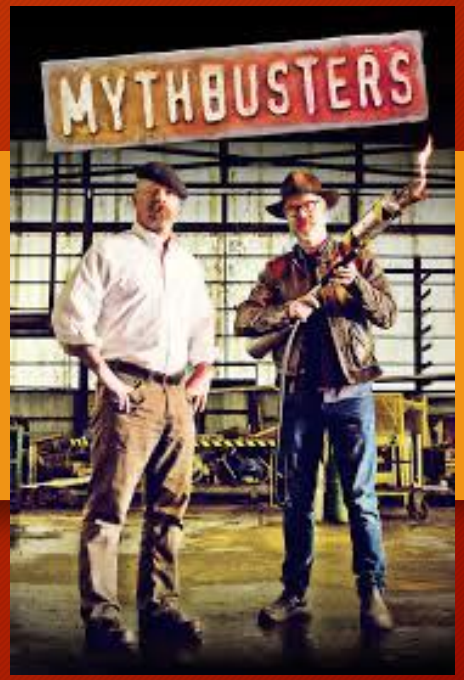
A Dozen New Things About Compartment Syndrome



Edward J Harvey MD MSc FAAOS FRCSC FIOTA

Professor | McGill University

Head of Surgery and Interventional Sciences Program | MUHC-RI

Disclosures

- Co-Editor in Chief | Canadian Journal of Surgery, OTA Patient Portal
- Editorial Board | OTA International, J Ortho Trauma
- Partnerships | Google

Corporate Ownership

- NXTSens Inc. | Co-Founder CSO
- MY01 Inc. | Co-Founder CMO
- Cananose Inc. | Co-Founder
- ChemSense Tech Inc. | Co-Founder CEO
- Stathera Inc. | Co-Founder
- NXTSens Starter | Founder CEO

- Board/Committee Member | Orthopedic Trauma Association

- Current Funding | US DOD, CIHR, CDN DND, NFRF

Compartment Syndrome
Major Pain Point in Medicine

- Mentioned in every ICU & ER daily
- Patient morbidity
- Costly Issue to Care Centers
- Physician practice not optimal

New Publications around Continuous Pressure Monitoring

1. Postfasciotomy Classification System for Acute Compartment Syndrome of the Leg. J Orthop Trauma. 2023 Nov 1;37(11):581-585.
2. Continuous Compartment Pressure Monitoring Allows the Early Detection of Compartment Syndrome After Arterial Revascularization. Cureus 16(3): e55451.
3. Use of a Novel Digital Continuous Pressure Sensor for Diagnosis of Compartment Syndrome: A Case Report of Three Patients. In press JBJS Case Connector
4. Diagnosis Accuracy for Compartment Syndrome: A Systematic Review and Meta-Analysis. J Orthop Trauma. 2023 Aug 1;37(8):e319-e325.
5. Novel digital continuous sensor for monitoring of compartment pressure: a case report. OTA Int. 2022 Jun 29;5(3):e208.
6. Porcine Model of Acute Compartment Syndrome. J Orthop Trauma. 2023 Mar 1;37(3):e122-e127.
7. Minimal Percutaneous Release for Acute Compartment Syndrome of the Foot: A Case Report. .JBJS Case Connect. 2022 Sep 8;12(3).
8. MEMS Sensors Driven Scientific Process to Solve Acute Compartment Syndrome. In Biosensors Preprints.org 2023, 2023050019.
9. Acute Compartment Syndrome Modeling with Sequential Infusion Shows the Deep Posterior Compartment Is Not Functionally Discrete. J Bone Joint Surg Am. 2022 May 4;104(9):813-820.
10. Predictors of Foot Acute Compartment Syndrome: Big Data analysis .J Foot Ankle Surg. 2023 Jan-Feb;62(1):27-30.
11. Big data insights into predictors of acute compartment syndrome. Injury. 2022 Jul;53(7):2557-2561.
12. Percutaneous Forefoot Decompression in a Foot Compartment Syndrome Model. JB JS Open Access. 2021 Nov 23;6(4):e21.00040.
13. Comparison of Three Devices to Measure Pressure for Acute Compartment Syndrome. Mil Med. 2020 Jan 7;185(Suppl 1):77-81.
14. Acute Thigh Compartment Syndrome due to an Occult Arterial Injury Following a Blunt Trauma: A Case Report. JBJS Case Connect. 2020 Jan-Mar;10(1):e0506.
15. Pathophysiology of Compartment Syndrome. In: Compartment Syndrome: A Guide to Diagnosis and Management [Internet]. Cham (CH): Springer; 2019.
16. A pilot study of surgical telementoring for leg fasciotomy. Compartment Release in Austere Locations Collaborators.J R Army Med Corps. 2018 May;164(2):83-86.
17. Sensors and digital medicine in orthopaedic surgery. OTA Int. 2022 Apr 18;5(2 Suppl): e189
18. An Early Cost-Effectiveness Analysis of a New Continuous Compartment Pressure Monitoring Device in Tibial Fracture Patients Who are at Risk of Developing Acute Compartment Syndrome (ACS). Value in Health Dec 2022, s104.
19. What's new in acute compartment syndrome?Harvey EJ, Sanders DW, Shuler MS, Lawendy AR, Cole AL, Alqahtani SM, Schmidt AH.J Orthop Trauma. 2012 Dec;26(12):699-702.
20. Abdominal compartment syndrome: Exploration of continuous monitoring in a rat model. Submitted to CJSurgery
21. Compartment Syndrome. In: McKee, Gardner, editors. Rockwood and Green – Fractures. Chapter 7. 2024 March
22. Capacitive MEMS Absolute Pressure Sensor using a Modified Commercial Microfabrication Process Microsystem Technologies epub: 20 June 2016 pp1-11.
23. Current view and prospect: Implantable pressure sensors for health and surgical care. Medical Devices and Sensors 2020

10 others in press

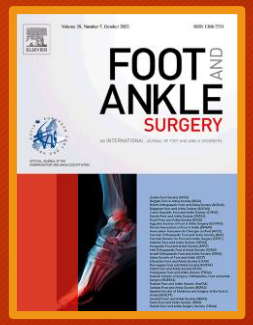
MYTH

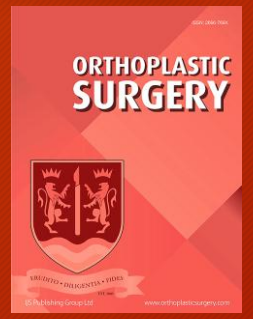
Disease of young males
We now understand the epidemiology

- Big Data Examination
- ACS Data - TQIP

- 203,500 tibia fractures post trauma

- Proximal and midshaft tibial
- Open fractures twice as likely
- Complex, smokers
- Young people

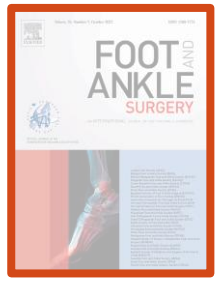


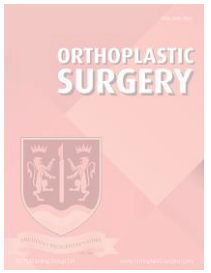


ACS AMERICAN COLLEGE OF SURGEONS

Tibia Fractures from TQIP Data

(Injury 2022, Orthoplastic Surgery 2022, Injury 2023)





- Increased likelihood of ACS with cirrhosis (*P*=0.002)
- Hypertension is protective
- Amputation resulted after 5.4% of fasciotomies
- 17% fasciotomies had necrosis
- Fasciotomies done 4X rate of ACS (!!)
- Fasciotomy for trauma SSI 20%

MYTH

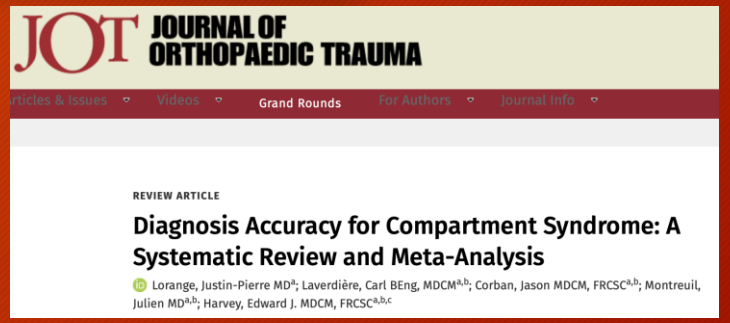
Dx with clinical signs is gold standard

Shock Trauma Data

Clinical findings of ACS are inherently subjective as a means of diagnosis.

