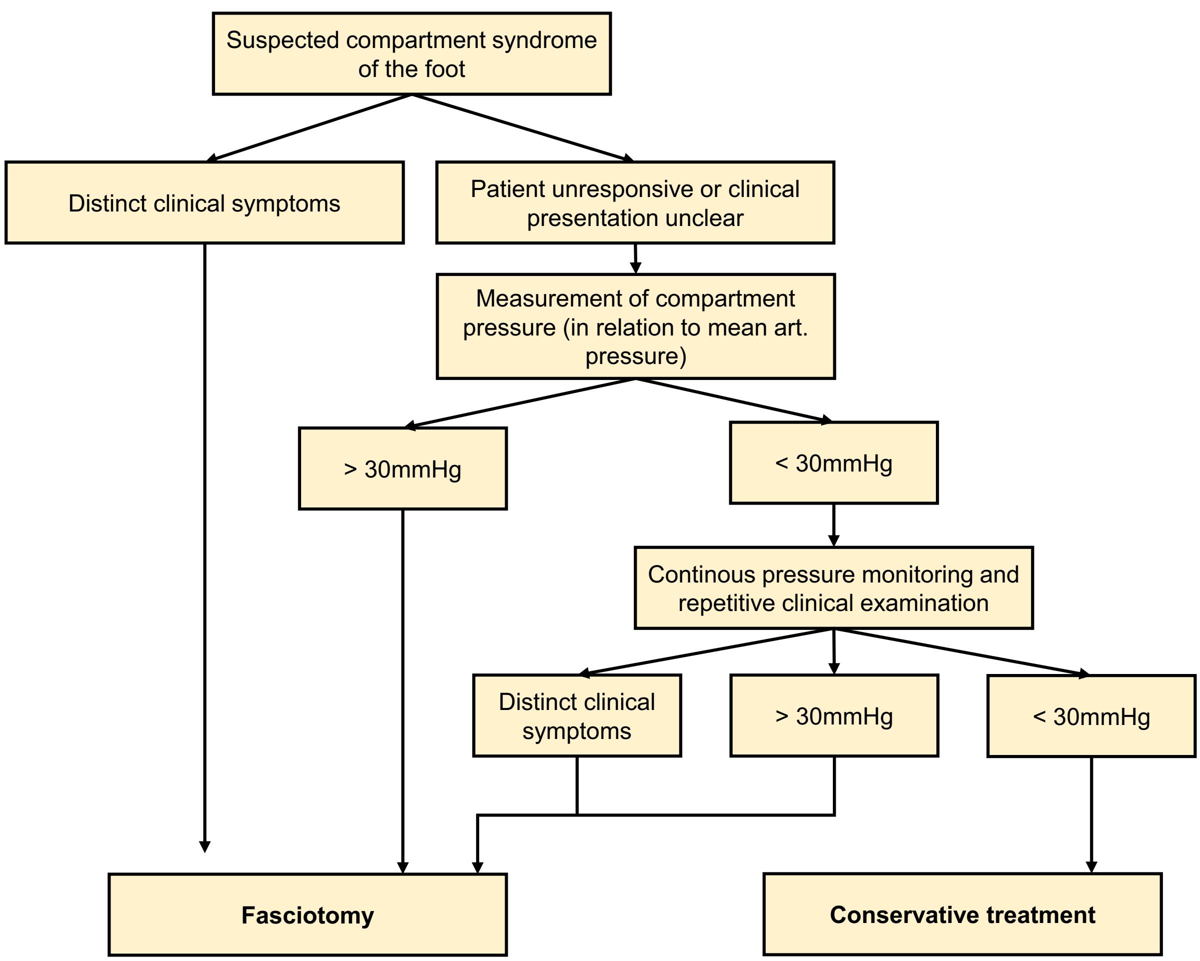

Fig. 2. Algorithm for diagnostic approach to compartment syndromes of the foot.

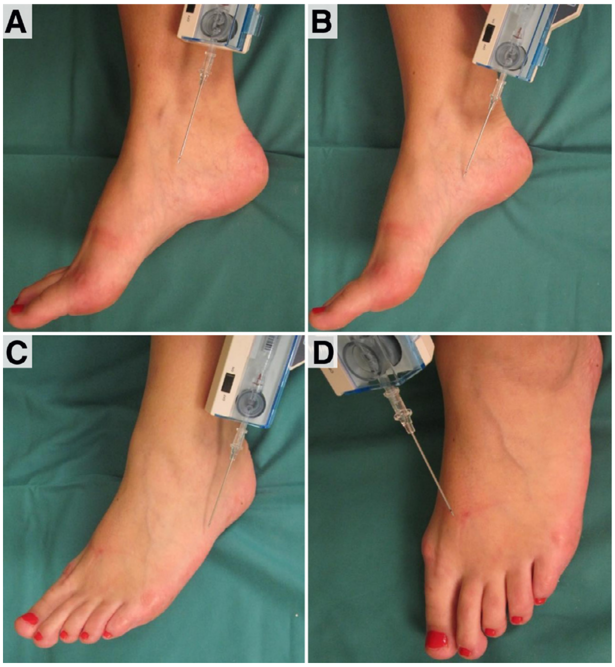

Fig. 3. (*A*) Needle insertion site to measure the intracompartmental pressure of the medial and calcaneal compartments (4 cm distal to the medial malleolus). (*B*) Needle insertion site to measure the intracompartmental pressure of the superficial compartment (ventral and plantar aspect; penetration of the flexor digitorum brevis muscle). (*C*) Needle insertion site to measure the intracompartmental pressure of the lateral compartment (plantar to the fifth metatarsal). (*D*) Needle insertion site to measure the intracompartmental pressure of the interosseous compartment (4,58).

