Injury, Int. J. Care Injured 50 (2019) 627–632

Contents lists available at ScienceDirect

Injury

journal homepage: www.elsevier.com/locate/injury

Use of standard musculoskeletal ultrasound to determine the need for fasciotomy in an elevated muscle compartment pressure cadaver leg model

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ARTICLE INFO

Keywords:
Compartment pressure measurement
Ultrasound
Non-invasive
Acute compartment syndrome

ABSTRACT

Introduction: Acute compartment syndrome (ACS) is a limb-threatening condition often associated with leg injury. The only treatment of ACS is fasciotomy with the purpose of reducing muscle compartment pressures (MCP). Patient discomfort and low reliability of invasive MCP measurements, has led to the search for alternative methods. Our goal was to test the feasibility of using ultrasound to diagnose elevated MCP.

Methods: A cadaver model of elevated MCPs was used in 6 cadaver legs. An ultrasound transducer was combined with a pressure sensing transducer to obtain a B-mode image of the anterior compartment, while controlling the amount of pressure applied to the skin. MCP was increased from 0 to 75 mmHg. The width of the anterior compartment (CW) and the pressure needed to flatten the bulging superficial compartment fascia (CFFP) were measured.

Results: Both the CW and CFFP showed high correlations to MCP in the individual cadavers. Average CW and CFFP significantly increased between baseline and the first elevated MCP states. Both Inter-observer and intra-observer agreements for the ultrasound measurements were good to excellent.

Discussion: Ultrasound indexes showed excellent correlations in compartment pressures, suggesting that there is a potential for the clinical use of this modality in the future.
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Introduction

Acute compartment syndrome (ACS) remains one of the few emergencies in orthopaedic trauma [1,2]. Early diagnosis and treatment of this condition are crucial to limiting poor outcomes [1–4]. Diagnosis of ACS is controversial and is based on a combination of subjective assessment of clinical symptoms and signs, possibly aided by objective measurements of the compartment pressure [5] using slit catheters, side-port needles, and ultrafiltration catheters [2]. Other methods for diagnosis of ACS, such as near infra-red spectroscopy and intra-muscular pH measurements, have been described but have yet to be widely adopted in clinical practice [1–4]. Regardless of the method used to diagnose ACS, the only known treatment of ACS is fasciotomy of all involved compartments, aimed at reducing the muscular compartment pressure (MCP) in the involved in extremity [5]. Fasciotomy itself, is associated with complications such as chronic pain, nerve injury, chronic muscle weakness, venous insufficiency, poor cosmesis and need for reoperation [5], thus heightening the need for accurate diagnosis of elevated MCP. Direct MCP measurement is not routinely performed by some surgeons due to its invasive nature, the considerable disagreement over the appropriate threshold pressure for diagnosis of ACS and the high (35%) false positive rate and variability of a single invasive MCP measurement [5–10].

The drawbacks of pressure-based methods to diagnose ACS have led to interest in alternative diagnostic methods. Near-Infrared Spectroscopy (NIRS) has shown good results in laboratory experiments [11,12] and some clinical studies [13,14] but has not shown diagnostic utility or established standards of use and has not gained wide acceptance in clinical practice [2,4,5,15].

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https://doi.org/10.1016/j.injury.2019.01.015
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Ultrasound-based methods such as the pulse-phase locked loop (PPLL) technique have shown value in examining cadaveric and healthy subjects [16–20]. However, no trials are available to demonstrate the utility of PPLL in the clinical situation. Ultrasound elastography (USE) involves measurements of deformation in response to applied stress or force [21]. The result is a mainly qualitative assessment the elastic modulus [22]. This qualitative assessment is also achieved by the acoustic radiation force impulse (ARFI) technique in which the ultrasound transducer generates a push beam within the tissue to apply stress and measures the tissue displacement along the push beam [23]. Shear-wave elastography (SWE) is an ultrasound elastography technique that uses shear waves to measure tissue stiffness quantitatively. Unlike the use of USE and ARFI, the use of SWE to characterize tissue stiffness does not require knowledge of applied stress [24]. The SWE technique has shown excellent correlations between shear elastic modulus and Young's elastic modulus in skeletal muscle [21,25,26] and seems promising in its clinical implication but is currently subject to high costs and limited availability.

