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Original article

A cadaveric model of anterior compartment leg syndrome: Subcutaneous minimally invasive fasciotomy versus open fasciotomy

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ABSTRACT

Objective: Because of disabling sequelae of open fasciotomy in anterior compartment syndrome (ACS) of the leg, we wanted to describe and validate a cadaveric model of ACS. We hypothesized that, first, anterior compartment syndrome (ACS) could be reproduced in cadaveric leg and, second, fasciotomy without complete skin incision could lower the intramuscular pressure (IMP) in an equivalent range to complete dermatofasciotomy.
Materials and methods: Lower limb ACS was reproduced by progressive injection of physiologic serum in the anterior compartment of 23 fresh frozen cadaveric legs with monitoring of IMP, in order to reach a maximal stabilised IMP higher than 30 mmHg. Subcutaneous minimally invasive fasciotomy was performed on 14 legs through 5 transversal mini-incisions of the skin (2 cm) along the axis from the tibial tuberosity to the posterior aspect of the lateral malleolus. Standard open fasciotomy of the anterior compartment was performed on the remaining 9 legs as control. IMP was measured after the skin incisions and after every fasciotomy through skin incisions in the first group and after skin and fascia incisions in the control group.
Results: A maximal IMP of 43 ± 2 mmHg was obtained by injection of 177 ± 9 ml physiologic serum into the anterior compartment of the leg. In the control open fasciotomy group, the skin incision alone did not lower IMP significantly, whereas fasciotomy lowered IMP to 10 ± 1 mmHg, which is statistically different from maximal IMP ($p < 0.001$). In the subcutaneous fasciotomy group, complete fasciotomy lowered significantly the IMP to 11 ± 4 mmHg ($p < 0.001$), without statistical difference with the control group.
Discussion: This cadaveric model is effective to reproduce the hyperpressure encountered in ACS. In this model, IMP release after fasciotomy is as efficient through minimally invasive subcutaneous incision as with control open fasciotomy. This in vitro technique appears as an attractive alternative treatment in anterior compartment syndrome of the leg. It should be tested in the other compartments of the leg and its in vivo feasibility in acute conditions has to be clarified.
Level of evidence: III, control laboratory study.

1. Introduction

Acute lower limb compartment syndrome has been extensively described since the seventies. It is mainly characterized by increased intramuscular pressure (IMP), which compromises the perfusion of a muscular compartment [1–4]. In the lower limb, acute compartment syndrome is usually located in the anterior compartment of the leg and is mainly due to a fracture of the tibia and/or fibula, although other aetiologies exist such as vascular occlusion, muscular contusion or acute intense exercise [3,5,6]. Diagnosis is based on clinical findings and direct measurement of IMP. The main symptom consists in a severe rest pain which increases with time and with passive solicitation of the muscle contained in the compartment; later on associated with paraesthesia and ultimately motor deficit at the ischemic stage [2,3,7,8]. Diagnostic confirmation usually requires IMP measurement in the four compartments of the leg with a wick catheter although it is

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not always performed in cases of high clinical suspicion [4,7,9–11]. It is considered that muscular and neurologic perfusion is compromised when the difference between diastolic blood pressure and IMP (= perfusion pressure) is lower than 30 mmHg, although in daily practice diagnosis is often made if IMP is higher than 30 mmHg [2,4,6,7,10]. In absence of treatment, acute compartment syndrome leads to devastating consequences like muscular and neurologic necrosis, which can compromise the limb viability. The only treatment of compartment syndrome consists in lowering IMP by opening the deep fascia. It is usually performed via open dermatofasciotomy of the muscular compartment affected [6,10,12–15]. However, skin closure cannot systematically be achieved and the large skin incision causes an unaesthetic scar with possible functional sequelae [10,16]. A previous study already tried to minimise the length of the incision, but longitudinal dermatofasciotomy remained as long as 10 cm [17]. The aim of this study was to validate a subcutaneous minimally invasive fasciotomy in an experimental compartment syndrome performed in the anterior compartment of cadaveric legs.

We hypothesized that, first, anterior compartment syndrome (ACS) could be reproduced in cadaveric leg and, second, fasciotomy without complete skin incision could lower the IMP in an equivalent range to complete dermatofasciotomy.