there is an altered relationship between the compartment pressure and arterial pressure (mean or diastolic). Willy et al (64) defined a limit value compartment pressure of 30 mmHg, whereas Frink et al (17) proposed a threshold at 40 mmHg (Fig. 2).

In addition to absolute pressure values, other authors describe maximum pressure limits as compartment pressure in relation to the diastolic blood pressure; for example, diastolic blood pressure−sub fascial pressure delta P <20 mmHg (17,29,58,59,65,66). If compartment pressure values are considered in relation to the mean arterial pressure, a discrepancy of >30 mmHg is considered pathologic (delta P 30 mmHg) (Fig. 2) (4,65).

Measurement Points

Based on the anatomic definition of a total number of 9 compartments (5), a complete investigation must include measurements of all 9 compartments. The calcaneus compartment normally shows the highest pressure values and can be used as broad indicator (5,66).

The puncture site for measurements of the medial compartment is located 4 cm below the medial malleolus (Fig. 3*A*) (58). The calcaneus compartment can be reached by inserting the cannula deeper within the same injection site. Measurements of the superficial compartment are made further ventrally and plantarly. Therefore, the flexor digitorum brevis muscle can be penetrated (Fig. 3*B*). Below the fifth metatarsal, the lateral compartment can be reached (Fig. 3*C*), and the interosseous compartments are reached from the dorsum of the foot (Fig. 3*D*). It is essential to measure pressure in all interosseous spaces to avoid the danger of underdiagnosis. The remaining adductor compartment can then be measured by deeper injection of the measuring device, using the same entry point, after the algorithm of the examination procedure described by Ojike et al (4,26).

Table 2
Differential diagnosis of compartment syndromes of the foot

Nerve lesion	Phlebothrombosis/thrombophlebitis
Vessel injury	Stress fractures
Soft tissue infections	Tenosynovitis
Claudicatio intermittens	Ergotism

Differential Diagnosis

Several differential diagnoses need to be considered when there is clinical suspicion of a CS (Table 2).

Diagnosis of ECS

Although an acute CS is relatively straightforward to diagnose, an ECS poses a diagnostic challenge and can mislead clinicians. As ECSs typically arise during sport-specific loads (e.g., running, dancing, biathlon), intracompartmental pressure measurements need to be performed during these activities (Fig. 4). A baseline pressure at rest is measured, and the sport-specific load is performed at increasing intensity until the athlete complains of the typical symptoms. Measurements are then performed directly after the exercise is terminated and during the recovery period. Exact break-off values are hard to define, and a variety of limits are reported in different sports (39–42,67). Manoli and Weber (5) and Manoli et al (28) recommend a threshold for surgical intervention at 30 mmHg intracompartmental pressure during exercise (4).

As well-founded experimental studies are still pending, Fulkerson et al (58) recommend following the evidence from research on the forearm. Our group (21) has established an algorithm for ECS of the forearm in healthy athletes that we also use as a guideline for the ECS of the foot (Fig. 5).

Management

The first step for safe effective treatment of any CS is early recognition, with immediate removal of all constricting bandages or casts. The limb should then be laid flat or slightly raised to a maximum of 10% above the patient's heart level. Higher levels are not recommended as the arteriovenous pressure difference decreases, which can cause or further impair insufficient circulation in the affected region (68).

Although the optimal treatment of CSF is controversial (69), surgical fasciotomy is still considered the most effective treatment. A wide fasciotomy with an incision of the skin and fascia for the whole length of the compartment is performed, and the wound is covered with vacuum therapy or left open, possibly using the shoelace technique to favor later closure. In acute CS, primary skin closure is to be avoided, as a rebound compartment syndrome can be induced (70). Soft tissue edema can be further reduced by vacuum-assisted closure therapy. Vacuum-assisted closure films commonly applied on the skin should not envelope the limb circumferentially, as this can cause an increase of pressure.

There are few published investigations on treatment and outcome of missed CS of the lower extremity and the foot (71). Rosenthal et al (72) described late sequelae such as toe clawing, permanent loss of function, persistent pain, contracture, painful warts, and sensory disturbances, and therefore recommend early and extensive surgical treatment (73).

Surgical Approaches for CSF

Several approaches are described for CSF, including: plantar approach (74), dorsal approach (74), medial-plantar approach (5), and lateral approach (68).