Rates of diagnosis have been shown to vary between **2% and 24%** in a single trauma hospital

Lot of Variability


JOT JOURNAL OF ORTHOPAEDIC TRAUMA

Grand Rounds

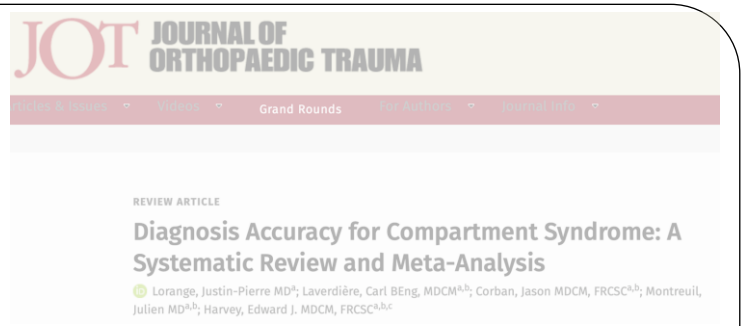
REVIEW ARTICLE

Diagnosis Accuracy for Compartment Syndrome: A Systematic Review and Meta-Analysis

Lorange, Justin-Pierre MD[a]; Laverdière, Carl BEng, MDCM[a,b]; Corban, Jason MDCM, FRCSC[a,b]; Montreuil, Julien MD[a,b]; Harvey, Edward J. MDCM, FRCSC[a,b,c]

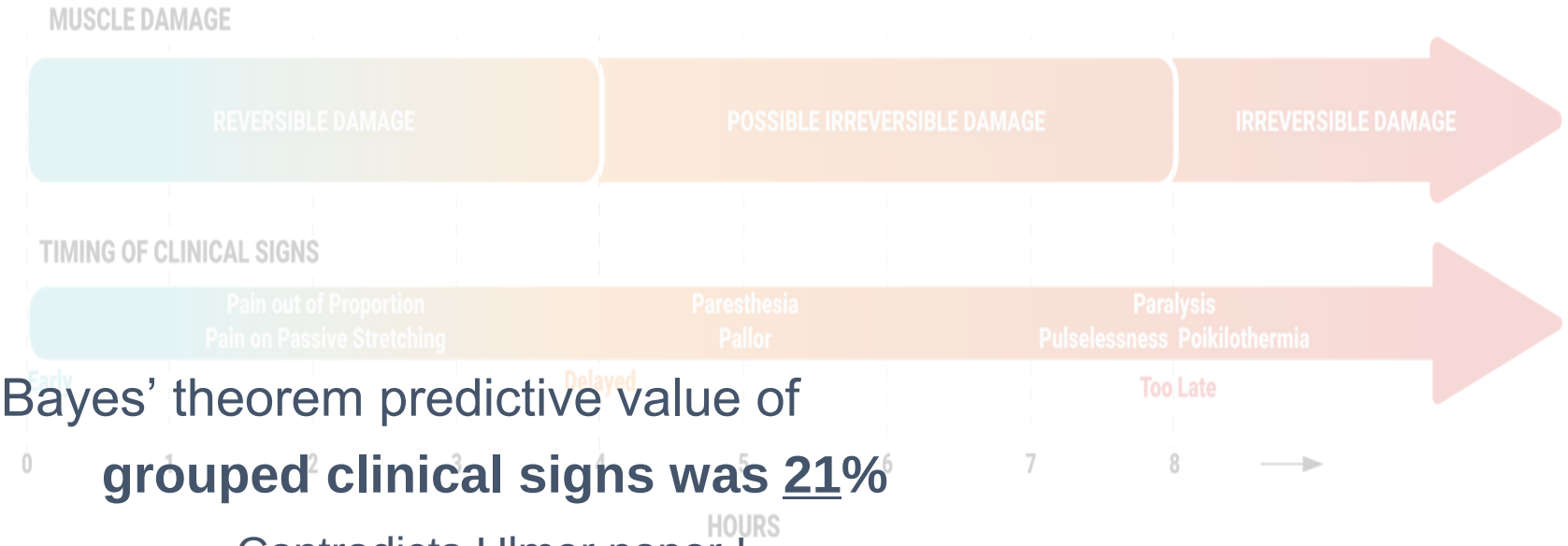
Are any Ps enough?

MYTH



Lorange et al JOT 2023

Meta-analysis for Dx of compartment syndrome based on clinical findings, ICP monitoring, or a combination of them



Bayes' theorem predictive value of

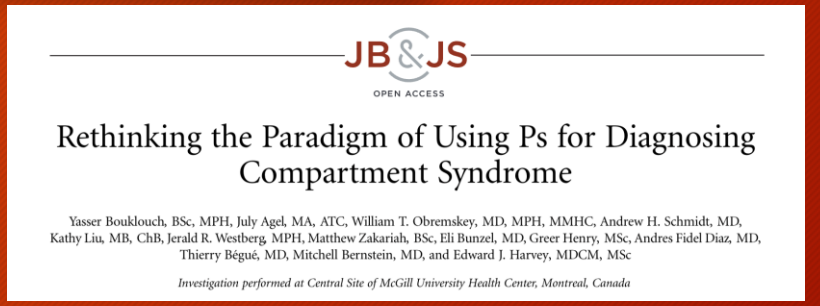
grouped clinical signs was 21%

Contradicts Ulmer paper !

the value was 29% for pressure monitoring (OLD devices)

× Publication bias – real numbers probably lower

Diagnosis is impossible with clinical signs


JB&JS
OPEN ACCESS

Rethinking the Paradigm of Using Ps for Diagnosing Compartment Syndrome

Yasser Bouklouch, BSc, MPH, July Agel, MA, ATC, William T. Obremskey, MD, MPH, MMHC, Andrew H. Schmidt, MD, Kathy Liu, MB, ChB, Jerald R. Westberg, MPH, Matthew Zakariah, BSc, Eli Bunzel, MD, Greer Henry, MSc, Andres Fidel Diaz, MD, Thierry Bégué, MD, Mitchell Bernstein, MD, and Edward J. Harvey, MDCM, MSc

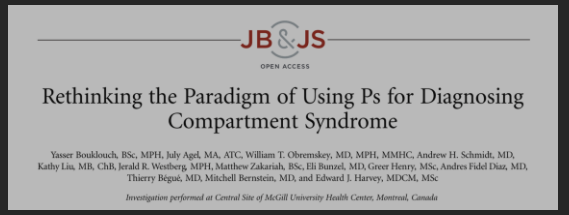
Investigation performed at Central Site of McGill University Health Center, Montreal, Canada

- We all thought clinical exam was useful
- But we found out that the Ps we were taught in residency are not helpful

