Predictors of Positive Outcomes and a Scoring System to Guide Management After Fasciotomy for Chronic Exertional Compartment Syndrome

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Background: Chronic exertional compartment syndrome (CECS) of the lower limb usually responds well to fasciotomy in patients with failed nonoperative treatment. Careful history taking and compartment pressure testing are both required to accurately diagnose CECS.

Purposes: To evaluate patients with CECS after fasciotomy to establish predictive criteria of positive outcomes and to develop a scoring system to aid clinicians in their management of such patients.

Study Design: Case-control study; Level of evidence, 3.

Methods: We reviewed data from 28 patients who underwent fasciotomy between 2017 and 2019. All patients had undergone preoperative dynamic intracompartmental pressure (ICP) monitoring. For each patient, subjective preoperative and postoperative pain scores were gained via a questionnaire. The point biserial and Pearson correlation coefficients were used to calculate the association between multiple diagnostic criteria and a reduction in visual analog scale (VAS) pain scores after fasciotomy.

Results: A reduction in VAS pain scores was strongly correlated with a peak ICP >40 mm Hg ($r = 0.71$; $P = .0007$) and an area under the receiver operating characteristic curve for an intraexercise ICP >22,000 mm Hg·s^2 ($r = 0.76$; $P = .0002$). A moderate correlation was found between a history of CECS pain ($r = 0.61$; $P = .005$), a duration of symptoms of <30 minutes after stopping exercise ($r = 0.60$; $P = .006$), and a gradient in the intraexercise ICP >10 mm Hg ($r = 0.60$; $P = .006$). When combined into an objective, weighted scoring system (2 points for factors with $r > 0.7$; 1 point for $r = 0.5$-0.7), a score of ≥4 points (of 7) had a strong correlation ($r = 0.85$; $P < .00001$) with postoperative improvement in the VAS pain score. Linear regression of this score demonstrated a good fit ($R^2 = 0.61$; $P < .0001$), indicating a degree of predictive power.

Conclusion: We identified diagnostic criteria in the history and examination of patients with CECS that can be used to help predict positive outcomes after fasciotomy. We propose a scoring system to aid clinicians in their management of such patients. We recommend taking these results forward in prospective trials to test the efficacy of predictive scoring.

Keywords: chronic exertional compartment syndrome; compartment syndromes; diagnosis; prognosis

Chronic exertional compartment syndrome (CECS) of the lower limb is an increasingly understood and diagnosed condition in a predominantly athletic population. If nonoperative treatment methods do not adequately relieve symptoms, surgery in the form of fasciotomy is often performed and is associated with positive reported outcomes. There is, however, a variability in published outcomes after this procedure, with good to excellent outcomes reported in 60% to 96% of patients.[11,13,14] Given the variability in reported surgical success, it is important that we, therefore, ascertain which patients do well and why and conversely which patients do less well and why. If we know why, then this can guide clinicians toward more successful patient selection for surgery. Fasciotomy is now a standardized procedure with techniques well described in the literature.[3,12] The technique is reproducible, with the main risks being nerve injuries, incomplete release, or wound complications.[2] It is, therefore, our view that the failure of surgery is more likely to be related to patient selection rather than the surgical procedure itself.

An accurate diagnosis of lower limb CECS is made after careful patient history taking and intracompartmental pressure (ICP) testing. Clinical examination findings are frequently normal. A classic history is that of pain in a muscle

compartment on exertion that is relieved by rest. If a diagnosis of CECS is considered, then ICP testing is performed. This can be either static testing of compartment pressures before and after exercise or continuous (dynamic) testing of pressures taken while exercise is performed. The most frequently cited pressure values for diagnosing CECS were produced by Pedowitz et al[8] in 1990, and the majority of published work since this time has utilized these figures. ICP testing itself is likely to have inherent inaccuracies because of probe placement and variations in ICP, and therefore, an accurate diagnosis will likely require a combination of criteria from both patient history and ICP testing.