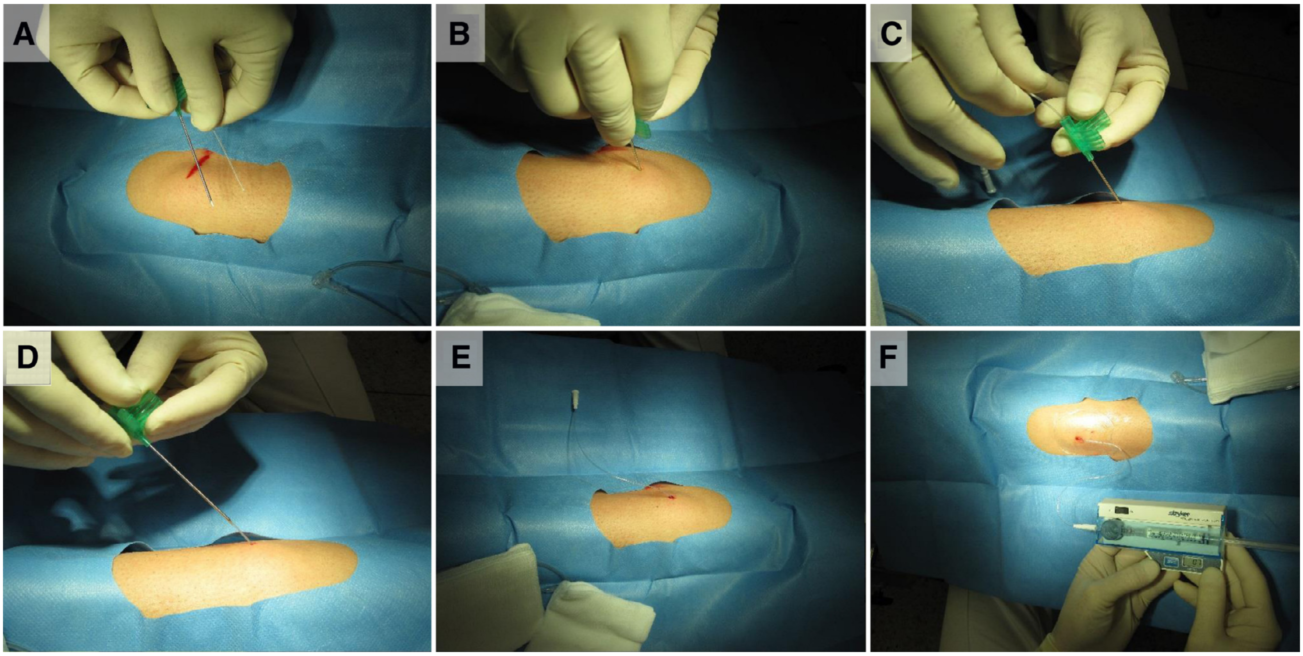

Fig. 4. Measurement technique for correct diagnosis of exertional compartment syndrome. (*A* and *B*) Puncture of the compartment with a cannula/catheter under sterile conditions. (*C*) Introduction of the catheter through the cannula into the compartment. (*D*) Removal of the cannula. (*E*) Catheter placed in the compartment. (*F*) Catheter connected to measuring device.

Plantar Approach

If patients present with an isolated CS of the calcaneal compartment, a single approach from the plantar margin of the foot can be used, but this is not frequent. An incision is made over the first metatarsal; after retraction of the abductor hallucis muscle, the other compartments can be reached (4).

Dorsal Approach

As the interosseous compartments are most frequently affected, Mubarak and Owen (74) described a double dorsal approach (66,75). This double approach enables the surgeon to access almost all compartments, and provides an opportunity for an open reduction and internal fixation of Chopart or Lisfranc fractures. However, the calcaneus compartment cannot be accessed through these approaches, and therefore requires a third incision. It is highly recommended to incise and dissect medial to the second metatarsal for the medial approach, and then incise lateral to the fourth metatarsal to reach the lateral compartments. With appropriate distance between these 2 dorsal incisions, the risk of intervening tissue necrosis can be reduced (Fig. 6) (4,17).