2. Materials and methods

We used 23 fresh frozen cadaveric legs of men and women older than sixty years who had legated their bodies to the Université Catholique de Louvain. All the limbs had been disarticulated at the hip joint and stored anonymously at −20 °C (for knee arthroscopy trainings). In order to mimick ACS, physiologic serum (0.9% NaCl) was progressively injected in the anterior compartment under monitoring of intramuscular pressure (IMP) (Fig. 1). We used a 3 ways system connecting the pressure monitor (Baxter TrueCal 59PXCAL, Deerfield, Illinois, U.S.), a 60 ml syringe and a 40-mm-long needle with a diameter of 0.9 mm. The puncture point on the leg was situated at one third of the distance from the tibial tuberosity (TT) to posterior aspect of the lateral malleolus (LM). The system was purged and a zero calibration was performed prior to injection. Intramuscular pressure was recorded after injection of every 25 ml of physiologic serum waiting 7 to 10 minutes with no change for one minute for pressure stabilization. Physiologic serum was progressively injected to reach the maximum stabilised IMP, at a value higher than 30 mmHg.

Subcutaneous minimally invasive fasciotomy was performed on 14 legs through 5 transversal mini-incisions of the skin (2 cm) along the axis TT-LM, 2 cm lateral to the anterior margin of the tibia. The first incision was lateral to the distal end of the TT. Passing the scissors through the skin incisions allowed to easily separate the skin from the fascia of the leg and then to incise the deep fascia longitudinally. In this group, fasciotomy was performed from TT to LM (proximo-distal) on 5 legs and from LM to TT (disto-proximal) on 9 legs. Pressure was measured after the skin incisions and after every fasciotomy through skin incisions. Skin was then incised along the TT-LM axis to confirm the complete incision of the deep fascia and to look for superficial nerve injury.

Standard open fasciotomy was performed on the remaining 9 legs as control, after preliminary skin incision. Pressure was measured successively after skin and fascia incisions. In one leg, skin and fascia were cut together in the first incision, making intermediate pressure monitoring impossible.

All IMP of 3 groups had been compared: proximo-distal subcutaneous fasciotomy, disto-proximal subcutaneous fasciotomy and open fasciotomy.

All quantitative data were expressed as mean ± SEM. Statistical analyses were conducted using Instat (Graphpad software). Kruskall Wallis test (non parametric ANOVA) was used to compare the data of the 3 groups before any incision and at the end of experiment, when the deep fascia was completely sectioned. In each of the 3 groups, the successive IMP data were compared with the paired Friedman test (non parametric repeated measures ANOVA). The differences were considered significant for $p < 0.05$.

3. Results

3.1. Maximal IMP higher than 30 mmHg in the 3 groups

A maximal IMP of 43 ± 2 mmHg was obtained by injection of 177 ± 9 mL physiologic serum into the anterior compartment of the leg (Table 1). In only one case, progressive injection of 250 ml physiologic serum did not allow to reach a maximal pressure higher than 24 mmHg. In the 3 groups, the mean IMP was higher than 30 mmHg, but showed a great inter-individual variability and required variable volumes to reach them. In the control open fasciotomy group, injection of 194 ± 15 ml allowed to obtain a maximal IMP of 36 ± 2 mmHg. In the subcutaneous proximo-distal fasciotomy group, injection of 150 ± 0 ml allowed to reach a maximal IMP of 52 ± 2 mmHg and in the subcutaneous disto-proximal fasciotomy group, injection of 175 ± 14 ml allowed to reach a maximal IMP of 44 ± 3 mmHg. No statistical difference was observed between the 3 groups in the volume of injected serum ($p > 0.05$) and in the maximal IMP, except a significant higher IMP in subcutaneous proximo-distal fasciotomy group than in control group ($p < 0.01$).

3.2. Only fasciotomy significantly decreases IMP

In the control open fasciotomy group, the skin incision alone did not lower IMP significantly, with a value of 30 ± 3 mmHg. The fasciotomy lowered IMP to 10 ± 1 mmHg ($p < 0.001$) (Fig. 2).

In the minimally invasive subcutaneous fasciotomy groups, the 5 incisions of the skin lowered the IMP to 47 ± 3 mmHg (proximodistal group) and 40 ± 3 mmHg (distoproximal group). This decrease was not significant as related to the initial IMP.