Regardless of the methods used for earlier more accurate diagnosis of ACS, the need for urgent fasciotomy should be established by the diagnosis of presently elevated MCPs. The ideal noninvasive technique for diagnosing elevated MCPs should be accurate, reliable and low in cost. In this study, we present an ultrasound-based method for the diagnosis of elevated MCPs. This technique uses a standard musculoskeletal ultrasound transducer combined with a pressure sensing transducer to assess MCP. The aims of this study are 1) To evaluate the accuracy of the proposed technique in quantifying MCP in a cadaveric lower extremity elevated MCP model and 2) To assess the reliability of the proposed method.

Methods

Cadaver model for elevated muscle compartment pressure

Six cadaveric legs from three donors (two male, one female, average age 71 years, BMI: 12.5 ± 1.1) were used for this study. All cadaveric specimens were evaluated fluoroscopically and cleared of any history of significant trauma or surgery. A previously described cadaveric model that allows MCP elevation was used [27]. Each leg was placed on a wooden stand and stabilized to the table with the ankle in a non-flexed position. A marking pen was used to mark the anterior compartments of the cadaver legs at 15 cm, 20 cm, and at 25 cm superior to the malleoli level of each leg. Under ultrasound guidance, a handheld MCP monitor (Stryker - Intra-Compartmental Pressure Monitor System, USA) was attached through an IV catheter to a slit catheter at the 15 cm mark to confirm anterior compartment pressure. We confirmed placement of the needle deep to the 20 cm mark using ultrasound. A saline inflow catheter needle was inserted into the anterior compartment at the 25 cm mark and confirmed to be in place deep to the 20 cm mark using US imaging. Both the inflow catheter and IV needle were sutured to the skin to prevent pullout (Fig. 1). Saline was introduced into the anterior compartment to increase MCP. We attached a container with a spigot to a metal IV tree and connected tubing with a stopper to the spigot. We placed a stopper and filled the pitcher with saline (1.0 g/mL3 density). The pitcher was elevated or lowered incrementally to adjust the required fluid-based MCP.

Assessment of compartment pressures using ultrasound

The standard musculoskeletal ultrasound transducer [Hitachi Noblus, Japan] was combined with a pressure sensing transducer (VeinPress, Switzerland). The coupled transducer allows for obtaining a B-mode image of the anterior compartment while controlling the amount of applied pressure (AP) to the skin, which is displayed on a monitor screen (Fig. 2).

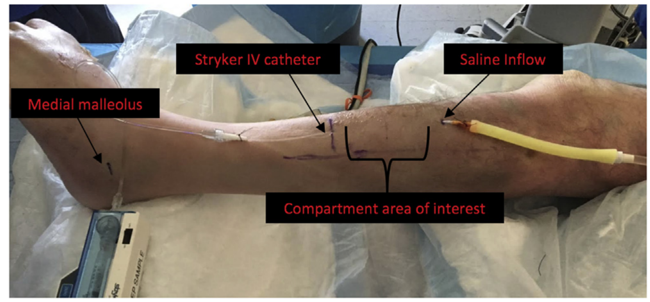

Fig. 1. Cadaveric model of acute compartment syndrome. Saline is infused into the anterior compartment until an invasive compartment pressure measurement is reached.

Ultrasound index measurements

The height of the saline container was adjusted sequentially to increase MCP from 0 to 30, 45, 60, and 75 mmHg as measured by the intra-compartment needle pressure monitor (Stryker, USA). Ultrasound indexes that were recorded were Compartment Width (CW) measured from the interosseous ligament to the superficial fascia of the anterior compartment (Fig. 3), and the Compartment Fascia Flattening Pressure (CFFP, Fig. 4) as measured by the

