Previous dye-infusion experiments on cadavers have suggested that the hindfoot should be divided into four muscle compartments including a newly described ‘calcaneal’ element containing quadratus plantae. Since there are no clinical data to support this proposed division, we re-examined the validity of the infusion experiment. We made infusions of dilute Omnipaque at a constant rate into flexor digitorum brevis of four cadaver feet. We monitored the spread of the infusate by real-time CT imaging and measured the pressures at the infusion site by side-ported needles.

In all feet, the barrier between flexor digitorum brevis and quadratus plantae became incompetent at pressures of less than 10 mmHg. Pressure gradients in this range cannot be expected to affect tissue perfusion significantly and independently generate compartment syndromes. These results do not confirm those of previous studies carried out by uncontrolled and unmonitored injections made by hand.

Injection studies in cadaver limbs can give dramatically different results depending upon the assumptions made when designing the experiment. The technique cannot adequately act as a model of the physiology of the compartment syndrome. As the existence of a physiologically significant compartmental boundary between flexor digitorum brevis and quadratus plantae is based solely on a cadaver infusion experiment the presence of a ‘calcaneal’ compartment has not been confirmed.

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Compartment syndromes of the foot have been under-diagnosed and until the last 15 years reported only on an anecdotal basis. Most authors have recognised the presence of four compartments, namely a forefoot compartment containing the interossei and adductor hallucis, and central, medial and lateral hindfoot compartments. These were first proposed by Wood Jones. Supporting evidence was provided by an injection experiment by Kamel and Sakla, and more recently by Myerson in a dye-injection study exploring the adequacy of various incisions for fasciotomy. His series of compartment syndromes of the foot is the largest in the literature.

The concept of four compartments was challenged by Manoli and Weber with results from an experiment in which they injected dyed gelatin solution into fresh cadaver specimens. After superficial central injection through the plantar fascia, they noted that the gelatin did not spread from the superficial portions of the central hindfoot compartment into the deep layer containing quadratus plantae. Conversely, separate injections directly into quadratus plantae confirmed that it could contain the gelatin solution without spread to the more superficial layer in which lay flexor digitorum brevis. They proposed that the hindfoot be divided into four compartments, the medial, the lateral, the superficial central, and a previously undescribed deep central or ‘calcaneal’ section. They described a series of three patients whom they believed to have ischaemic contractures of quadratus plantae with late rigid claw-toe deformities and dysesthesia, although measurements of compartment pressure were not reported. They suggested that as it communicates with the deep compartment of the leg, the deep or ‘calcaneal’ compartment of the hindfoot represents a potential site of morbidity if overlooked after injury to the hindfoot. As a result of their finding that the gelatin dye solution could be confined in each of four interosseous spaces and by adductor hallucis, they proposed that the total number of foot compartments be increased from four to nine.

Although their study offered no technical advance over the earlier injection and clinical studies on which the four-compartment model was based, the nine-compartment concept has been rapidly accepted. It now appears in standard orthopaedic review textbooks, review articles, and the Orthopaedic In-Training Examination, and, more recent-
ly, in clinical series. In this study, we have re-examined the validity of the cadaver injection technique as applied to the hindfoot, by repeating the infusion studies of the central compartment while monitoring the intracompartmental pressure and the spread of infusate.

Materials and Methods

Our technique for the infusion experiment has been described in detail elsewhere. We obtained four fresh cadaver legs amputated below the knee and without identifiable deformity or trauma. After localisation of the needle under CT guidance, volume-controlled infusions of the superficial central space (flexor digitorum brevis) were performed at 1.12 cm³/min using a dilute Omnipaque solution. Pressures in the space were measured by a separate 18-gauge sideported needle (Stryker, Kalamazoo, Michigan). Extreme care was taken during placement of the needle in penetration of the plantar fascia and in avoiding overpenetration past the plane of the flexor tendons into quadratus plantae. Real-time CT images of the spread of infusate were taken and correlated with the recorded measurements of pressure. Each infusion was continued until contrast material appeared in the space occupied by quadratus plantae, showing continuity of fluid and pressure across the proposed compartmental boundary.

Results

Pressure recordings. In all four specimens pressures in flexor digitorum brevis during the infusion were successfully recorded, but there was difficulty in placing the needle in this thin muscle. CT guidance was crucial in avoiding penetration beyond the transverse septum into quadratus plantae while at the same time burying the needle sufficiently to place the side opening beneath the plantar fascia.

Figure 1 shows the graph of tissue pressure versus time and volume infused. The central hindfoot proved to be quite capacious and pressure increased relatively slowly with considerable volumes of infusate; 30 to 40 ml were typically required to reach 10 mmHg. In all cases the infusions were stopped before pressures reached 15 mmHg.

An asymptotic decrease in pressure was seen after the end of the infusion. This indicates that some portion of the detected increase of pressure arose from the dynamic resistance of fluid flow into the deeper tissues rather than from an underlying increase in static pressures. Imaging data. Seven or more CT scans, each consisting of 40 1 mm thick slices, were obtained for each foot during the infusion. Axial images through the midfoot and distal hindfoot were analysed for spread of infusate and the corresponding pressures in flexor digitorum brevis were noted (Fig. 2).

Initially, the infusate was confined by the transverse septum between flexor digitorum brevis and quadratus plantae. As the volume increased, the space increased in size with modest changes in pressure. Once pressures reached approximately 10 mmHg, the infusate began to appear beyond the transverse septum adjacent to quadratus plantae.