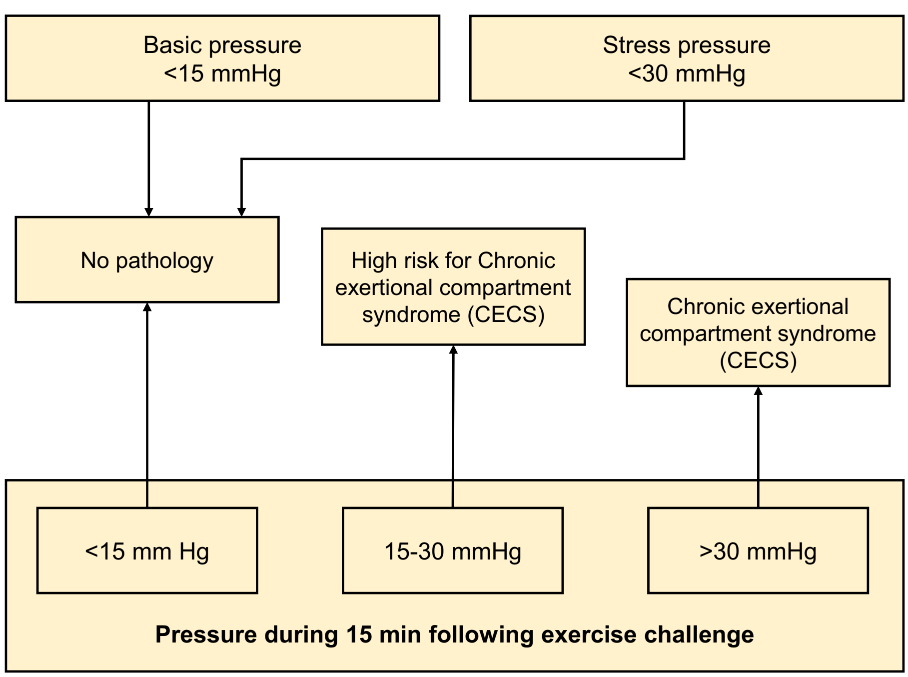

Fig. 5. Algorithm for diagnostic approach of exertional compartment syndromes (4).

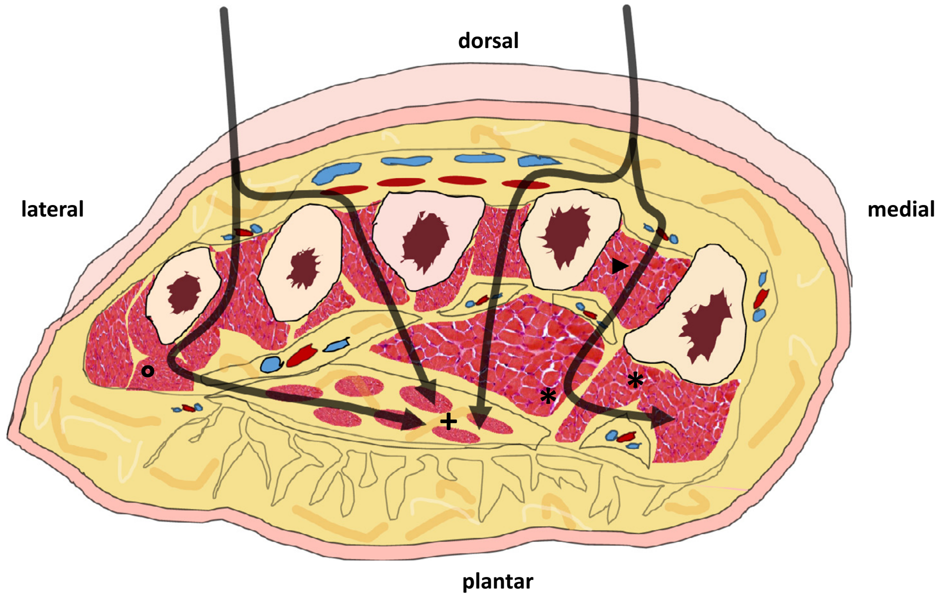

Fig. 6. Dorsal approach for emergency fasciotomy. *Black arrows* indicate approaches. *, medial and adductor compartments; +, superficial compartments; °, lateral compartments; ►, interosseous compartments.

Medial Plantar Approach

In addition to the dorsal incisions, the medial plantar approach can be used to access the calcaneal compartment. The medial 6-cm incision starts over the origin of the abductor hallucis muscle and is parallel to the plantar aspect of the foot (5). After incision of the skin, the fascia overlying the abductor hallucis muscle is incised over its entire length. The medial compartment can then be opened, and the abductor hallucis muscle is retracted dorsally. The fascia that is then visualized separates the abductor hallucis muscle from the calcaneal compartment. After opening the fascia longitudinally, the remaining compartments can be reached (Figs. 7 and 8) (4).

Lateral Approach

The lateral approach was initially described in 1982 by Echtermeyer et al (68,76). The skin incision starts at the lateral malleolus and continues along the forefoot to the head of the fourth and fifth metatarsals. This approach is now used less frequently (4).

Chronic ECS

In chronic ECS, conservative management can be attempted. Cessation of the activities that caused the injury and practice of alternative sports can be effective. Additional treatments such as cryo- or physical therapy, antiinflammatory medications, or compression sleeves and insoles might be considered, although only low levels of evidence-based scientific articles are currently available. However, these measures rarely offer a cure, and, when the patient resumes the desired sport, the symptoms classically recur (42).

Functional imbalances that can be detected using video analysis of treadmill walking and running are associated with chronic ECS. We routinely perform such analysis, and athletes can thus be advised regarding rebalance training. Surgical treatment with open or minimally invasive fasciotomy should be the last resort but is very effective (4,77).

Complications and Outcome

Lokiec et al (40) showed that neurologic complications (52%), claw toes (12%), amputations (12%), or deep skin defects (12%) are the most common complications after CSF. Necrosis of the muscles and varus or valgus deformity were less frequent (4,78).