Ps Useful? MYTH

Patients had fasciotomy for ACS

Study across 5 Level-1 TCs USA CANADA FRANCE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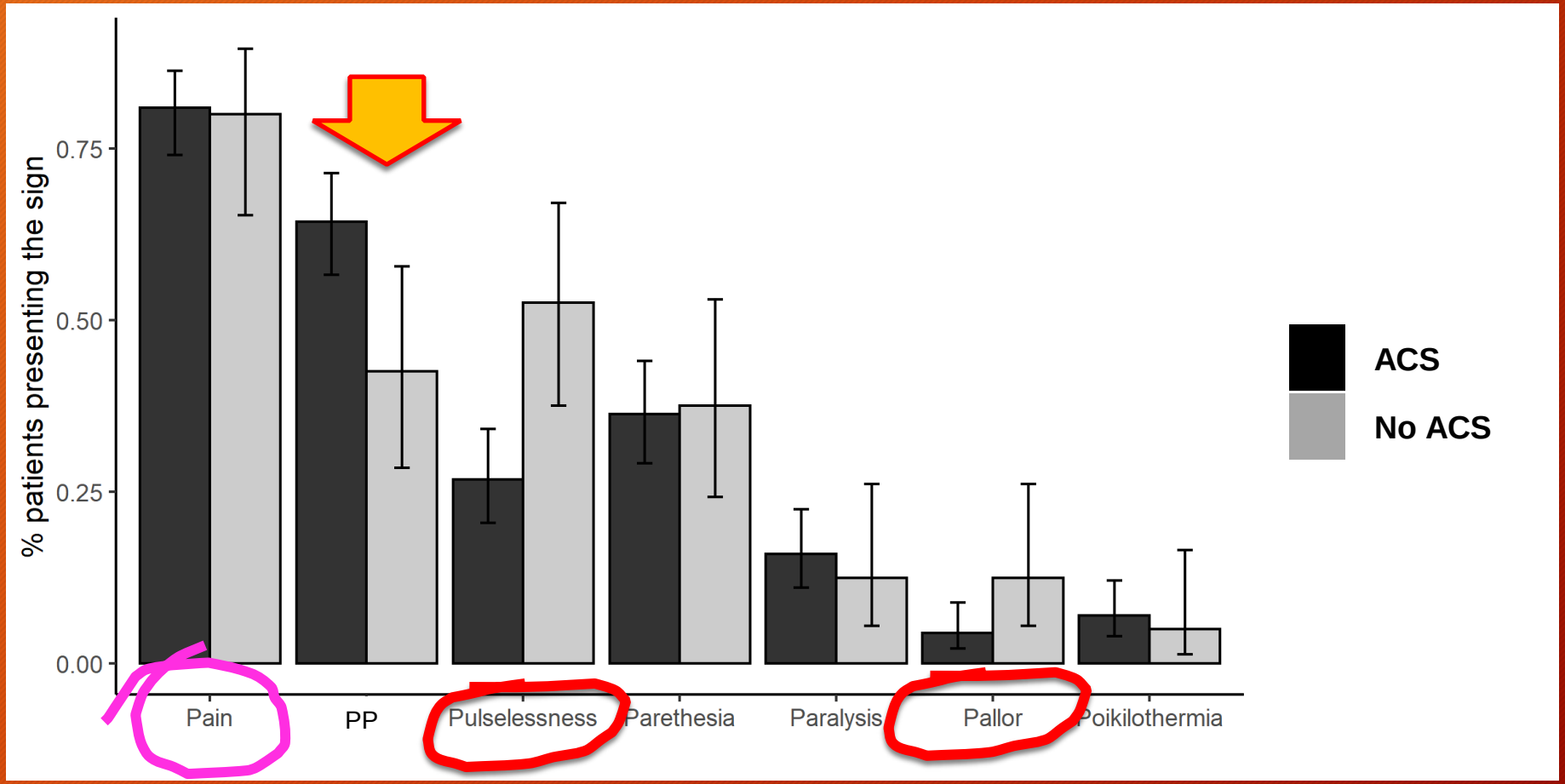
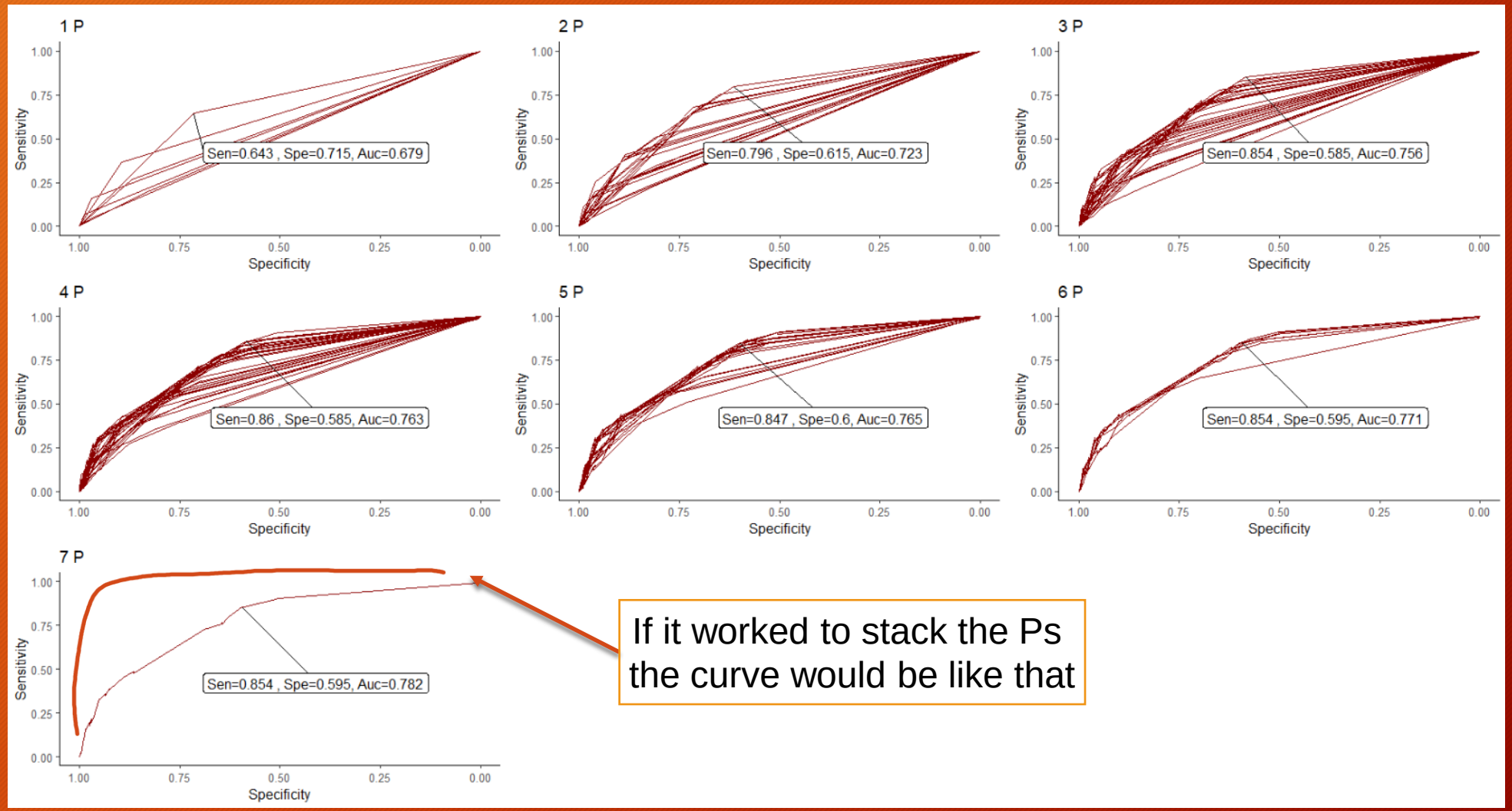


Model Building
Stacking the Ps
clearly not enough



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Rethinking the Paradigm of Using Ps for Diagnosing Compartment Syndrome

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Investigation performed at Central Site of McGill University Health Center, Montreal, Canada

Maybe Palpation of Pressure ?

MYTH

- Can it be tested?
- People have tried

- Physicians' Ability to Manually Detect Isolated Elevations in Leg Intracompartmental Pressure
  - Franklin D. Shuler and Matthew J. Dietz JBJA A. 2010

  Manual detection of compartment firmness associated with critical elevations in intracompartmental pressure is poor

- Accuracy of Measurement of Hand Compartment Pressures: A Cadaveric Study
  - Justin C. Wong, MD, et al. J Hand Surg Am. 2015

  Digital palpation alone was insufficient to detect elevated compartment pressures in hands at risk for compartment syndrome.

- Manual Forearm Palpation in Acute Forearm Compartment Syndrome Is Not Accurate: A Cadaveric Study
  - Haydar, Jouad, MD, et al. JBJS 2024

  Manual palpation of compartment pressure had a low accuracy in the forearm and was not improved by clinician experience.

~~Everyone thinks they can make the diagnosis with clinical signs~~

- Nobody can make the diagnosis **early** with clinical signs
- If you wait till the compartment(s) is/are rock hard everybody can make the diagnosis
  - Too late
  - Needed a biomarker that is more objective

MEMS devices are the most accurate

- Mil Med 2020

MILITARY MEDICINE, 185, S1:77, 2020

Comparison of Three Devices to Measure Pressure for Acute Compartment Syndrome

Geraldine Merle, PhD†; Marianne Comeau-Gauthier, MD*; Vahid Tayari, PhD‡; Mohamad Nizar Kezzo, BEng‡; Chrouk Kasem, BEng‡; Faisal Al-Kabraiti, BEng‡; Carl Laverdiere, BEng*; George Xeras, PhD‡; Edward J. Harvey, MD, MSc*†‡*

ABSTRACT Introduction: Acute compartment syndrome (ACS) is a well-recognized and common emergency. Undiagnosed ACS leads to muscle necrosis, limb contracture, intractable pain, and may even result in amputation. Methods: Three devices (Synthes, Stryker, and MY01) were compared in a pre-clinical rat abdominal compartment syndrome simulation. Simultaneous measurements of intracompartmental pressures allowed concurrent comparison among all devices. Results: Large variations from the reference values are seen with the Synthes and Stryker devices. Variances are large in these two devices even under ideal conditions. The MY01 device was the truest indicator of reference pressure in this ACS model (over 600% more accurate). Conclusions: The MY01 device was the most accurate device in tracking pressure changes in this rat model of abdominal compartment syndrome.

INTRODUCTION

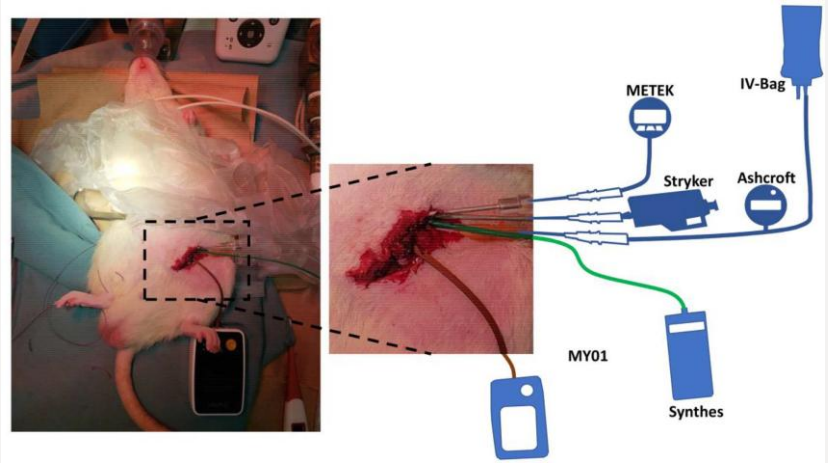
Acute compartment syndrome (ACS) remains a clinical problem for all trauma victims. High-energy trauma causes swelling and increased pressure within the affected muscle compartments resulting in reduced blood flow. ACS is a well-recognized and common emergency.[1] The usual cause of this condition is trauma. Undiagnosed ACS leads to muscle necrosis, contracture, and could eventually result in chronic infection or amputation. The only way to avoid these complications is early recognition and attendant decompression of the affected muscle with a large incision to release the fascial containment of the compartment.[2] Missed compartment syndromes are an issue in combat situations.[3] A failure to release the supra-physiological pressure within a few hours will result in muscle death and severe intractable pain, paralysis, or sensory deficits.[4,5] A reliable method for the accurate and reproducible diagnosis of ACS, especially in the obtunded, polytrauma, or distracted patient, has yet to be developed. Currently, the diagnosis of ACS is made on the basis of physical exam and repeated needle sticks over a short timeframe to measure intracompartmental pressures. Existing technology for continuous pressure measurements is insensitive,[6] particularly in the deep tissues and compartments,[7] and their use is restricted to highly trained personnel.[8] They are of little use in field conditions. Consequently, resolution or clarification of the diagnosis of ACS would be a great asset. Although newer technologies are being tested,[7,9–12] many newer techniques seem to have major diagnostic problems and/or interfere with complete care of the patient. There is therefore a need for an always-on minimally invasive device that does not interfere with transportation or total care of the patient. An insert and forget technique for continuous monitoring is also desirable. Newer technology needs to monitor all potential areas of interest without being labor-intensive, relying on highly educated technicians, or be excessively user dependent.