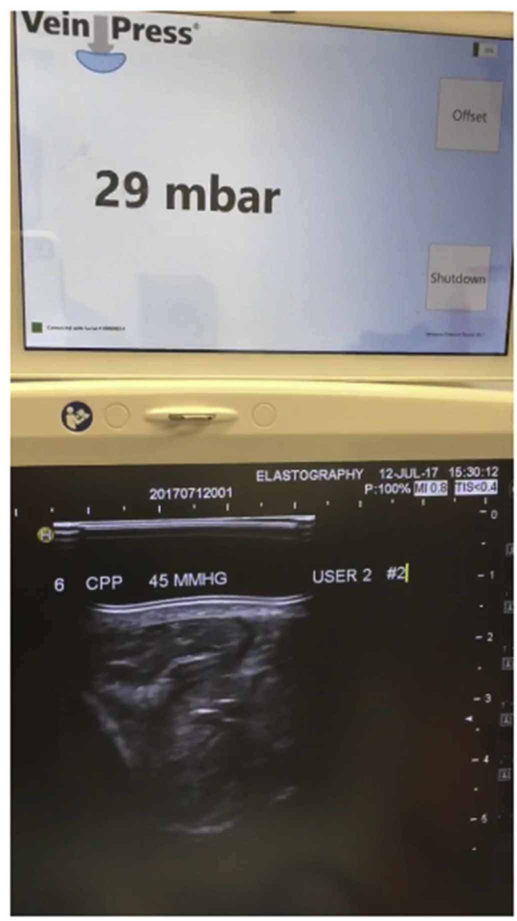

Fig. 2. The coupled transducer allows for obtaining a B-mode image of the anterior compartment while controlling the amount of applied pressure (AP) to the skin, which is displayed on a monitor screen.

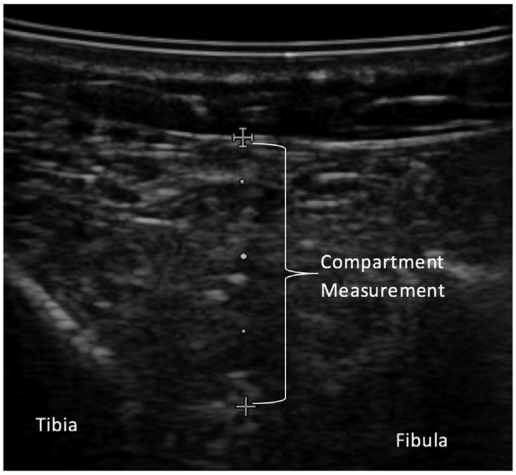

Fig. 3. B-mode image of the anterior compartment, 20 cm above the lateral malleolus. Compartment Width (CW) measured from the interosseous ligament to the superficial fascia of the anterior compartment.

and at 100 mbar (CW_{100}) of applied pressure to the skin. The CFFP was obtained by slowly applying increasing pressures with the transducer until the superficial fascia was subjectively visualized as flat on the ultrasound monitor (Fig. 4A and B). This maneuver was repeated three times until the observer felt convinced of the CFFP measurement. All ultrasound measurements were performed by a fellowship-trained trauma surgeon without prior training in musculoskeletal ultrasound imaging. The authors felt that the simplicity of the described technique and our wish have it wide spread, justified not using an experienced ultrasonographist to perform the measurements. In order to determine the inter- and intra-observer agreement of the proposed method, three additional orthopedic surgeons without prior training in musculoskeletal ultrasound performed all of the measurements on one of the cadaveric legs (the 6^{th} and final leg). All observers collected the data independently during the same experiment, while being blinded to the measurement results of the other observers.