The aim of this study was to evaluate a cohort of patients with lower limb CECS for proposed predictive features of a positive surgical outcome after fasciotomy. The secondary aim was to produce guidance for clinicians as to which patients are more likely to have a positive outcome after surgery. We hypothesized that predictive factors of a positive surgical outcome would be identifiable from analysis of a patient cohort against previously suggested diagnostic criteria.

METHODS

Participant Recruitment

Ethical approval for this study was not required by the National Health Service Health Research Authority. Patients with failed nonoperative management for clinically diagnosed CECS, underwent dynamic ICP monitoring of the lower limb, and subsequently underwent decompression surgery were included. All patients assessed between 2017 and 2019 were assessed for inclusion in the study (n = 58). The only exclusion criterion was not undergoing fasciotomy. All patients who had a history suggestive of CECS were offered fasciotomy, regardless of pressure testing results. Half of the patients seen were ultimately diagnosed with other conditions based on history taking or declined surgical treatment. The remaining 29 patients underwent decompression surgery and were eligible for the study. All pressure testing was performed at our regional center for the treatment of this condition. Decompression surgery was performed either at the study center (n = 19) or at the referring hospital (n = 10). When fasciotomy was performed, all compartments were released in all cases.

Patients were given a questionnaire regarding preoperative disability and postoperative outcomes. A reminder telephone call was made to those who did not respond. Patients were asked to rate their preoperative and postoperative exertional pain on a visual analog scale (VAS) from 1 to 100 (worst pain) and were also asked to provide qualitative ratings of their preoperative and postoperative

exertional pain. The qualitative assessments included the type of activity that gave them symptoms, the level of their activity, whether they were able to return to their premorbid activity level, and their overall satisfaction with the outcome of surgery. Surgery was deemed successful primarily by a subjective reduction in the VAS pain score, although we did not define any prescriptive criteria for how much reduction was deemed "successful."

Compartment Pressure Testing

Dynamic ICP testing was conducted on all patients in the clinic. Patients had a pressure catheter inserted into the compartment being investigated under landmark guidance. Guided by symptoms, pressure tests were performed in either the anterior or deep posterior compartment. If symptoms were in both compartments, the worst affected would be measured first and the lesser affected measured if the patient wished. The lateral compartment was not included for testing because, despite new literature on the topic of isolated lateral compartment CECS,[21] at the time of the study design, this evidence was not clear, and we believed that further compartment testing did not warrant more discomfort for patients.

ICP measurements were obtained continuously and pressures mapped onto a graph. The patients were asked to lie down, stand, and then begin to run (or walk) on a treadmill for up to 10 minutes. They were then asked to stop, and pressures were continuously monitored for a further 5 minutes. A similar method of dynamic testing has been described in the literature.[4] An example of a graph generated can be seen in Figure 1.

The ICP graph was analyzed in a number of ways. The gradient in the intraexercise ICP was calculated first. This was calculated by placing a line of best fit for the intraexercise curve. The pressure value at which the line of best fit intersected the y-axis at the end of exercise was subtracted from that at the point at which rest commenced (Figure 2).

The area under the receiver operating characteristic curve (AUC) of the ICP graph was calculated by smoothing out variations in the lines and determining the number of boxes under the curve line on the graph. Each box represents 2000 mm Hg·s^2. The total AUC for the intraexercise section of the graph was calculated. The system automatically recorded the maximum pressures reached before exercise, during exercise, and 5 minutes after exercise.

Cutoff Values for Positive Predictive Outcomes

The cutoff for peak ICP was decided based on the literature. A defined cutoff of 30 mm Hg as a diagnostic peak