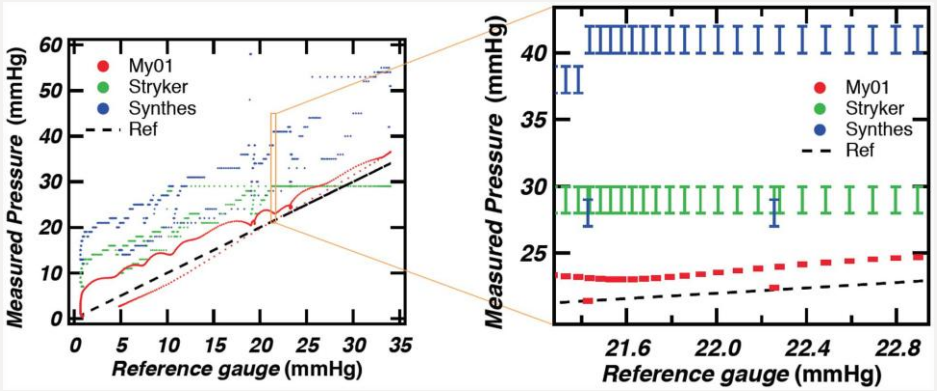
Over the past several years, tremendous advances in silicon microfabrication techniques have led to the development of miniaturized sensors (including but not limited to pressure, temperature, acceleration, flow, angular acceleration, touch) that are finding many applications in video gaming devices, automotive and aerospace industries, process control and industrial monitoring, and medical monitoring. A newer device based on this technology is being brought to the market that seems to have the potential of fulfilling these criteria. MY01 (NXTSens Inc., Montreal, Canada) is a temporary, indwelling compartment-based sensor that can be accurately inserted by technical personnel with minimal training via a single needle syringe. The authors represent an academic-corporate relationship with interests in the corporate entity in the form of ownership and future possible stock holdings. The device is currently undergoing FDA regulatory approval. The device is capable of single point measurements or continuous real-time monitoring. The goal of this project was to compare its performance against two currently used technologies (Stryker [Stryker Inc., Kalamazoo, MI, USA] and Synthes [Depuy-Synthes Inc., West Chester, PA, USA] compartment pressure measurement devices). Building on prior laboratory work, a preclinical pilot study was carried

AMSUS
MILITARY MEDICINE
International Journal of AMSUS

Comparison of Three Devices to Measure Pressure for Acute Compartment Syndrome

Merle et al Mil Med 2020

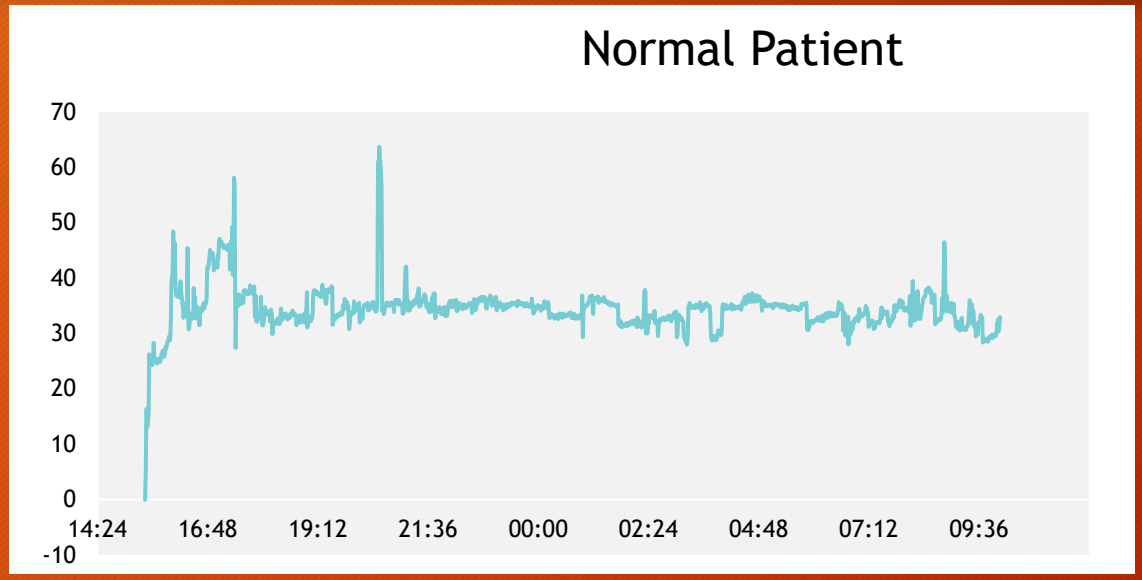




Large variations seen with the Synthes and Stryker devices (30 mmHg)
Variances are large in these two devices even under ideal conditions
MY01 device was the truest indicator of reference pressure
(over 600% more accurate)