Statistical analysis

The correlations between the two ultrasound-based indexes

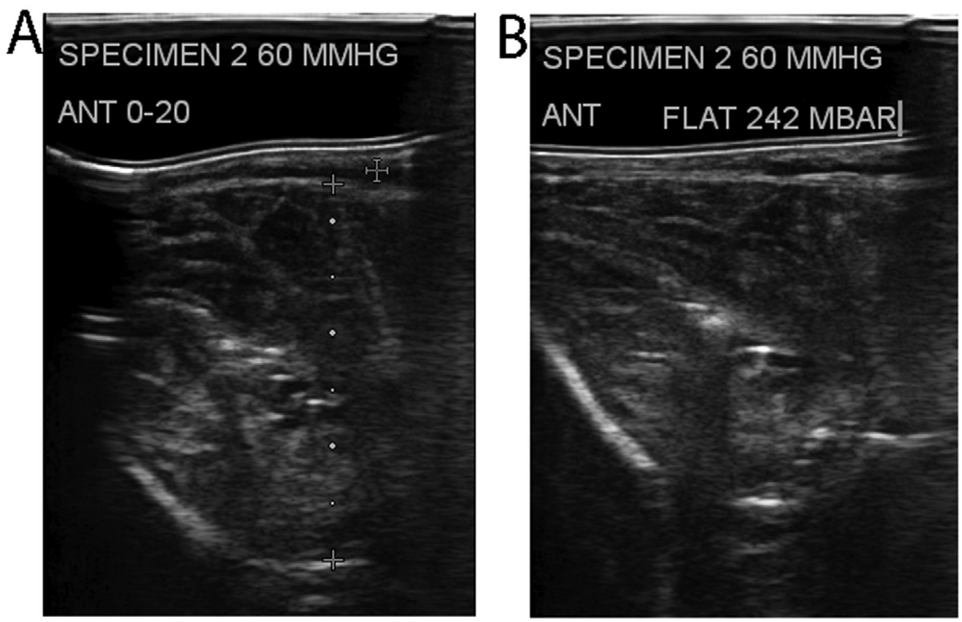

Fig. 4. Pressure applied to the cadaver skin above the anterior compartment is measured by the pressure sensing transducer (VeinPress, Switzerland) and displayed on a monitor screen.
A: B-mode image of anterior compartment at a CP of 60 mmHg. Note the curved anterior compartment fascia to indicate increased compartment pressure.
B: B-mode image of anterior compartment with 60 mmHg of intra-compartment pressure. A pressure of 242 mbar applied to the skin was required to flatten the anterior compartment fascia (CPP = 242 mbar).

pressure required to flatten the superficial fascia of the anterior compartment. Both indexes were measured at CP of 30, 45, 60, and 75 mmHg. CW was measured at 0 mbar (CW_0), 50 mbar (CW_{50}), (CW and CFFP) and the invasively measured MCPs were assessed using the non-parametric Spearman correlation coefficients. Correlations were done independently for each of the specimens.

Table 1
Correlations of ultrasound indexes to rising compartment pressures in the individual specimens.

	Applied Pressure (mbar)	Specimen 1		Specimen 2		Specimen 3		Specimen 4		Specimen 5		Specimen 6	
		rho	p*	rho	p*	rho	p*	rho	p*	rho	p*	rho	p*
CW	0	0.90	0.04	0.70	0.19	0.90	0.04	1.00	<0.0001	0.90	0.04	1.00	<0.0001
	50	0.90	0.04	1.00	<0.0001	1.00	<0.0001	1.00	<0.0001	0.90	0.04	1.00	<0.0001
	100	1.00	<0.0001	1.00	<0.0001	1.00	<0.0001	1.00	<0.0001	0.90	0.04	1.00	<0.0001
CFFP**		n/a	+	1.00	<0.0001	1.00	<0.0001	1.00	<0.0001	0.80	0.20	1.00	<0.0001

+Only two measurements were made for the CFFP measurements of Specimen 1.
* All p-values were calculated using Spearman correlation coefficients ($p < 0.05$ statistically significant).

A rho of 1 is considered a perfect correlation. Intra-class correlation coefficients (ICC) were used to assess the inter- and intra-observer agreement for the CW and CFFP at each induced MCP. ICC values were interpreted as follows: < 0.40 poor; 0.40 to 0.59 fair; 0.60 to 0.74 good, 0.75–1.00 excellent (40). Linear regression generalized estimating equations (GEE) techniques were used to perform a multiple pairwise analysis of different combinations of compartment pressure and applied pressures. A Bonferroni adjustment was made to account for multiple comparisons; as a result, alpha level was set at 0.002.

Results

Table 1 displays pooled measurement results for the CFFP and CW at different MCPs. Both the CW and CFFP showed high non-parametric Spearman correlations to MCP in the individual cadavers. For an applied pressure (AP) of 50 and 100 mbar, a rho of 0.9–1.0 was calculated for all specimens in regards to the CW. This is also true for the correlation at 0 mmHg except for the measurements in specimen 2. The correlation for CFFP was 0.8–1.0 for all the specimens.

Fig. 5 demonstrates the large jump (almost doubling) in average CW between baseline and the first elevated MCP state (30 mmHg). Additional elevation of MCP (45, 60 and 75 mmHg) did not increase the CW much but were still high compared to baseline. Applying more pressure to the skin (AP increased from 0 to 50 and 100 mbar) decreased the average CW but did not change the response pattern (Fig. 5). Table 2 shows pairwise analysis of CW measurements at different combinations of compartment pressure and applied pressure with summarized p-values. The table indicates statistically significant differences in most pairwise comparisons.