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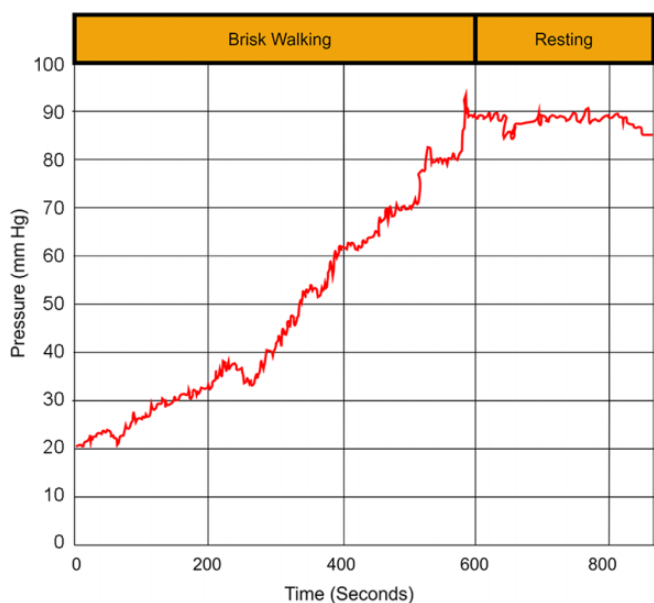†Trauma and Orthopaedic Department, Royal United Hospitals, Bath, UK.

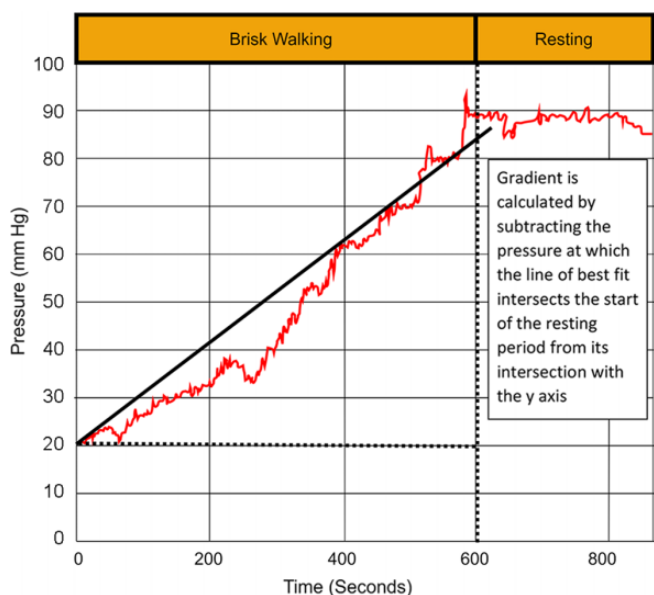**Figure 1.** Example of an intracompartmental pressure graph.

Figure 2. Calculation of the gradient in the intraexercise intracompartmental pressure.

compartment pressure value is often cited,[16] but this figure is not universally accepted.[1] As such, we chose a cutoff of 40 mm Hg to clear the bar of contention.

The cutoff for the gradient in the intraexercise ICP was selected to be 10 mm Hg, as this would include all graphs with a significantly positive trend. It would exclude graphs with a probable neutral or negative line of best fit.

The choice of a cutoff for the intraexercise AUC was more difficult to make, as there are no published studies that have reported this number in a recognizable format. The only studies that have previously assessed this variable used the total graph (including pre-exercise and resting figures), and neither reported the area in numerical terms with units.[18,19] As such, we chose a value that reflected the mean point of our reported range of AUCs in all patients tested for CECS. This figure was 22,000 mm Hg·s^2.

Statistical Analysis

The predictive factors that we chose to study were those that have previously been theorized to have a causative or predictive link by the studies mentioned above.[5,7-9,11,15,17-19] These factors included demographic data (age and sex), clinical aspects (history of CECS pain, duration of symptoms from onset to resolution with rest), and dynamic ICP data (pre-exercise standing pressure, peak intraexercise pressure, AUC of the intraexercise ICP graph, gradient in the intraexercise ICP, and 5-minute postexercise pressure). Analysis of the correlation between these aspects and a reduction in VAS pain scores was performed using either the Pearson correlation coefficient if the data were continuous or the point biserial correlation coefficient if they were categorical. A correlation coefficient of 0.5 to 0.7 was deemed "weak"; a correlation coefficient of >0.7 to 1.0 was deemed "strong." A statistical significance of $P = .05$ was assumed.