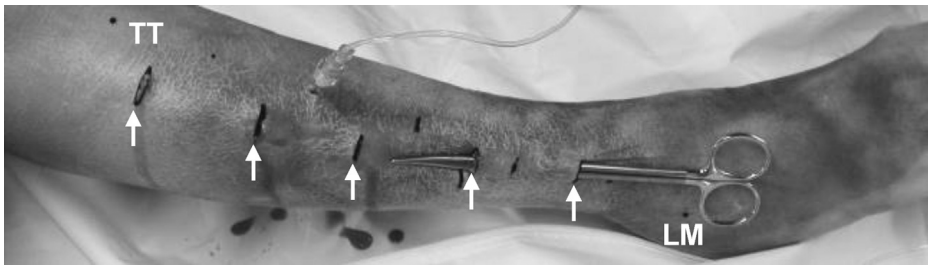

Fig. 1. Anterolateral view of the right leg of a fresh-frozen cadaver after injection of serum in order to obtain maximal IMP, illustrating the location of the needle in the anterior compartment, the skin mini-incisions (arrows) along the TT-LM axis and the dissection of the cutaneous and fascial planes with scissors.

Table 1
Total volume of injected serum and maximal intramuscular pressure (IMP) in the 3 experimental groups. Mean ± SEM.

Fasciotomy group	*n*	Injected volume(mL)	Maximal IMP(mmHg)
Open	9	194 ± 15	36 ± 2
Subcutaneous proximo-distal	5	150 ± 0	52 ± 2*
Subcutaneous disto-proximal	9	175 ± 14	44 ± 3
Total	23	177 ± 9	43 ± 2

* $p < 0.01$ versus open fasciotomy group.

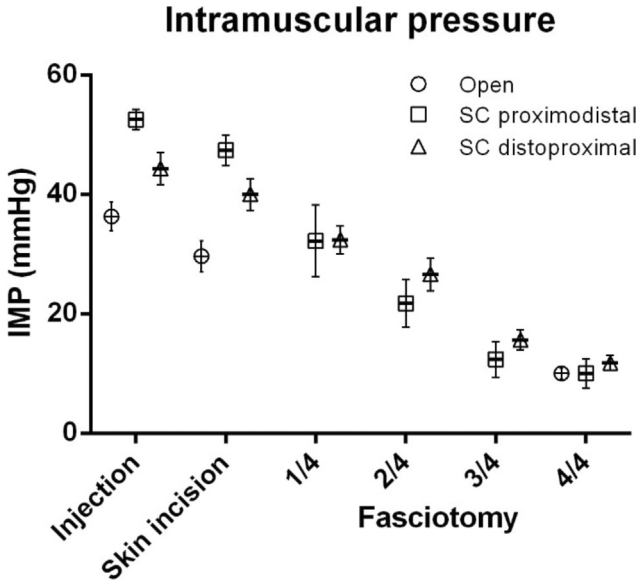

Fig. 2. Intramuscular pressure (IMP, mmHg) in the open fasciotomy (Open) and subcutaneous (SC) proximodistal and distoproximal fasciotomy groups after serum injection in the anterior compartment of the leg (maximal IMP), after skin incision and after deep fascia section. M ± SEM; $^{*}p < 0.05$; $^{**}p < 0.01$ and $p < 0.001$ by comparison with injection maximal IMP.

In the subcutaneous proximo-distal fasciotomy group, incision of the fascia in the proximal two quarters of the leg lowered IMP to 32 ± 6 mmHg ($p > 0.05$) and 22 ± 4 ($p > 0.05$), respectively, without significant difference with the maximal IMP (Fig. 2). A significant decrease of IMP was obtained when incising the third quarter (12 ± 3 mmHg, $p < 0.01$) and the last fascia incision lowered IMP to 10 ± 2 mmHg ($p < 0.001$). Compared to the IMP after skin incision, the difference was significant with the last fascia incision only ($p < 0.05$).

In the subcutaneous disto-proximal fasciotomy group, incision of the fascia in the distal quarter of the leg did not significantly lower IMP (32 ± 2 mmHg, $p > 0.05$) (Fig. 2). Incision of the second, third and last quarters significantly reduced IMP to 27 ± 3 mmHg ($p < 0.05$), 16 ± 2 mmHg ($p < 0.001$) and 12 ± 1 mmHg ($p < 0.001$), respectively. In comparison with skin incision, the reduction of IMP was significant only after the third ($p < 0.05$) and last ($p < 0.001$) fascia incisions.

In both these groups, the longitudinal skin incision made after fasciotomy confirmed that complete fasciotomy was achieved in all the cases. IMP did not further decrease after this longitudinal skin incision. Although no significant nerve lesions were clearly identified, the main branch of the superficial fibular nerve was very close to the fascia incision.