Fig. 6 shows a box plot of CFFP measurements of the six specimens at increasing MCPs. The CFFP could only be measured when MCP was higher than 20 mmHg. At lower pressures, the superficial fascia appeared flat on US under any applied pressure (CFFP = 0 mmHg). CFFP at 30 mmHg were elevated compared to baseline. The CFFPs at CP = 45 mmHg were also clearly elevated compared to baseline and 30 mmHg. CFFPs at 60 and 75 mmHg of CP seemed to plateau compared to CFFPs at 45 mmHg but were elevated compared to baseline and CP = 30 mmHg (Fig. 6). Using linear regression generalized estimating equations (GEE) techniques, CFFPs demonstrated a significantly increasing trend with an increase of MCP from 30 to 75 ($p < 0.001$, test for linear trend).

Inter-observer agreement of CW was fair (0.57, 95% CI 0.16-0.93, $p = 0.002$). The inter-observer agreement for CFFP was good (0.65, 95% CI 0.15-0.97, $p = 0.008$). Intra-observer agreement for CFFP was good to excellent (0.74, 0.81 and 0.96 for the three observers). Two observers performed the CFFP measurements blinded (they did not see the applied pressure measurement) and achieved good and excellent intra-observer agreement as well (ICC = 0.74 and 0.94 respectively).

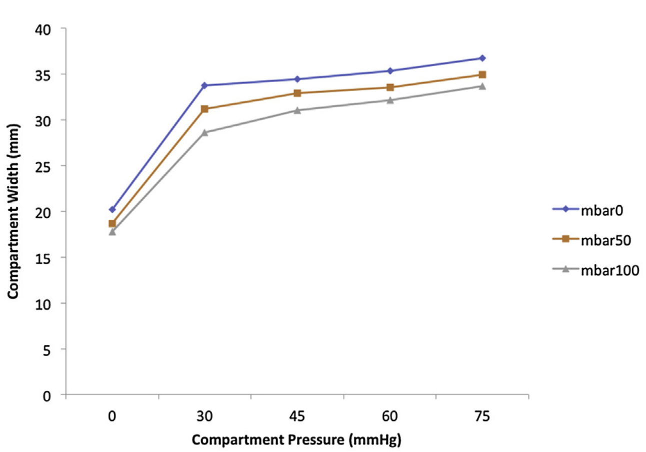

Fig. 5. Average compartment width measured at different compartment pressures with different applied pressures (0, 50 and 100 mbar).

Table 2
p-values* for pair-wise (AP,MCP) combinations for, measuring CW while holding AP constant and varying MCP.

AP held constant at 0 mbar				
	(0,30)	(0,45)	(0,60)	(0,75)
(0,0)	<0.001	<0.001	<0.001	<0.001
(0,30)		1.00	0.14	<0.001
(0,45)			0.46	0.06
(0,60)				1.00
AP held constant at 50 mbar				
	(50,30)	(50,45)	(50,60)	(50,75)
(50,0)	<0.001	<0.001	<0.001	<0.001
(50,30)		<0.001	<0.001	<0.001
(50,45)			1.00	0.25
(50,60)				0.03
AP held constant at 100 mbar				
	(100,30)	(100,45)	(100,60)	(100,75)
(100,0)	<0.001	<0.001	<0.001	<0.001
(100,30)		1.00	0.14	<0.001
(100,45)			0.46	0.06
(100,60)				1.00

*Bonferroni correction was used to adjust α-level for multiple comparisons.
AP – Applied Pressure; MCP – Muscle Compartment Pressure; CW – Compartment Width.