As most reports on CS of the foot are case reports, the outcome of this injury has not yet been sufficiently assessed. A meta-analysis (26) reported the outcome described in 4 studies with a total of 39 patients

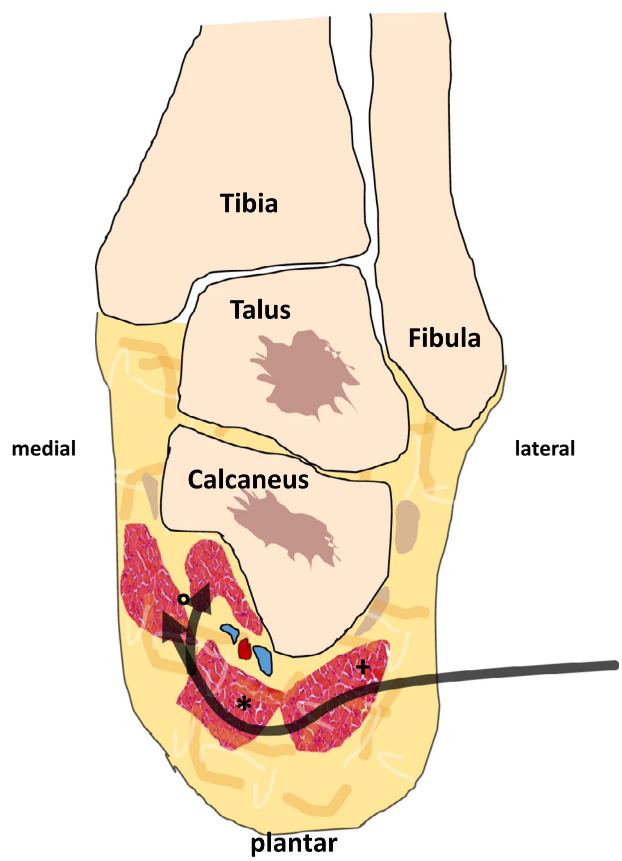

Fig. 7. Medial plantar approach for the hindfoot. +, calcaneal compartments; *, medial and superficial compartments; °, lateral compartments.

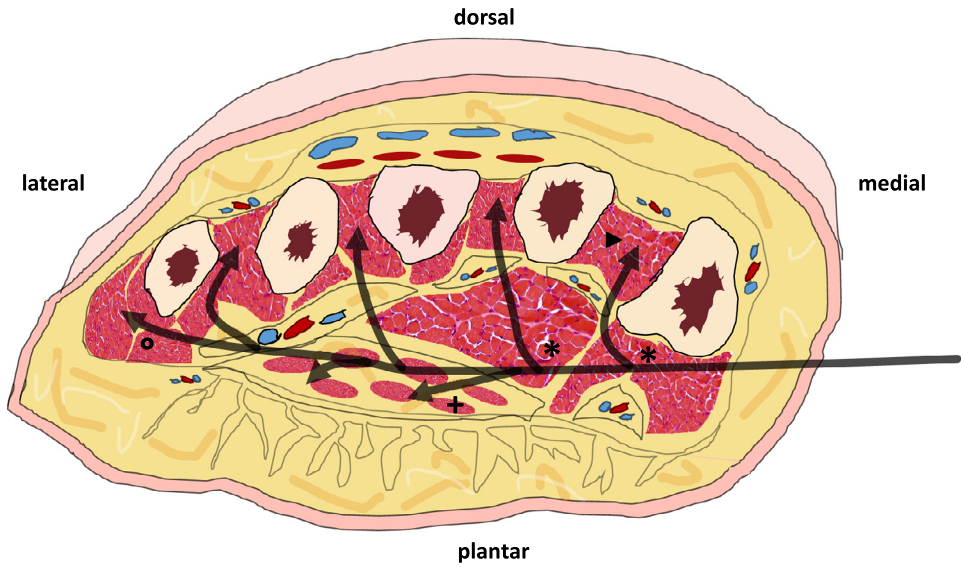

Fig. 8. Medial plantar approach for emergency fasciotomy. *Black arrows* indicate approaches. *, medial and adductor compartments; +, superficial compartments; °, lateral compartments; ►, interosseous compartments.

(27–30). Ten percent (4 patients) returned to their employment, 13% (5 patients) were able to walk again without restrictions, and 39% (15 patients) were able to walk with minor limitations. Secondary arthrodesis was required in 5% (2 patients), and no further information about the outcome was available in 33% (13 patients). In contrast to these figures, a recent prospective study reports a satisfactory return to sports and quality of life outcome in 14 patients who had been treated by emergency fasciotomy; 79% of patients returned to work, 14% suffered from claw toe deformities, and 21% had sensory deficits (79).

Limitations

All these studies involve only a small number of patients, and they offer only limited evidence-based data to support the therapeutic strategies; many considerations are based solely on expert opinion or best practice recommendations. Data in reviewed articles showed a strong heterogeneity. However, despite our appreciation of the limitations of our investigation, we believe that the results of this study could be useful in the future development of prospective cohort studies and randomized controlled trials that focus on CSF.

In conclusion, the present work provides a structured overview of the injury mechanisms, underlying pathophysiologic foundations, diagnostics, and treatment of this injury. CSF need to be recognized as a severe complication of injuries to the foot, from which permanent damage can result if undiagnosed. If a CSF is diagnosed, the only effective therapy is surgical treatment. However, diagnostic approaches are still limited. There is a compelling need for further studies, including high-quality investigations to evaluate the different diagnostic modalities. Clearly defined parameters should support the decision-making progress during diagnosis and management planning of CSF.