We assigned those predictive factors that had a strong correlation ($r > 0.7$) 2 points each and factors with a moderate correlation ($r = 0.5$-0.7) 1 point each. This created a potentially predictive score that we have called the compartment syndrome (CoSy) score. This score was plotted against a reduction in VAS scores and underwent linear regression modeling. In addition to this, we calculated the point biserial correlation coefficient for a reduction in VAS scores with having a CoSy score of ≥ 4 (ie, half of the available points or more). The number of patients with a CoSy score of >4 or <4 who returned to a higher level of sports postoperatively was also determined, and the chi-square test was performed to establish if this difference was significant. Statistics calculated using SPSS 28 (IBM).

RESULTS

Of 29 eligible patients, 28 (97%) patients responded. Patient characteristics can be seen in Table 1. The correlation coefficients for each potentially diagnostic criterion are displayed in Table 2. There were 5 predictive factors that correlated strongly or moderately ($r \geq 0.5$) with positive outcomes: AUC of an intraexercise ICP >22,000 mm Hg·s^2, peak intraexercise ICP >40 mm Hg, history of CECS pain, gradient in the intraexercise ICP >10 mm Hg, and symptoms lasting <30 minutes from rest.

The CoSy score was determined based on predictive factors with strong to moderate correlations and is shown in Table 3. The total score possible, therefore, was 7. We performed linear regression modeling on whether this score was likely to predict a reduction in VAS pain scores (Figure 3). The R^2 value for this graph was 0.61 ($P < .0001$), indicating a good fit and a significant relationship between an increasing CoSy score and a reduction in VAS pain scores. The graph showed a clear split at a score of 4, which

TABLE 1
Patient Characteristics (N = 28)[a]

	Value
Age, mean (range), y	36 (16-63)
Sex, male:female	15:13
Leg affected, left:right	14:14
Compartment	
Anterior	15
Deep posterior	14
Premorbid level of activity	
Recreational	13
Local	14
National	1
Follow-up time, mean (range), y	2 (2-6)

[a]Data are shown as No. unless otherwise indicated.

TABLE 2
Correlation of Predictive Criteria With Improvement in
VAS Pain Score[a]

	r Value	P Value
AUC of intraexercise ICP >22,000 mm Hg·s^2	0.76	**.0002**
Peak intraexercise ICP >40 mm Hg	0.71	**.0007**
History of CECS pain	0.61	**.005**
Gradient in intraexercise ICP >10 mm Hg	0.60	**.006**
Symptoms lasting <30 min from rest	0.60	**.006**
Change in peak vs postexercise ICP	0.46	**.01**
Change in standing pre-exercise vs peak ICP	0.40	.08
Pre-exercise ICP >15 mm Hg	0.39	**.03**
Compartment (anterior vs deep posterior)	0.27	.26
5-min postexercise ICP >20 mm Hg	0.22	.2
Age	0.08	.6
Sex	0.06	.7

[a]Boldface P values indicate statistical significance (P < .05).
AUC, area under the receiver operating characteristic curve;
CECS, chronic exertional compartment syndrome; ICP, intracompartmental pressure; VAS, visual analog scale.

TABLE 3
CoSy Score[a]

	Score
AUC of intraexercise ICP >22,000 mm Hg·s^2	2
Peak intraexercise ICP >40 mm Hg	2
History of CECS pain	1
Gradient in intraexercise ICP >10 mm Hg	1
Symptoms lasting <30 min from rest	1

[a]AUC, area under the receiver operating characteristic curve;
CECS, chronic exertional compartment syndrome; CoSy, compartment syndrome; ICP, intracompartmental pressure.

was also the predetermined level that we assumed we would use for a "positive" score. We undertook further point biserial correlation analysis of the data to explore the correlation between a CoSy score ≥4 and VAS pain scores, which showed an r value of 0.85 (P < .00001).
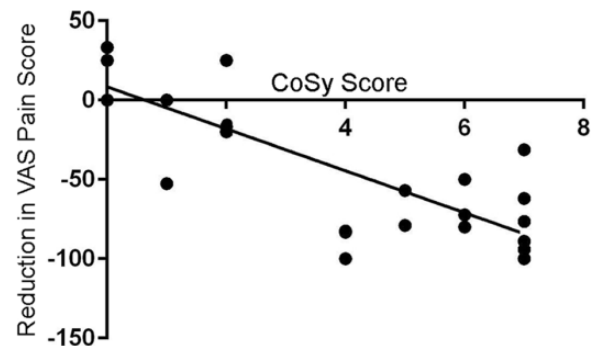

Figure 3. Linear regression model for compartment syndrome (CoSy) score and reduction in visual analog scale (VAS) pain score ($R^2 = 0.61$; $P < .0001$).