Discussion

There are a number of subtly different interpretations of the possible fascial divisions of the hindfoot. Grodinsky first carried out a series of gelatin injections and dissections in an effort to reproduce, in the foot, the level of understanding Kanavel brought to the spread of infection in the hand. He described lateral and medial spaces corresponding to the current concept of the lateral and medial compartments, as well as a series of four potential spaces in the central portion of the hindfoot separated by quadratus plantae, flexor digitorum brevis, and adductor hallucis. As Manoli and Weber have pointed out, he erroneously illustrated all three muscles as coexisting adjacent to each other in a single transverse section of the foot at the mid-
Serial CT images taken during the infusion as follows: a) pressure, 4.3 mmHg; volume infused, 6.5 ml; b) pressure, 5.5 mmHg; volume infused, 12.9 ml; c) pressure 7.5 mmHg; volume infused, 25.9 ml; and d) pressure, 9.0 mmHg, volume infused, 38.8 cm. The dye is initially confined superficial to the transverse septum between flexor digitorum brevis and quadratus plantae. Despite the low pressure gradient between the two spaces, several long wisps of dye have tracked beyond the transverse septum into the deep layer of the central compartment. The cuts shown are in the coronal plane of the body at the level of the cuboid. Soft-tissue windows are used.
metatarsal level. In fact, the oblique head of the adductor does not arise until the level of the forefoot, while the muscle bellies of quadratus plantae and flexor digitorum brevis are confined to the distal hindfoot and midfoot. The error was propagated in the orthopaedic literature until 1990.

Using real-time fluoroscopic guidance, Feingold et al. injected a series of plantar compartments with a radiological contrast medium. They found that continued injection into all three major hindfoot compartments would cause dye to extravasate into adjacent compartments before the injected compartment was entirely filled.

Loeffler and Ballard undertook an injection study using radiological contrast in two feet and latex in four. In agreement with Grodinsky, they found a series of spaces between the muscle layers of the central compartment. With sufficient volume, the infusate ultimately flowed between all the potential spaces.

In 1995, the division of the hindfoot compartments was re-examined using MRI by Goodwin et al. both by analysing the clinical patterns of the spread of infection through the feet of 11 diabetic patients who had developed abscesses, and by monitoring MR contrast injections into four cadaver feet. Although the injections were carried out under fluoroscopy, the injection catheters were not localised by cross-sectional imaging. After injection of the central compartment at a distal site, just proximal to the metatarsal heads, they found contrast material extending into the plane between flexor digitorum brevis and quadratus plantae.

Moving forward in the foot, adductor hallucis was not surrounded by contrast. The medial compartment was thought to contain the entire flexor hallucis brevis, the tendon of flexor hallucis longus and abductor hallucis. They interpreted their results as arguing against the separation of quadratus plantae from the central hindfoot into a separate ‘calcaneal’ compartment as proposed by Manoli and Weber, but they could not demonstrate that their injection needles did not transgress the surrounding fascia during placement.

The central hindfoot compartment is indeed separated into superficial and deep layers by a transverse septum originating from the calcaneus and extending distally. This structure has been seen in numerous dissections, and has most clearly been illustrated by Sarrafian in his atlas of foot anatomy. Our results have shown that in a cadaver, this septum impedes the flow of fluid between the two spaces, but once tissue pressures of approximately 10 mmHg are reached in the superficial layer, flow into quadratus plantae regularly occurs. The differences in the experimental results achieved by previous authors depend on the volume of the infusate, the peak transient pressure achieved and the viscosity of the liquid, none of which has previously been experimentally controlled.

There are a number of distinct differences between our experimental design and that of Manoli and Weber. We used a large volume of a fully fluid infusate rather than gelatin, took real-time pressure measurements and CT images, and avoided the pressure transients possible with injections by hand by using a calibrated mechanical pump. Although these subtle modifications of the experiment led to a dramatically different result, we cannot contend that our modifications yield a valid experimental technique. Rather, they point to its profound limitations.

The findings of injection studies undertaken in human cadavers are not in themselves sufficient to establish a muscular space as a separate compartment, particularly if they used very low pressures and volumes of infusate. Not all connective-tissue layers are recognised as compartmental boundaries. In addition, infused cadaver limbs differ in many ways from a living arm or leg. The interaction of lymphatic, arterial, and venous flows and the diffuse leak of fluid from damaged capillary beds present in the injured limb will alter dramatically the interstitial pressure environment, an observation borne out by the occasional presence
of clinical compartment syndromes even when the compartmental boundary is partially disrupted by an open fracture.

Numerous studies and case reports of foot compartment syndromes have been published since the report of Manoli and Weber and their reported sites of pressure measurement are summarised in Table I. While a few of these describe pressure measurements in the ‘calcaneal’ compartment, none report pressure differentials between that space and the more superficial portion of the central compartment. In addition, Michelson reported a case of apparent compartment syndrome in the central hindfoot, based upon the presence of claw toes and MRI signal changes adjacent to the calcaneus several months after surgery for plantar fasciitis. The absence of pressure measurements and recent surgery in the area of the MRI changes render this case report difficult to interpret.

The paucity of published data begs the question: can isolated pressures in the small intrinsic hindfoot muscles be accurately measured in a practical clinical setting? It is certainly difficult. Based on our experience with the idealised conditions of an unswollen, immobile foot and a CT scanner to provide localisation of the needle, it is only with extreme care and constant referral to imaging guidance that a standard pressure-monitoring needle can be placed entirely within the very thin flexor digitorum brevis without overpenetration into quadratus plantae or underpenetration and measurement of pressure in the subcutaneous tissue. In the case of a swollen foot, an uncomfortable patient, and the lack of three-dimensional imaging guidance, the task is impossible.

We conclude that unless and until credible clinical data are presented showing relevant pressure differentials accompanied by careful proof of localisation of the needle, the division of the central hindfoot compartment into separate superficial and calcaneal compartments cannot be supported.

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References