References

1. Jeffers RF, Tan HB, Nicolopoulos C, Kamath R, Giannoudis PV. Prevalence and patterns of foot injuries following motorcycle trauma. J Orthop Trauma 2004;18:87–91.
2. Richter M, Thermann H, Wippermann B, Otte D, Schratt HE, Tscherne H. Foot fractures in restrained front seat car occupants: a long-term study over twenty-three years. J Orthop Trauma 2001;15:287–293.
3. Izadi FE, Richie DH Jr. Exertional compartment syndrome of the medial foot compartment: diagnosis and treatment. J Am Podiatr Med Assoc 2014;104:417–421.
4. Schöffl V. Das Kompartmentsyndrom des Fußes. In: M Walther, ed. MyMedibookde. GmbH, Berg, Bavaria, Germany; 2012. p. 1–15. [in German].
5. Manoli A 2nd, Weber TG. Fasciotomy of the foot: an anatomical study with special reference to release of the calcaneal compartment. Foot Ankle 1990;10:267–275.
6. Jager C, Echtermeyer V. [Compartment syndrome of the lower leg and foot. Anatomy and pathophysiology]. Unfallchirurg 2008;111:768–770, 772-775.
7. Hon KL, Chow CM, Cheung KL, Leung TF. Snakebite in a child: could we avoid the anaphylaxis or the fasciotomies. Ann Acad Med Singapore 2005;34:454–456.
8. Volkmann R. Die ischämischen Muskellähmungen und Kontrakturen. Zentralbl Chir 1881;8:801–803. [in German] .
9. Hildebrand O. Die Lehre von den ischämischen Muskellähmungen und Kontrakturen. Samml Klin Vorträge 1906;122:437. [in German].
10. Moher D, Liberati A, Tetzlaff J, Altman DG, Group P. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ 2009;339: b2535.
11. Astrid K. *Das Fußkompartmentsyndrom—eine experimentelle Studie*. Hohen Medizinischen Fakultät der Ruhr-Universität, Bochum, Germany, 2002. p. 1–86.
12. Kamel R, Sakla FB. Anatomical compartments of the sole of the human foot. Anat Rec 1961;140:57–60.
13. Seidel U. *Topographische Anatomie des Fußkompartiments und der Bedeutung für das Kompartmentsyndrom des Fußes*. University of Cologne, Germany, 2001. p. 1–104.
14. Faymonville C, Andermahr J, Seidel U, Muller LP, Skouras E, Eysel P, Stein G. Compartments of the foot: topographic anatomy. Surg Radiol Anat 2012;34:929–933.
15. Oestern HJ. [Compartment syndrome. Definition, etiology, pathophysiology]. Unfallchirurg 1991;94:210–215.
16. Glass GE, Nanchahal J. Why haematomas cause flap failure: an evidence-based paradigm. J Plast Reconstr Aesth Surg 2012;65:903–910.
17. Frink M, Hildebrand F, Krettek C, Brand J, Hankemeier S. Compartment syndrome of the lower leg and foot. Clin Orthop Rel Res 2010;468:940–950.
18. Kerrigan CL, Stotland MA. Ischemia reperfusion injury: a review. Microsurgery 1993;14:165–175.
19. Stotland MA, Kerrigan CL. The role of platelet-activating factor in musculocutaneous flap reperfusion injury. Plast Reconstr Surg 1997;99:1989–1999.
20. Starling EH. On the absorption of fluids from the connective tissue spaces. J Physiol 1896;19:312–326.
21. Schoeffl V, Klee S, Strecker W. Evaluation of physiological standard pressures of the forearm flexor muscles during sport specific ergometry in sport climbers. Br J Sports Med 2004;38:422–425.
22. Thakur NA, McDonnell M, Got CJ, Arcand N, Spratt KF, DiGiovanni CW. Injury patterns causing isolated foot compartment syndrome. J Bone Joint Surg Am 2012;94:1030–1035.
23. Salvi AE, Roda S, Florschutz AV. Acute compartment syndrome of the foot in a 17-year-old boy. Pol Orthop Traumatol 2012;77:27–28.
24. Towater LJ, Heron S. Foot compartment syndrome: a rare presentation to the emergency department. J Emerg Med 2013;44:e235–e238.
25. Dodd A, Le I. Foot compartment syndrome: diagnosis and management. J Am Acad Orthop Surg 2013;21:657–664.
26. Ojike NI, Roberts CS, Giannoudis PV. Foot compartment syndrome: a systematic review of the literature. Acta Orthop Belg 2009;75:573–580.
27. Fakhouri AJ, Manoli A 2nd. Acute foot compartment syndromes. J Orthop Trauma 1992;6:223–228.