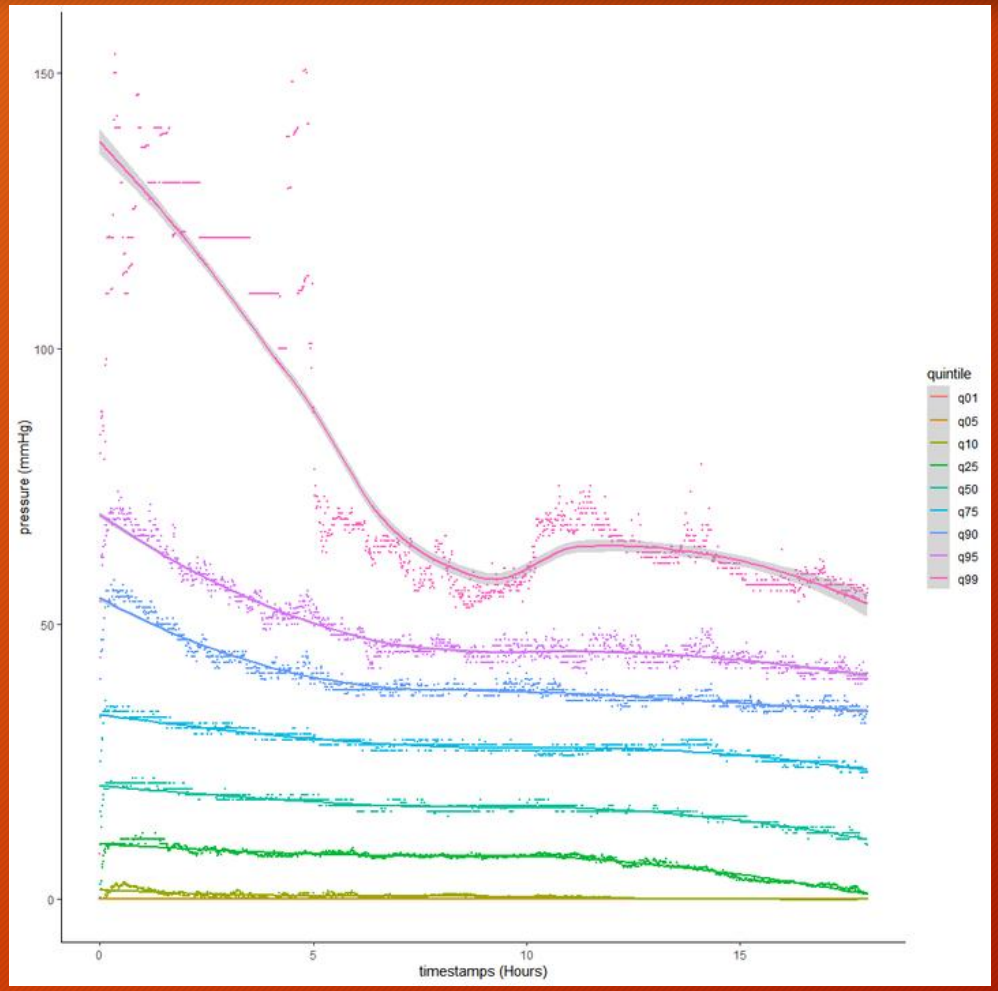
MYTH

Magic Single Point Measurement



- Absolute values can spike over 80-120 mm Hg with movement or muscle spasm

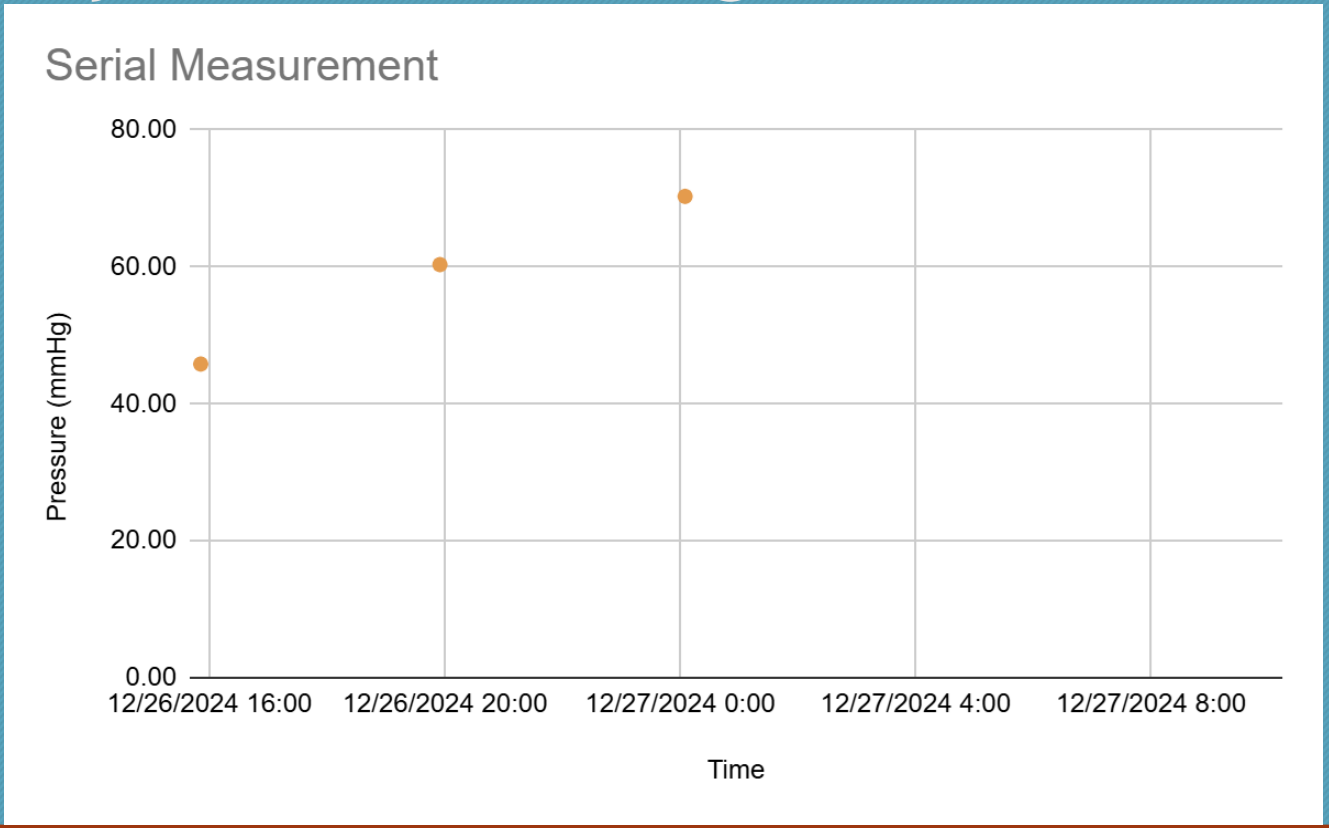
Single point values are inaccurate
After initial spasm pressure tails off ?



Single Points less effective than Trends

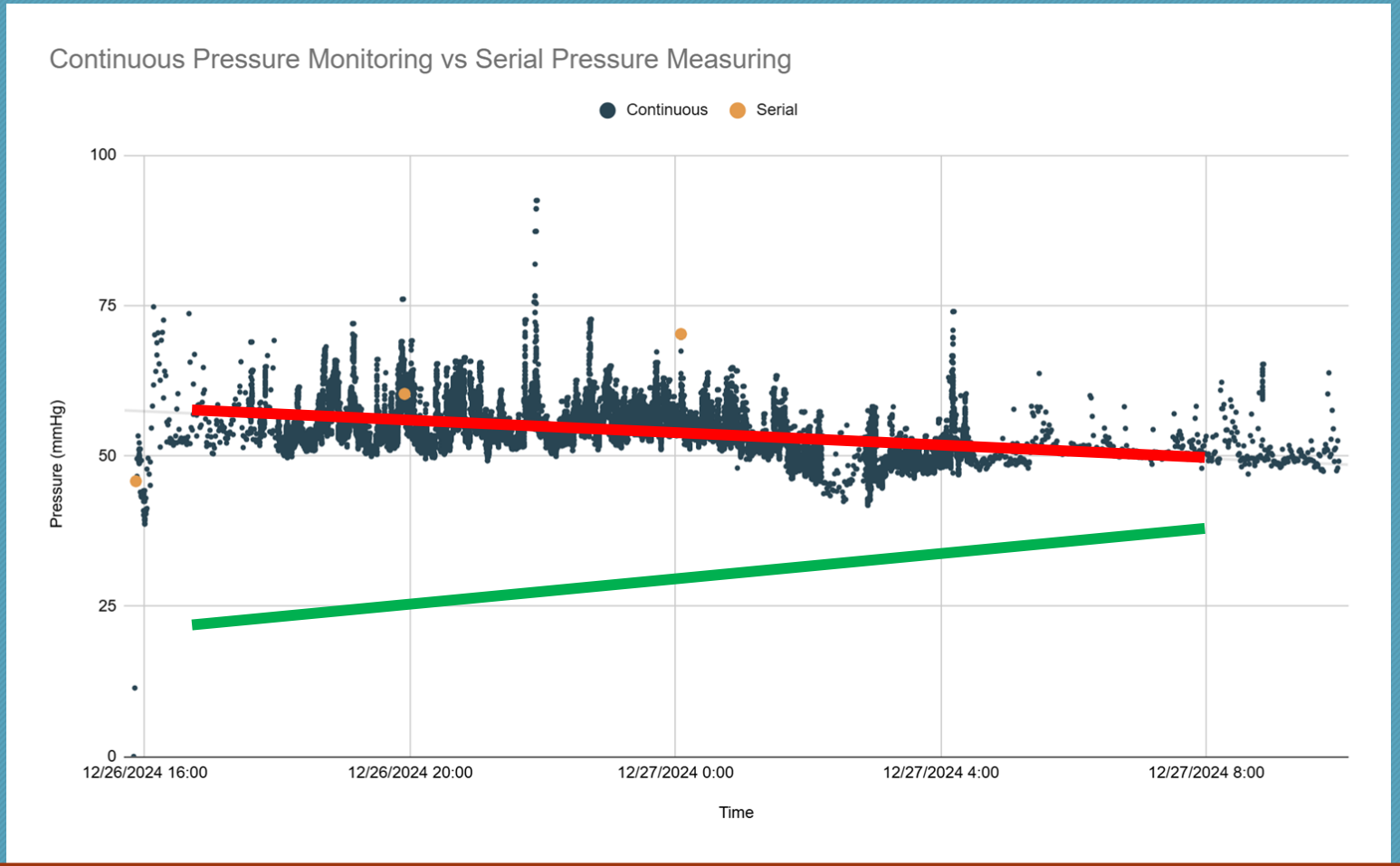
Even if you do serial single sticks

Serial Pressure Measuring as a choice
Do you have enough information?



3 data points over 8 hours

Continuous Pressure Monitoring



In same 8 hour period you get up to 28,800 data points with continuous monitoring

Next wanted to compare studies
Do away with literature variance

- Every article was different
  - Magic numbers = 40
- Previous literature can be examined?
- Outcomes can be measured?

Getting a common communication language

Group of experts solicited (CROCS Network)

- Modified Delphi approach with clinical correlation
- Built a Grading System
  - Now validated
    - JOT 2023

ACS Grade	Criteria defining the ACS grade
1	Primary closure or 1–2 day delayed primary (for prophylactic cases) => no Acute Compartment Syndrome (ACS)
2	Delayed primary closure of ACS (w/ or w/out pie crusting) – minimal necrotic muscle
3	Some or no necrosis of 1–4 compartments with complex wound closure (STSG, local flaps, or prolonged vac treatment)
4	Extensive muscle necrosis in >2 compartments and/or advanced leg salvage with complex coverage
5	Amputation

Price to Treat ACS plus Tibia FX

(YHEC – Pub Economics)

(Sen et al – JBJS - in press)

(Duckworth et al - submission in process)

(Van Lancker – submitted)

Initiative to stop missing cases (True Positives)

Money is in Stopping False Positives

ACS Grade	Criteria defining the ACS grade
1	Primary closure or 1–2 day delayed primary (for prophylactic cases) => no Acute Compartment Syndrome (ACS)
2	Delayed primary closure of ACS (w/ or w/out pie crusting) – minimal necrotic muscle
3	Some or no necrosis of 1–4 compartments with complex wound closure (STSG, local flaps, or prolonged vac treatment)
4	Extensive muscle necrosis in >2 compartments and/or advanced leg salvage with complex coverage
5	Amputation

Price to Treat ACS plus Tibia FX
American TQIP data + UK Data

(YHEC – Pub Economics)
(Sen et al – JBJS - in press)
(Duckworth et al - submission in process)
(Van Lancker – submitted)

American average total costs per outcome	Clinical event costs
Standard of care - standard fracture care – no ACS	$56,300
Gr 1. Incorrect ACS di	$74,800
Gr 2. Minimal necrotic	$93,300
Gr 3. Minimal necrotic	$120,400
Gr 4. Complex and ext	$201,150
Gr 5. Amputation	$521,000

YHEC –
When used for every tibia fx
(4(123) B,C)

If you had the right device
could save
4800$ per case US

Money saved with timely correct Dx

MYTH

Fasciotomies are safe and best option

- Stopping unnecessary fasciotomies is the real economic benefit
  - Fasciotomy = 8 hospital days
  - 20% infection rate
  - Long term issues