Of 18 patients with a CoSy score ≥4, overall, 16 (89%) returned to a higher level of sports after fasciotomy. Only 2 (20%) of 10 patients with a CoSy score <4 returned to a higher level of sports. This difference was significant ($\chi^2 = 13.3$; $P = .0002$).

DISCUSSION

The work behind CECS has centered on its pathophysiology and on its treatment.[2] However, there has been little work done on the predictive factors for a successful postoperative outcome in this patient population, and such aids for diagnosis and management are recognized as potentially useful.[20] A literature review of PubMed for articles looking at predictive factors or risk factors for a successful or unsuccessful surgical outcome in adult patients with CECS found 9 studies[5,7-9,11,15,17-19] in the past 20 years. We identified 5 factors that were moderately to strongly correlated with an improvement in VAS pain scores: intraexercise AUC >22,000 mm Hg·s^2, peak intraexercise ICP >40 mm Hg, gradient in the intraexercise ICP >10 mm Hg, history of CECS pain, and symptoms lasting <30 minutes from rest.

We found a significant correlation between an increased AUC of the intraexercise ICP and a reduction in VAS pain scores, with a strong correlation if the AUC was >22,000 mm Hg·s^2 ($r = 0.76$; $P = .0002$). This value reflects the cumulative pressure in the compartments during exercise. This has only been studied by 1 research group previously, which has reported conflicting results between its studies.[18,19] In their first retrospective study of 52 patients, Winkes et al[19] found a weak predictive relationship between the ICP immediately after exercise, the AUC of a 4-point ICP graph, and an improvement in pain scores. However, later, the same group provided data that were in contrast with the previous findings, showing no relation between these factors.[18] The group studied a graph that included the whole duration of testing, so pre-exercise and postexercise pressures were included. We aimed to study intraexercise pressures only, as symptoms occur during this time, and found positive results.

We also found a correlation of a peak ICP >40 mm Hg with an improvement in pain ($r = 0.71$; $P = .0007$). This

association was analyzed by Packer et al,[7] who found non-significant increases in the number of patients with poor postoperative outcomes if their peak ICP was <40 mm Hg. This evidence is backed up by experimental data that showed a moderate correlation between increasing ICP and increasing pain during exercise.[15] However, 2 further retrospective reviews found no correlation at all between peak ICP or postexercise ICP and improvement after surgery.[5,9] Yet, only 1 of these studies explicitly sought to identify these predictive factors in the study design,[9] so these results are of weaker quality in answering this specific question.[9] Our result, therefore, is broadly in keeping with the published literature.

There was also a correlation with the gradient in dynamic pressure in the current study in that a positive gradient in the intraexercise ICP was associated with an improvement in pain after fasciotomy ($r = 0.60$; $P = .006$). This has not previously been studied, so we cannot compare this with the published literature.

A history of pain ($r = 0.61$; $P = .005$) and the duration of symptoms from onset to the cessation of pain ($r = 0.60$; $P = .006$) were both correlated with an improvement in pain after fasciotomy. Previous studies have reported the importance of good history taking on the diagnosis of CECS,[1] but as noted, the relationship between diagnosis and improvement after fasciotomy is not clear. Our findings suggest that the more classic the history, the more likely the patient is to improve after surgery. Most importantly from the history was that pain resolves within 30 minutes of rest.