28. Manoli A 2nd, Fakhouri AJ, Weber TG. Concurrent compartment syndromes of the foot and leg. Foot Ankle 1993;14:339.
29. Myerson MS. Management of compartment syndromes of the foot. Clin Orthop Rel Res 1991;239–248.
30. Ziv I, Mosheiff R, Zeligowski A, Liebergal M, Lowe J, Segal D. Crush injuries of the foot with compartment syndrome: immediate one-stage management. Foot Ankle 1989;9:185–189.
31. Brink F, Bachmann S, Lechler P, Frink M. Mechanism of injury and treatment of trauma-associated acute compartment syndrome of the foot. Eur J Trauma Emerg Surg 2014;40:529–533.
32. Cortina J, Amat C, Selga J, Corona PS. Isolated medial foot compartment syndrome after ankle sprain. Foot Ankle Surg 2014;20:e1–e2.
33. Laframboise MA, Muir B. Acute compartment syndrome of the foot in a soccer player: a case report. J Can Chiropr Assoc 2011;55:302–312.
34. Neilly D, Baliga S, Munro C, Johnston A. Acute compartment syndrome of the foot following open reduction and internal fixation of an ankle fracture. Injury 2015;46:2064–2068.
35. Patil SD, Patil VD, Abane S, Luthra R, Ranaware A. Acute compartment syndrome of the foot due to infection after local hydrocortisone injection: a case report. J Foot Ankle Surg 2015;54:692–696.
36. Barshes NR, Pisimisis G, Kougias P. Compartment syndrome of the foot associated with a delayed presentation of acute limb ischemia. J Vasc Surg 2016;63:819–822.
37. Toney J, Donovan S, Adelman V, Adelman R. Non-necrotizing streptococcal cellulitis as a cause of acute, atraumatic compartment syndrome of the foot: a case report. J Foot Ankle Surg 2016;55:418–422.
38. Helmhout PH, Diebal-Lee MA, Poelsma LR, Harts CC, Zimmermann LW. Modifying marching technique in military service members with chronic exertional compartment syndrome: a case series. Int J Sports Phys Ther 2016;11:1106–1124.
39. Mollica MB. Chronic exertional compartment syndrome of the foot. A case report. J Am Podiatr Med Assoc 1998;88:21–24.
40. Lokiec F, Siev-Ner I, Pritsch M. Chronic compartment syndrome of both feet. J Bone Joint Surg Br 1991;73:178–179.
41. Muller GP, Masquelet AC. [Chronic compartment syndrome of the foot. A case report]. Rev Chir Orthop Reparatrice Appar Mot 1995;81:549–552.
42. Padhiar N, Allen M, King JB. Chronic exertional compartment syndrome of the foot. Sports Med Arthrosc 2009;17:198–202.
43. Kelsey NR, Edmonds LD, Biko DM. Acute exertional medial compartment syndrome of the foot in a teenager. Radiol Case Rep 2015;10:1092.
44. Chambers L, Hame SL, Levine B. Acute exertional medial compartment syndrome of the foot after playing basketball. Skel Radiol 2011;40:931–935.
45. Miozzari HH, Gerard R, Stern R, Toman J, Assal M. Acute, exertional medial compartment syndrome of the foot in a high-level athlete: a case report. Am J Sports Med 2008;36:983–986.
46. Lam SK, McAlister J, Oliver N, Pontell D. Bilateral medial foot compartment syndrome after an aerobics class: a case report. J Foot Ankle Surg 2012;51:652–655.
47. Sinikumpu JJ, Lepojarvi S, Serlo W, Orava S. Atraumatic compartment syndrome of the foot in a 15-year-old female. J Foot Ankle Surg 2013;52:72–75.
48. Hill CE, Modi CS, Baraza N, Mosleh-Shirazi MS, Dhukaram V. Spontaneous compartment syndrome of the foot. J Bone Joint Surg Br 2011;93:1282–1284.
49. Griffiths DL. The management of acute circulatory failure in an injured limb. J Bone Joint Surg Br 1948;30:280–289.
50. Via AG, Oliva F, Spoliti M, Maffulli N. Acute compartment syndrome. Muscles Ligaments Tendons J 2015;5:18–22.
51. Cascio BM, Wilckens JH, Ain MC, Toulson C, Frassica FJ. Documentation of acute compartment syndrome at an academic health-care center. J Bone Joint Surg Am 2005;87:346–350.
52. Ulmer T. The clinical diagnosis of compartment syndrome of the lower leg: are clinical findings predictive of the disorder? J Orthop Trauma 2002;16:572–577.
53. Wallin K, Nguyen H, Russell L, Lee DK. Acute traumatic compartment syndrome in pediatric foot: a systematic review and case report. J Foot Ankle Surg 2016;55:817–820.
54. Geis S, Gehmert S, Lamby P, Zellner J, Pfeifer C, Prantl L, Jung EM. Contrast enhanced ultrasound (CEUS) and time intensity curve (TIC) analysis in compartment syndrome: first results. Clin Hemorheol Microcirc 2012;50:1–11.
55. Sellei RM, Waehling A, Weber CD, Jeromin S, Zimmermann F, McCann PA, Hildebrand F, Pape HC. Contrast enhanced ultrasound (CEUS) reliably detects critical perfusion changes in compartmental muscle: a model in healthy volunteers. Eur J Trauma Emerg Surg 2014;40:535–539.