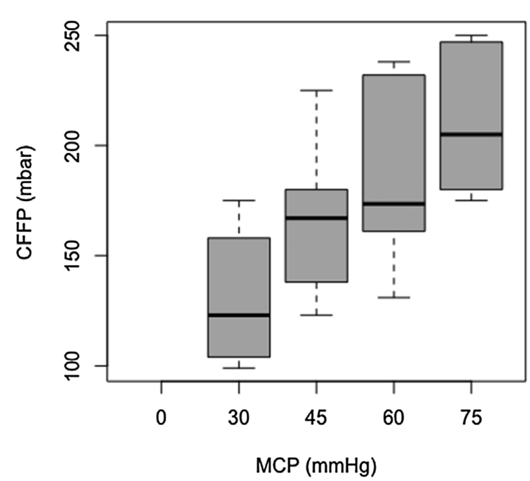

Fig. 6. Compartment Fascia Flattening Pressure (CFFP) measured at simulated muscle compartment pressures (MCP) of 30,46, 60 and 75 mmHg (Stryker needle direct pressure measurement).

Discussion

This cadaveric study tested the feasibility of using clinically available ultrasound technology to diagnose elevated muscle compartment pressure (MCP). The ultrasound-based indexes of compartment fascia flattening pressure (CFFP) and compartment width (CW) were diagnostic of elevated compartment pressures. Although previous studies have demonstrated the use of ultrasound-based technology to diagnose high compartment pressures, this is the first study to do so with clinical readily available US devices.

The diagnosis of ACS remains a challenge. Despite the wide availability of invasive direct compartment pressure measurement devices, clinical assessment remains a cornerstone for diagnosis of this condition [1–4]. Regardless of the method of diagnosis, there is only one treatment available for ACS and that is to reduce MCPs by performing a fasciotomy. It is therefore, highly beneficial to know if compartment pressures are elevated beyond the acceptable range before performing a fasciotomy. Measuring compartment pressure is even more important in obtunded or ventilated patients that are not able to complain of pain [10]. The concern about the reliability of invasive measurement coupled with the need for objective diagnostic criteria of elevated compartment pressure has been the driving force for the development of noninvasive methods for detection of elevated MCP. As the MCP increases the elasticity of the muscle compartment decreases. Methods of measuring this elasticity, such as muscle elastography have shown some promise in this regard but are not readily available and therefore not widely used. In a porcine model of ACS, fascial displacement correlated with clinically relevant changes in muscle perfusion pressure [17]. Using a pulse-phase locked loop (PPLL) ultrasound technique, that measures fascial displacement waveforms, the authors were able to demonstrate excellent correlations to MCPs in both cadaver legs and healthy volunteers [18,19]. The PPLL method was shown to be a slightly better diagnostic predictor than NIRS with less subject-to-subject variability and marginally better sensitivity and specificity [15]. However, currently, no clinical trials have demonstrated the utility of PPLL. Shear wave elastography (SWE) techniques assume that the underlying tissue is isotropic, elastic, and locally homogeneous, such as that of breast, liver, or thyroid. Muscle, however, is anisotropic [28]. Despite this, studies using SWE technique showed excellent correlations between shear elastic modulus and Young's elastic modulus in skeletal muscle [21,25,26]. Compared to other US-based methods for detection of elevated MCPs, the method described herein is simple to perform and uses readily available low-cost US equipment.

Most emergency departments use standard B mode (two dimensional) ultrasonography for the diagnosis of a wide range of medically urgent conditions [29]. This modality would therefore be a natural choice for diagnosis of elevate MCPs. In this study, we have demonstrated that standard B mode ultrasonography coupled with a commercially available pressure sensor, can be used to detect elevated compartment pressures. An attempt to use widely available ultrasound technology for assessment of muscle compartments suspected of ACS was done by measurement of the width of the anterior compartment of the leg in patients taken to the operating room for fasciotomy. However, compartment thickness (width) was shown not to correlate to increasing compartment pressures in a retrospective clinical case series [30]. The current study supports this finding. As can be seen in Fig. 5, measuring CW alone will plateau after MCP of 30 mmHg, so there will be a poor correlation between MCP and CW. Ultrasound was also used to measure anterior compartment fascial displacement in an ACS model done on healthy volunteers. The authors were able to demonstrate a sensitivity of 0.61 and specificity of 0.94 for detecting compartment pressure above 30 mmHg[16]. The current study supports these findings, as well. Both CFFP and CW at various applied pressures was very different from baseline when MCP was 30 mmHg or greater.