MYTH that non-MEMS based techniques or exam alone works
Now have clinical data

JOT JOURNAL OF ORTHOPAEDIC TRAUMA

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ORIGINAL ARTICLE

Clinical trial of a new continuous compartment pressure monitoring to aid in the diagnosis of Acute Compartment Syndrome

Balhareth, Mohammed Ali M.D[1]; Vaile, Kate M.D[1]; Schneider, Prism M.D[2]; Liew, Allan[3]; Hall, Jeremy M.D[4]; Guy, Pierre[5]; Lawendy, Abdel-Rahman M.D[6]; Doornberg, Job M.D[7]; Jaarsma, Ruurd[8]; Leighton, Ross M.D[9]

Author Information

Journal of Orthopaedic Trauma ():10.1097/BOT.0000000000002980, April 08, 2025. | ***DOI:*** 10.1097/BOT.0000000000002980

Final Clinical Study Results

no missed cases of ACS

no false positives or negatives

150 clinical cases over 2 independent studies

2100 Cases

Pressure and Trends

- Pressure is the first indicator
  - Only homogenous early indicator
- Before pain !
- Before O2 changes
- Before pH change

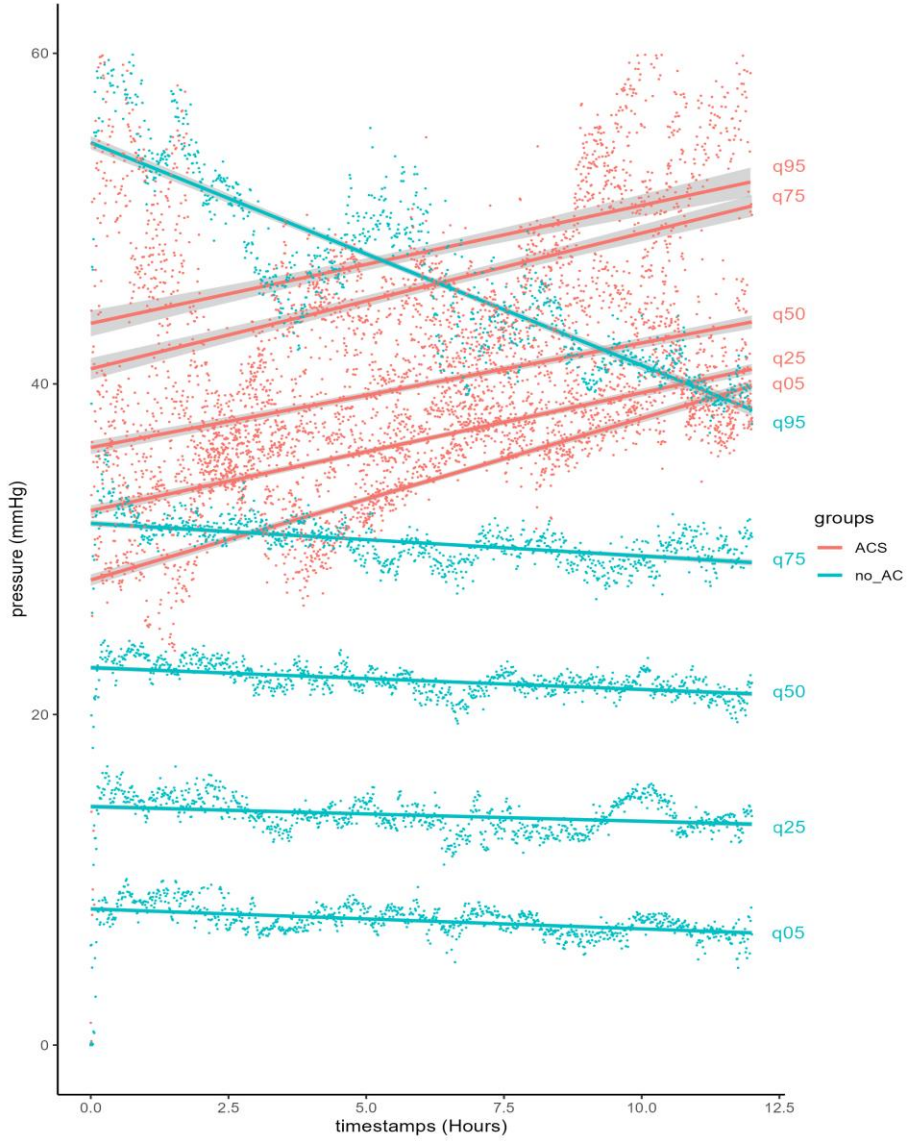
- **Shows promise as a real objective measure with an accurate device**

Continuous pressures

- Quintiles

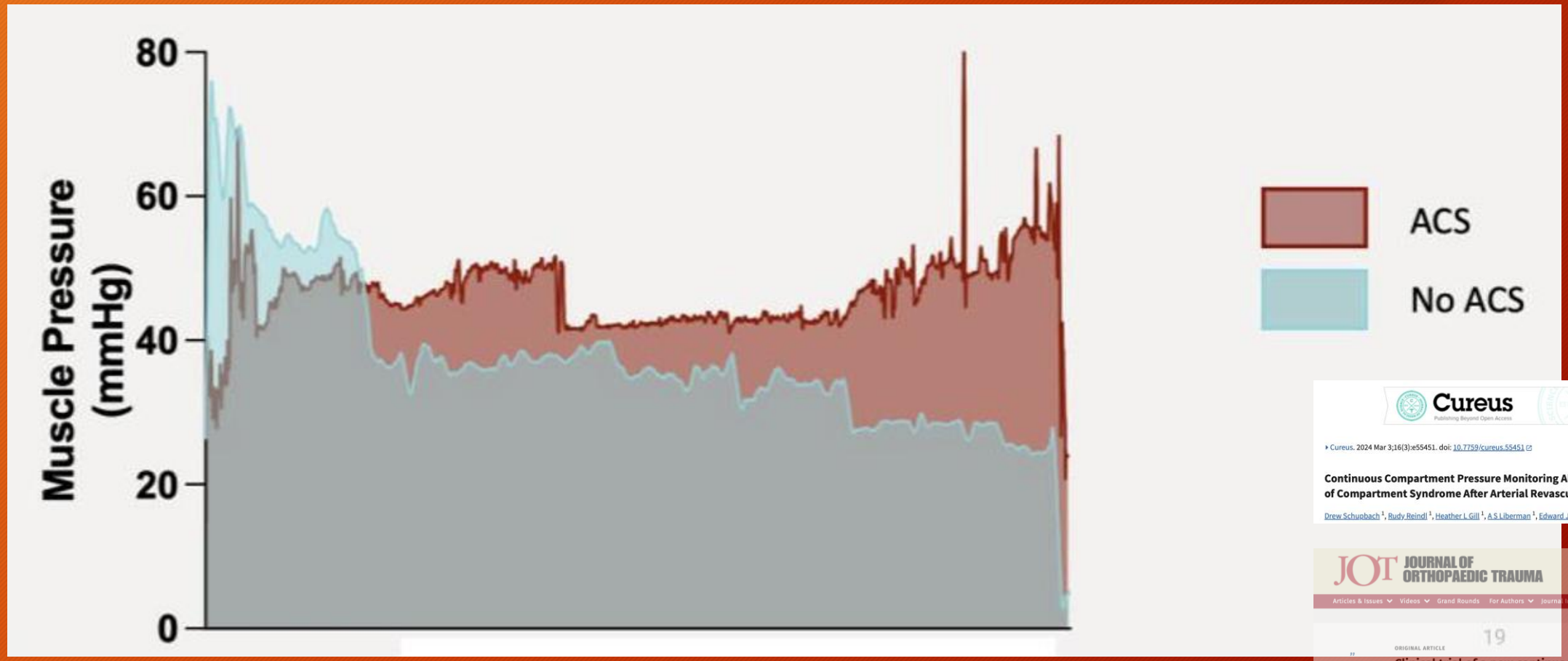
ACS

Non-ACS



Diagnosis in obtunded patients is possible

Fasciotomy is not the right answer always



Cureus

Publishing Beyond Open Access

Cureus. 2024 Mar 3;16(3):e55451. doi: 10.7759/cureus.55451

Continuous Compartment Pressure Monitoring Allows the Early Detection of Compartment Syndrome After Arterial Revascularization

Drew Schupbach [1], Rudy Reindl [1], Heather L Gill [1], A S Liberman [1], Edward J Harvey [1,✉]

JOT JOURNAL OF ORTHOPAEDIC TRAUMA

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ORIGINAL ARTICLE

Clinical trial of a new continuous compartment pressure monitoring to aid in the diagnosis of Acute Compartment Syndrome

Balhareth, Mohammed Ali M.D[1]; Vaile, Kate M.D[1]; Schneider, Prism M.D[1]; Liew, Allan[1]; Hall, Jeremy M.D[1]; Guy,

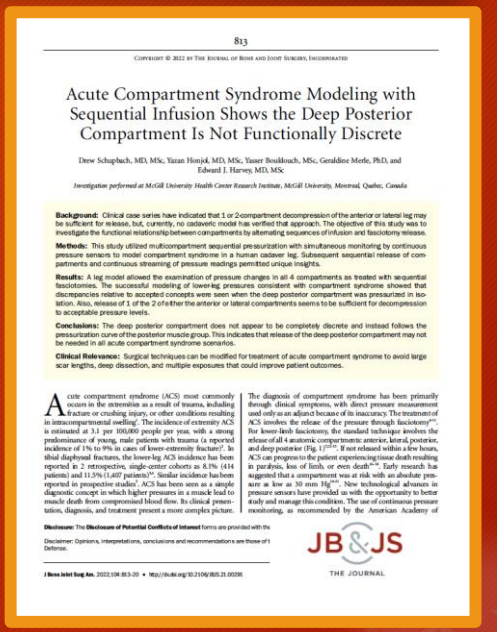
Only need to measure one compartment

- JBJS 2022

MYTH

No need to measure all 4 compartments

Continuous values have done away with this



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Acute Compartment Syndrome Modeling with Sequential Infusion Shows the Deep Posterior Compartment Is Not Functionally Discrete

Drew Schupbach, MD, MSc, Yazan Honjol, MD, MSc, Yaser Bouldouch, MSc, Geraldine Merle, PhD, and Edward J. Harvey, MD, MSc

Investigation performed at McGill University Health Center Research Institute, McGill University, Montreal, Quebec, Canada

Background: Clinical case series have indicated that 1 or 2 compartment decompression of the anterior or lateral leg may be sufficient for release, but, currently, no cadaveric model has verified that approach. The objective of this study was to investigate the functional relationship between compartments by alternating sequences of infusion and fasciotomy release.