56. Davidson BP, Belcik JT, Mott BH, Landry G, Lindner JR. Quantification of residual limb skeletal muscle perfusion with contrast-enhanced ultrasound during application of a focal junctional tourniquet. J Vasc Surg 2016;63:148–153.
57. Shuler MS, Roskosky M, Kinsey T, Glaser D, Reisman W, Ogburn C, Yeoman C, Wanderman NR, Freedman B. Continual near-infrared spectroscopy monitoring in the injured lower limb and acute compartment syndrome. Bone Joint J 2018;100-b:787–797.
58. Fulkerson E, Razi A, Tejwani N. Review: acute compartment syndrome of the foot. Foot Ankle Int 2003;24:180–187.
59. Whitesides TE Jr, Haney TC, Harada H, Holmes HE, Morimoto K. A simple method for tissue pressure determination. Arch Surg 1975;110:1311–1313.
60. Awbrey BJ, Sienkiewicz PS, Mankin HJ. Chronic exercise-induced compartment pressure elevation measured with a miniaturized fluid pressure monitor. A laboratory and clinical study. Am J Sports Med 1988;16:610–615.
61. Becker HP, Gerngross H, Schreiber M, Hartel W. [Measuring compartment pressure of the tibia with the intracranial probe]. Unfallchirurg 1987;90:212–217.
62. Gerngroß H. Kompartmentdruckmessung: ein neues, rationelles Verfahren mit dem MCDM-I. Wehrmed Monatsschr 1992;1:8–11.
63. Botte MJ, Santi MD, Prestianni CA, Abrams RA. Ischemic contracture of the foot and ankle: principles of management and prevention. Orthopedics 1996;19:235–244.
64. Willy C, Sterk J, Volker HU, Sommer C, Weber F, Trentz O, Gerngross H. [Acute compartment syndrome. Results of a clinico-experimental study of pressure and time limits for emergency fasciotomy]. Unfallchirurg 2001;104:381–391.
65. Olson SA, Glasgow RR. Acute compartment syndrome in lower extremity musculoskeletal trauma. J Am Acad Orthop Surg 2005;13:436–444.
66. Myerson M, Manoli A. Compartment syndromes of the foot after calcaneal fractures. Clin Orthop Rel Res 1993;142–150.
67. Jowett A, Birks C, Blackney M. Chronic exertional compartment syndrome in the medial compartment of the foot. Foot Ankle Int 2008;29:838–841.
68. V E. Das Kompartmentsyndrom: Diagnostik und Therapie. Springer Verlag 1982;85:144–152. [in German].
69. Bedigrew KM, Stinner DJ, Kragh JF Jr, Potter BK, Shawen SB, Hsu JR. Effectiveness of foot fasciotomies in foot and ankle trauma. J R Army Med Corps 2017;163:324–328.
70. Poon H, Le Cocq H, Mountain AJ, Sargeant ID. Dermal fenestration with negative pressure wound therapy: a technique for managing soft tissue injuries associated with high-energy complex foot fractures. J Foot Ankle Surg 2016;55:161–165.
71. Glass GE, Staruch RM, Simmons J, Lawton G, Nanchahal J, Jain A, Hettiaratchy SP. Managing missed lower extremity compartment syndrome in the physiologically stable patient: a systematic review and lessons from a level I trauma center. J Trauma Acute Care Surg 2016;81:380–387.
72. Rosenthal R, Tenenbaum S, Thein R, Steinberg EL, Luger E, Chechik O. Sequelae of underdiagnosed foot compartment syndrome after calcaneal fractures. J Foot Ankle Surg 2013;52:158–161.
73. Park YH, Ahn JH, Choi GW, Kim HJ. Exertional medial compartment syndrome of the foot: referred pain and sequelae of delayed diagnosis—a case report. Clin J Sports Med 2018 Apr 4. doi:10.1097/JSM.0000000000000582. [Epub ahead of print].
74. Mubarak S, Owen CA. Compartmental syndrome and its relation to the crush syndrome: a spectrum of disease. A review of 11 cases of prolonged limb compression. Clin Orthop Rel Res 1975;81–89.
75. Myerson MS. Experimental decompression of the fascial compartments of the foot—the basis for fasciotomy in acute compartment syndromes. Foot Ankle 1988;8:308–314.
76. Echtermeyer V, Muhr G, Oestern HJ, Tscherne H. Surgical treatment of compartmental syndromes. Unfallheilkunde 1982;85:144–152.
77. Maffulli N, Loppini M, Spiezia F, D'Addona A, Maffulli GD. Single minimal incision fasciotomy for chronic exertional compartment syndrome of the lower leg. J Orthop Surg Res 2016;11:61.
78. Dayton P, Haulard JP. Hallux varus as complication of foot compartment syndrome. J Foot Ankle Surg 2011;50:504–506.
79. Han F, Daruwalla ZJ, Shen L, Kumar VP. A prospective study of surgical outcomes and quality of life in severe foot trauma and associated compartment syndrome after fasciotomy. J Foot Ankle Surg 2015;54:417–423.