3.3. IMP reduction by subcutaneous fasciotomy is as efficient as open fasciotomy

After complete fasciotomy, IMP (10 ± 2 mmHg in subcutaneous proximo-distal fasciotomy group, 12 ± 2 mmHg in subcutaneous disto-proximal fasciotomy group and 10 ± 1 mmHg in the control open fasciotomy group) was not statistically different between the groups (Fig. 2).

4. Discussion

The present study showed that increased intramuscular pressure comparable to acute compartment syndrome could be obtained in anterior compartment of cadaveric legs. This validated our first hypothesis, although the pathophysiology of this syndrome involves a cascade of events that cannot be only summarized by an elevated IMP.

ACS could be reproduced with accuracy in our cadaveric model. In all legs, except one, we obtained a maximal IMP higher than 30 mmHg. However, the data showed a large inter-individual variability and the volume injected to reach maximal IMP was also highly variable from one leg to another. In our experiment, we considered only a stabilised value of IMP, after 7 to 10 minutes and with no change for one minute. Indeed, IMP has been shown to decrease after a longer delay [9], because of the slight fluid tissue diffusion. In absence of information concerning the cadaveric subjects, particularly their age, comorbidity, corpulence and BMI, the inter-individual variability cannot be related to individual characteristics. Furthermore, quality of conservation might play a role in the level of IMP, although macroscopic aspect of all legs was normal. It could explain why maximal IMP could not exceed 24 mmHg in one leg. Precautions should be taken when interpreting the results of an experimental study performed on legs from subjects older than 60 years whereas acute syndrome occurs typically in the young male population. As older muscular and connective tissue could be more compliant [18], the onset of compartment syndrome could be delayed in older patient.

This experimental model allowed us to show an efficient reduction of IMP when sectioning the deep fascia through subcutaneous mini-incisions. This answered our second hypothesis. The IMP release after fasciotomy was as efficient through minimally invasive subcutaneous incision as with open dermatofasciotomy. The pressure reduction after the skin incision only, although not significant, was lower in the subcutaneous group than in the dermatofasciotomy group. That is easily understandable and do not compromise the significant pressure decrease with the fasciotomy. Those results are in contradiction with the notion that the skin envelope is a contributing factor in acute compartment syndrome of the lower limb [13].

Our technique seems as effective as a previous in vitro study with 10-cm-long dermatofasciotomy combined with transverse fasciotomy, but even less invasive [17]. In chronic compartment syndrome, an endoscopic method with only one small skin incision had been extensively described in vitro [19]. The technique

was then tested in vivo, however the use of pressurized fluid and the need of learning curve make it unusable in acute situations [20,21].

Experimental reproduction of compartment syndrome in cadaveric legs nevertheless differs from real post-traumatic acute compartment syndrome. The inflammatory response, the contusion and the fracture misalignment may play an important role in subcutaneous swelling that is not accounted for in this model. We cannot conclude that skin do not contribute to compartment syndrome in acute traumatic situation, but only in the cadaveric model.

Superficial fibular nerve is at risk when performing the distal third subcutaneous fasciotomy along the axis TT-LM. Its course and, especially, its emergence out of the fascia are known to be highly variable. This nerve emerges through fascia of lateral compartment in two third of the cases, but could also pierce the anterolateral intermuscular septum and emerge in anterior compartment, or divide into two main branches before crossing the septum, giving ramifications in both compartments [22–24]. In a recent meta-analysis including 665 lower limbs [25], the emergence of the superficial fibular nerve as a single structure through the fascia, before bifurcating into medial and intermediate dorsal cutaneous nerves, had a general prevalence of 82% (Fig. 3). As the nerve course has been demonstrated symmetrical in the same individual [23], it could be clinically located in the uninjured contralateral leg with the foot in maximal inversion and plantar flexion. Endoscopic-assisted fasciotomy could help to avoid the neuro-vascular bundles, but it cannot be performed in acute conditions [19–21]. Lesion to the nerve could be avoided by incomplete section of the inferior fascia. As therapeutic effect has been reached with the 2nd or 3rd incision in the subcutaneous group, the most distal fascia incision could be avoided without compromising therapeutic effect. A tourniquet effect is unlikely as IMP decrease with fasciotomy, the muscles extending by their tendons in the distal part of the leg. The superficial fibular nerve could also be preserved by changing the fasciotomy axis to follow the tibial crest slightly laterally. Finally, the role of the superficial fibular nerve has to be put into perspective as this nerve is used as autologous graft for the treatment of upper limb peripheral nerve injuries [24]. In case of lesion, the morbidity would be limited to partial sensitive defect of the lateral dorsal ankle and foot, without walking complain [26].