More recently, clinically available ultrasound technology was used to measure compartment elasticity both in an in-vitro model and a cadaver model [31,32]. The authors measured compartment displacement before and after application of a 100 mmHg of pressure on the anterior compartment of six cadaveric legs as a surrogate to compartment elasticity [31]. Compartment displacement was highly correlated to MCPs, leading the authors to conclude that pressure-related ultrasound of single compartments might be suitable for early detection of ACS [31]. However, the authors also mentioned that technical difficulties in the calibration of their experimental measurement device might limit its clinical reliability [31]. In the current study, we used a standard musculoskeletal ultrasound transducer coupled with the VeinPress pressure sensor to quantify two ultrasound-based indexes - CW and CFFP. The VeinPress pressure sensor was originally developed to measure central venous pressure [33], doing so by measuring the pressure needed to fully occlude by compression the cephalic or jugular vein, while using B mode ultrasonography for imaging. Similarly, we sought to correlate applied pressure to MCP. Since it is not possible to completely compress the compartment, we needed to develop different indexes. As pressure increased in the muscle compartment, the ultrasound image of the superficial fascia (adjacent to the subcutaneous fat) changes its contour from flat to convex/bulged. We have found that it is possible to re-flatten the fascia by applying varying amounts of pressure to the overlying skin with the ultrasound transducer. The recorded pressure, compartment press pressure (CFFP) correlated to the MCP in this study. Similar to the findings of Sellei et al., application of 50 or 100 mbar of pressure changed the width of the compartment in proportion to the compartment pressures. It is noteworthy that both compartment width (CW) and CFFP measurements were different in the pathologic states compared to normal. Interestingly, the correlation between the US indexes and MCP were much better in the individual specimens (see Table 1) than when they were averaged as a group (Figs. 5 & 6). This would suggest that these indexes, in the clinical setting, should best be used by comparing the injured to the uninjured limb, as opposed to using a pre-defined cutoff value for diagnosing elevated MCPs.

This study showed a clinically feasible and readily testable ultrasound based method for the diagnosis of elevated MCP. However, this study has some noteworthy limitations. This is a cadaver study, with a published cadaver model that elevates MCP by injecting saline into the muscle compartment. While this model may simulate one of the features of ACS, namely elevated MCP, it does not reproduce all elements, and the injured leg with developing ACS may behave differently than expected by our model. Other, more physiologic, methods such as muscle pH measurements may be better suited for earlier diagnosis of ACS. However, the method described in this paper, addresses the diagnosis of the need for immediate fasciotomy. Since the only effect of fasciotomy is to reduce MCP, knowing that the MCP is elevate would seem to be the best indication for this procedure to be done urgently. The small number of specimens and the fact that our cadaver models where quite emaciated (BMI 12.5), do not account for the clinical variability in limb size, subcutaneous fat thickness and injury patterns that may be present in an injured patient limb. However, because the described method uses US imaging, we believe that it will be possible to visualize compartment fascia displacement in the presence of subcutaneous edema or an obese leg. Furthermore, US imaging will be able to differentiate between elevated MCPs cause by hematoma as opposed to muscle swelling. Rather than adding more cadaveric legs to the limbs, the authors believe that we have collected enough data to justify testing of this simple and noninvasive technique on patients in a prospective clinical study. Finally, the ability of this method to assess compartments other than the anterior compartment in the leg or other muscle compartments in the body was also not demonstrated in this study. This study is primarily a proof of concept study. We chose to focus on the anterior compartment because it is easily accessible and the compartment that is most involved in ACS. It is reasonable to assume that variations of this technique will be applicable to the lateral and superficial posterior compartments since they are equally accessible to ultrasound imaging. Future studies will focus on ways of applying this concept to the deep posterior compartment, or to more challenging muscle compartments in the body.

Conclusion

This study demonstrates the feasibility of using readily available and relatively low-cost ultrasound technology to diagnose elevated compartment pressures. Future clinical studies will have to determine the applicability of measurement of compartment width (CW) at different applied pressures (CW_0, CW_{50}, CW_{100}) and the compartment fascial flattening pressure (CFFP) to clinical practice and their ability to aid in the diagnosis of the need for urgent fasciotomy.

Conflict of interest

The authors have no conflict of interest to declare.

Acknowledgements

Funding from AO Trauma North America supported this research project. We will also like to thank Dr. Karl Siebuhr, and our Surgical Training Facility staff for their excellent assistance and support.

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