Methods: This study utilized multicompartment sequential pressurization with simultaneous monitoring by continuous pressure sensors to model compartment syndrome in a human cadaver leg. Subsequent sequential release of compartments and continuous streaming of pressure readings permitted unique insights.

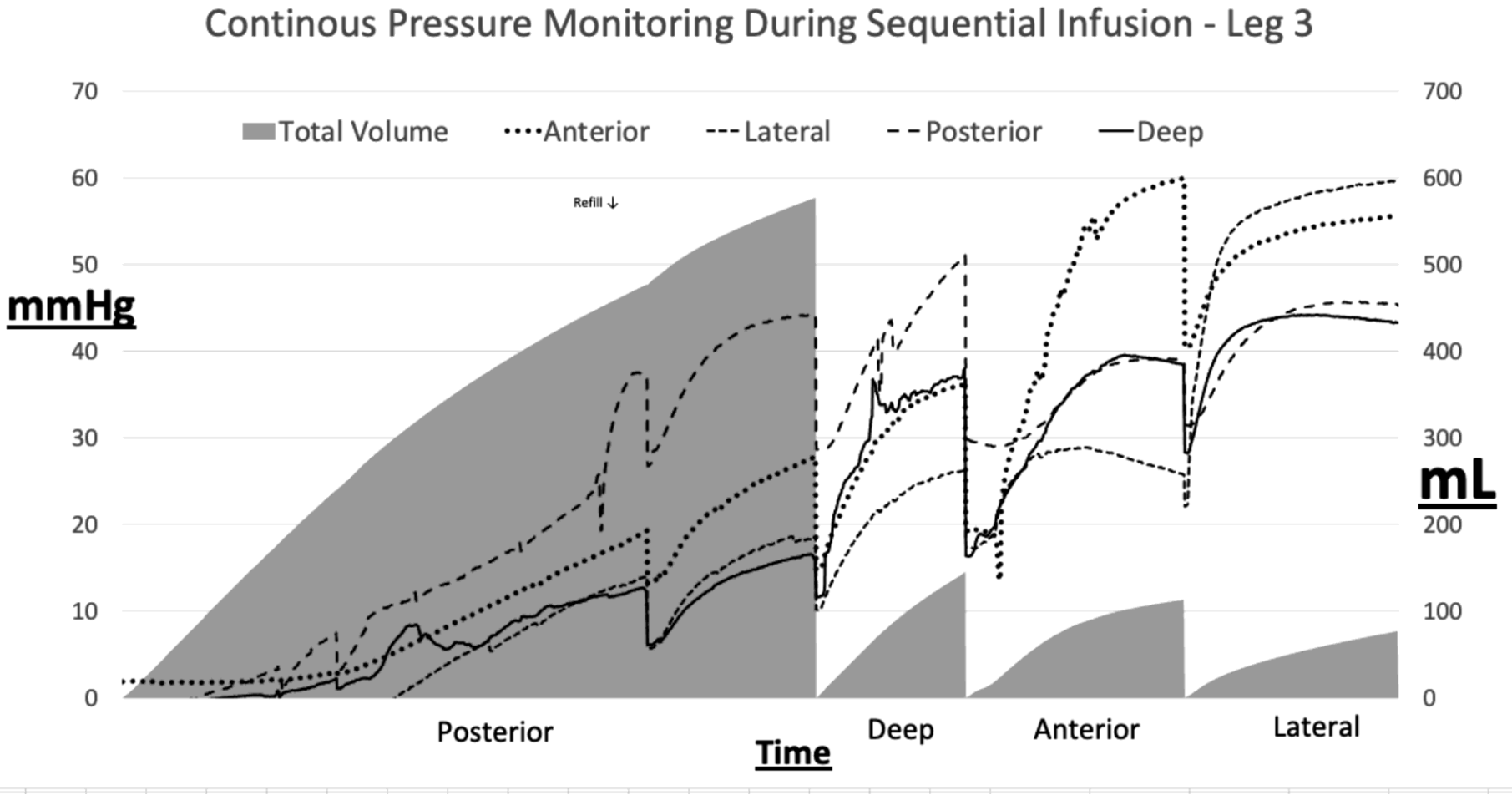
Results: A leg model allowed the examination of pressure changes in all 4 compartments as treated with sequential fasciotomies. The successful modeling of lower-leg pressures consistent with compartment syndrome showed that discrepancies relative to accepted concepts were seen when the deep posterior compartment was pressurized in isolation. Also, release of 1 of the 2 of either the anterior or lateral compartments seems to be sufficient for decompression to acceptable pressure levels.

Conclusions: The deep posterior compartment does not appear to be completely discrete and instead follows the pressurization curve of the posterior muscle group. This indicates that release of the deep posterior compartment may not be needed in all acute compartment syndrome scenarios.

Clinical Relevance: Surgical techniques can be modified for treatment of acute compartment syndrome to avoid large scar lengths, deep dissection, and multiple exposures that could improve patient outcomes.

JB&JS THE JOURNAL

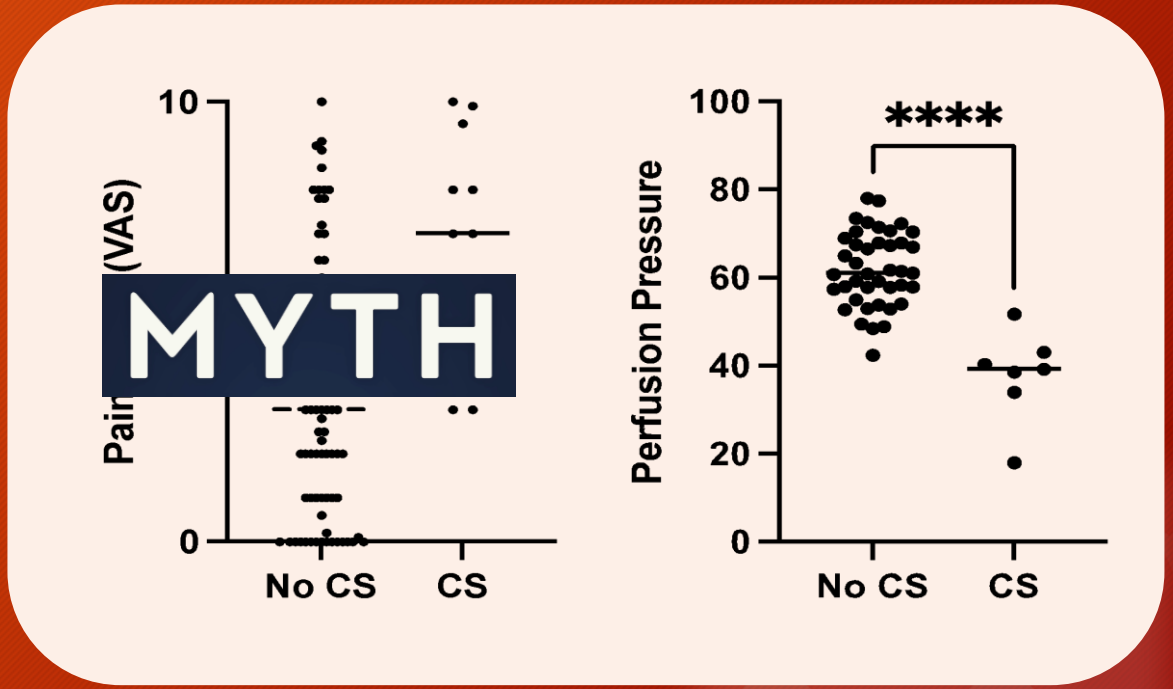
Cadaver Leg


Continous Pressure Monitoring During Sequential Infusion - Leg 3
Total Volume
Anterior
Lateral
Posterior
Deep
Refill
mmHg
mL
Time
Posterior
Deep
Anterior
Lateral
70
60
50
40
30
20
10
0
700
600
500
400
300
200
100
0

Perfusion Pressure is objective

- Pain is not so useful

- Perfusion pressures provided more **objective data** points to both rule in or out CS