This study was limited to the leg anterior compartment. Nevertheless, the axis TT-LM of the 5 transversal mini-incisions of the skin permits to reach and incise the fascia of lateral compartment. The lateral compartment could not be opened if the incision axis followed the tibial crest. In all the cases, access to the posterior compartments requires another skin incision axis. Other compartments of the leg should be studied.

Our model shows some limitations, as discussed above. Firstly, we reproduced excessive IMP of compartment syndrome but not the entire pathophysiology of the acute disease. Furthermore, the tissue elasticity of elderly cadaver leg differs from young male tissue involved in acute situation. Finally, only a single compartment was pressurized whereas, in a traumatized limb, the whole leg is often involved.

In conclusion, the cadaveric model is valid and subcutaneous minimally invasive fasciotomy appears in vitro as an attractive alternative treatment in ACS of the leg, as the IMP decrease is comparable to the open fasciotomy. Further investigations should be performed in order to transpose our results to patients.

Disclosure of interest

The authors declare that they have no competing interest.

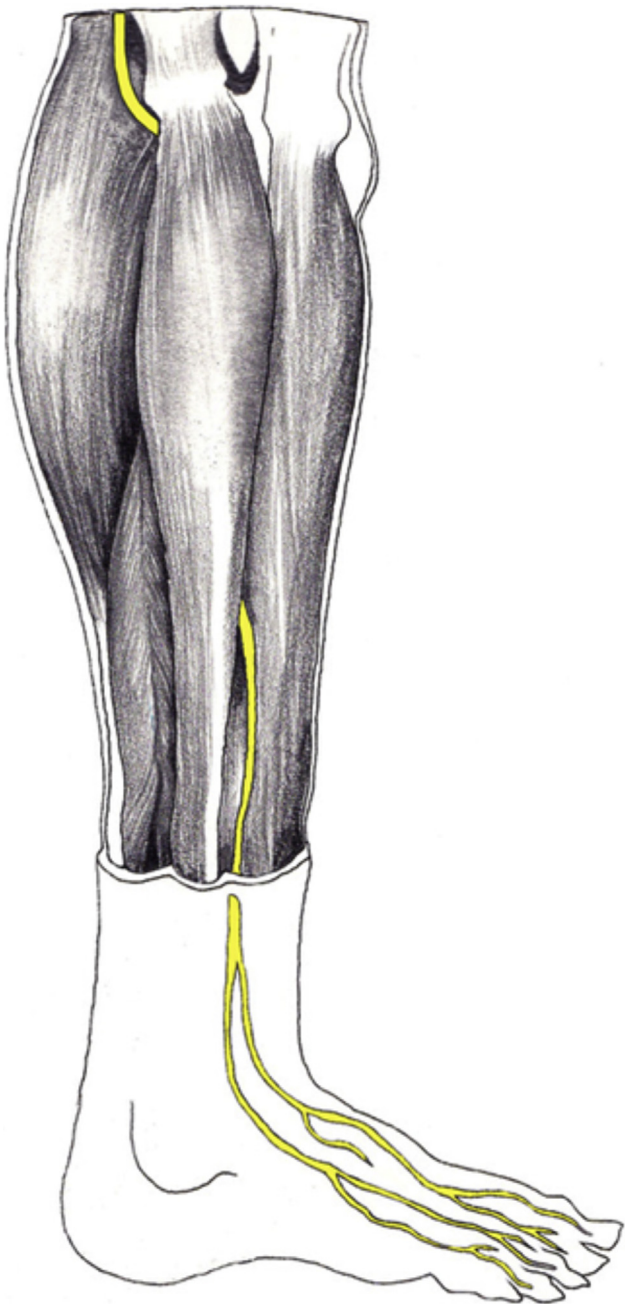

Fig. 3. Most common course of the superficial fibular nerve: emerges through fascia of lateral compartment as a single structure before bifurcating into medial and intermediate dorsal cutaneous nerves.

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Contribution

Simon Vandergugten: technical manipulation, text redaction.
Laurent Zemmour: helping technical manipulation.
Benoît Lengelé: original idea, relecture.
Catherine Nyssen-Behets: promotor, helping technical manipulation, manuscript correction.

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