In our data set, we found no correlation between an improvement in pain and patient age, patient sex, or involved compartment. A number of studies have evaluated age as a predictive factor. In a large retrospective cohort of military participants, Waterman et al[17] found that older age was an independent predictive factor for surgical failure, and Packer et al[7] also found that high school pupils and college students fared better after fasciotomy than postcollege-aged patients. A recent abstract also hinted that age can be a predictive factor.[6] The difference between our results and the results of these articles is that our mean age was older than that in the Packer et al study, and the inclusion of more young patients may alter our results.

The data around sex and outcomes are relatively settled. Our study agrees with the largest and highest quality work that has evaluated this topic.[7,17,19] There are data from a recently published abstract[6] that suggested that male patients have better outcomes; however, without the full data, we cannot evaluate this claim adequately.

One study reported poorer outcomes for deep posterior compartment CECS[11] than for anterolateral CECS. This study was a similarly sized analysis to ours, but the follow-up period was significantly shorter. As such, the difference in these results may represent the small sample sizes of both studies, and the shorter follow-up period may have missed patients with a successful long-term outcome, who were reflected in our data.

We found no correlation with other reported ICP measurements such as pre-exercise pressure or 5-minute postexercise pressure.[8,15] The difference in these results may reflect methodological differences. For example, Tam et al[15]

only reported significant findings for these measures when using verbally reported pain scales. When using the VAS, they found no significant correlation between these static measures and pain improvement. As they themselves mentioned, comparing pain across different tools is difficult, and our results on the VAS tool agree. One other published result shows no correlation between postexercise pressure and pain reduction,[5] so the data here are conflicting.

There is also evidence to support a delay of >12 months from the diagnosis as a predictor of poor outcomes after surgery.[13,19] This is an important reminder that nonoperative treatment methods and time are often prerequisites to attempting surgical therapy. Further minor evidence showed that runners are less likely than other athletes to return to their chosen sport after fasciotomy.[10]

Linear regression analysis of the CoSy score ($R^2 = 0.61$) suggested a good predictive element for a high score and better pain reduction after fasciotomy. The correlation data also suggested that the cutoff score for a positive outcome is likely 4. Another positive indicator was the increased likelihood of returning to a higher level of sports after fasciotomy in patients with a CoSy score ≥ 4.

Limitations

The small sample size of this cohort and lack of a comparative nonoperative management arm are limitations of the study and represent a difficulty in extrapolation. The exclusion of patients treated nonoperatively indicates that it is unclear whether the CoSy score accurately predicts poor outcomes after nonsurgical treatment as well. This will be studied directly at a later date. There is a further limitation in that the lateral compartment was not assessed. Given recent data on isolated lateral compartment CECS, this may suggest that we missed patients with a treatable disease, which could have altered our results. Further, approximately half of those treated were operatively treated at centers other than our own, indicating that we had no control over the quality of the operative procedures performed or guarantee that all compartments were adequately released according to our protocol. Additionally, as this study was retrospective, there was certainly the potential for recall bias because preoperative VAS scores were provided later.

Finally, the value suggested for the AUC cutoff was arbitrary and has not been validated by other literature, as this is the first study that has used such a criterion. Further work should be undertaken to validate a "normal" AUC. However, this figure suggests that there are predictive factors in history taking and dynamic ICP testing that can inform clinicians in their decision of whether to offer their patients fasciotomy.

We are aware that not all centers utilize dynamic pressure monitoring and instead use static pressure testing before or after exercise. This would prevent the use of AUC measurements and the gradient in pressure changes as guides for a diagnosis. However, if patients provided a classic history of symptoms that improved after 30 minutes' rest and had peak pressures >40 mm Hg after exercise, then this would still provide evidence that they could

potentially be good surgical candidates for decompression with a CoSy score of 4.

There is a need to explore these data further via a prospective, larger cohort of patients, and this work is ongoing. In the meantime, we suggest that there is sufficient evidence to use the CoSy score as a guide to decision making in the management of potential lower limb CECS.

CONCLUSION

We have identified diagnostic criteria in the history and examination of patients with CECS that can be used to help predict positive outcomes after fasciotomy. We propose a scoring system to aid clinicians in their management of such patients. We recommend taking these results forward in prospective trials to test the efficacy of predictive scoring.

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