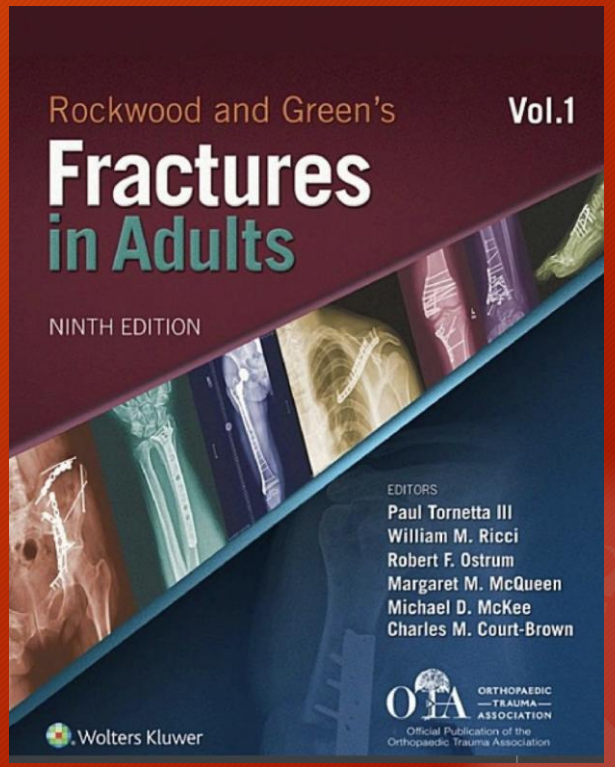


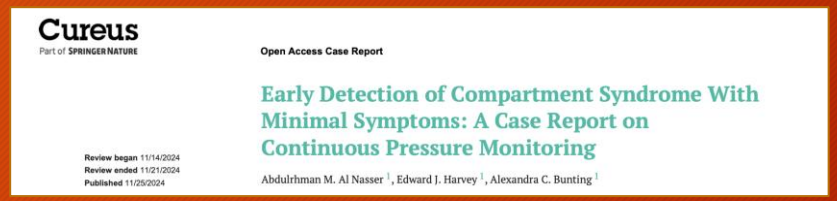
COTS data- 2023

Able to eliminate variability Physician and patient

Rockwood and Green

Duckworth et al
2024




Cureus
Part of SPRINGER NATURE

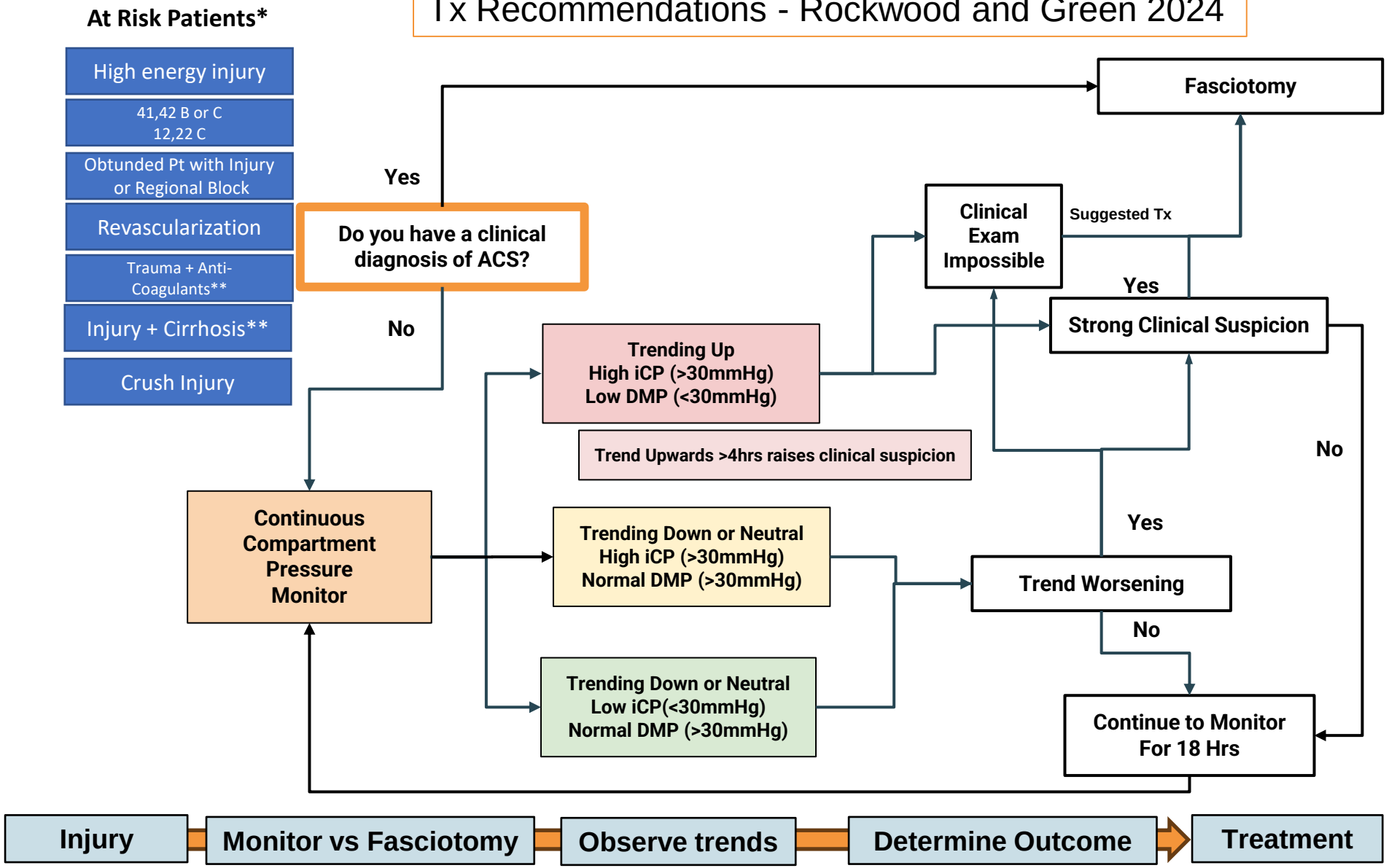
Open Access Case Report

Early Detection of Compartment Syndrome With Minimal Symptoms: A Case Report on Continuous Pressure Monitoring

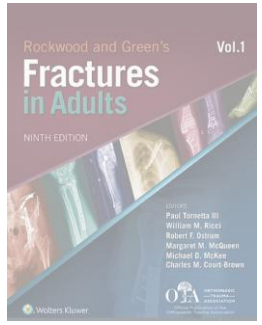
Review began 11/14/2024
Review ended 11/21/2024
Published 11/25/2024

Abdulrhman M. Al Nasser [1], Edward J. Harvey [1], Alexandra C. Bunting [1]

Tx Recommendations - Rockwood and Green 2024



New ACS protocol at our center
McGill - Edinburgh Protocol

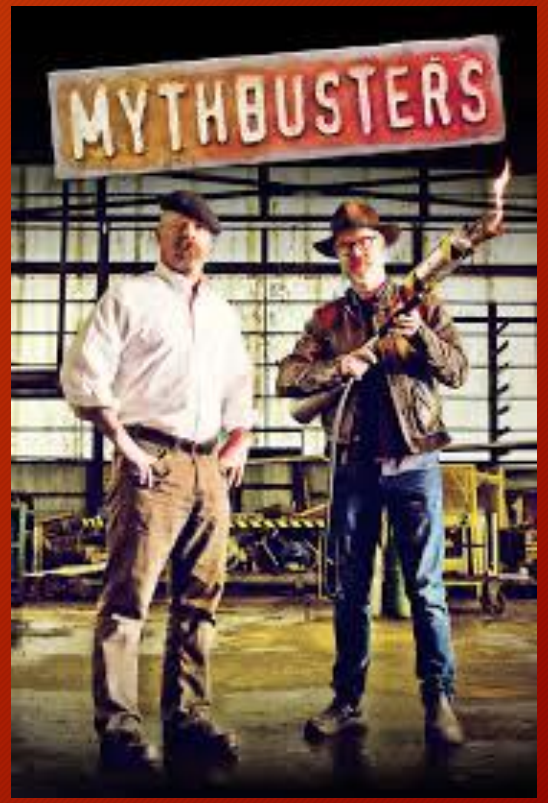


- All patients that have clinical diagnosis of ACS – go directly to OR
- All patients with possible elevated pressures will receive a continuous pressure monitoring device if they are not going to the OR.
  - **This group that requires monitoring includes:**
    - **High Energy Injuries**
    - **Tibia fx (41, 42 - B and C)**
    - **Forearm fx (22C)**
    - **Obtunded Patients with injury**
    - **Revascularization patients without fasciotomy**
    - **Crush Injuries**

  - Patients after surgery that need monitoring.
    - **Acute Lengthening Osteotomies about the knee**
    - **Block after surgery in lower limb**
- Other scenarios that need monitoring are at the discretion of the surgical team.
    - Suggested to monitor **Trauma plus anticoagulants and/or cirrhosis**

Acute Compartment Syndrome Myths Busted

- We understand the epidemiology
- Diagnosis with clinical signs may not be easy
- Diagnosis is impossible with clinical signs alone
- No Magic Single Point Measurement
- Single Points less effective than Trends
- Now able to compare studies
- Financial Benefit is Stopping Fasciotomies
- MEMS Sensor Based Trends are Accurate
- Diagnosis in obtunded patients is possible
- Only need to measure one compartment in leg or arm
- Perfusion Pressure is objective
- MEMS devices are the most accurate
- Able to eliminate physician variability



Thanks

Clinical Pubs

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