

Traumatic Injuries & Hyperbaric Medicine

**Michael B. Strauss, MD, FACS, AAOS,
AOFAP, UHM**



Traumatic INJURIES & Hyperbaric Oxygen

Michael B. Strauss, MD, FACS, FAAOS, FUHM
 Medical Director, Retired, Hyperbaric Medicine Program
 Memorial Care, Long Beach Medical Center
 Long Beach, CA-90801

Clinical Professor
 Orthopaedic Surgery
 University of California Irvine

Orthopaedic Consultant
 Foot & Ankle/PAVE Clinic
 VAMC, Long Beach, California



Traumatic Injury



Hyperbaric O₂ Therapy

DISCLAIMER

 I have *no financial interests* in *equipment* or *products* mentioned in this talk

 I do *receive royalties* and *honorariums* for *educational activities* including:



2010



2023

- Best Publishing Company, *MasterMinding Wounds* and *Diving Science...Revisited*
- Guest Speaker, National Baromedical Services
- Faculty Grand Rounds Presentations at Memorial Care Long Beach Medical Center

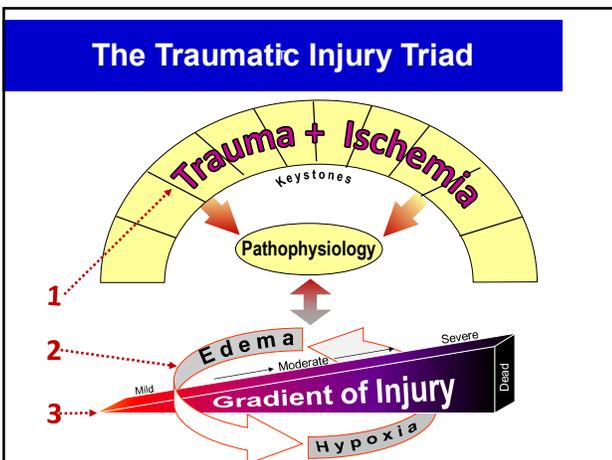
Objectives

By the end of this talk you will

- **Appreciate** the spectrum of the **Traumatic Injuries** with special emphasis on crush injuries & compartment syndromes
- **Become aware of** their unifying **pathophysiology** findings & **severity** classifications
- **Know** why & when **HBO** is indicated for their management

Introduction

- Trauma—a **great challenge** to our health care system \$672 billion spent in 2016 www.NatTrauma.Org
- **Predictable** complication rates ~50% in severe injuries
- HBO is a **logical adjunct** for **severe** traumatic injury care



Crush Injury

The **major TI** consideration

A **frequent** trauma center **presentation**

Good supporting information to justify HBO

Never HBO or...; rather HBO in addition...

Tissue Injury & Death

Acute

Damage proportional to **energy exchange** ($F = ma$)

Irreparable Injury

	Ft-lbs	Factor
Fall	50	1
Ski	100	2
GSW	2,000	40
MVA	10,000	2,000

Tissue viability

1st component of the Traumatic Injury Triad

Acceleration (speed)

Speed (MPH)	Deaths (%)	Factor
20	5	
30	45	
40	85	17x

US Dept/Transportation; Nat HW Safety Administration

Tissue Death / Amputation

In Traumatic Ischemias

Sub-acute Delay

Reperfusion injury

Infection

Hypoxia

Edema

Hypoxia

↳ Impaired function

↳ Non-healing

Late Delayed Amputations

Intractable pain

Uncontrollable deformities

Non-functional extremity

Time to tissue death

4 mins (brain)

Heart

Kidneys

Eyes (retina)

Viscera

Bone

to >24 hr (skin & CTs)

Ischemia

The "Big Bang"

At time of injury

O₂ Needs Greatest

O₂ Availability Lowest

For the

- Inflammatory response
- Managing bioburden

All oxygen dependent

Oxygenation Impediments

- Disruption of microcirculation
- Sludging, stasis
- Edema → compartment syndrome
- Hypotension

Metabolic Activity in Healing

O₂ Needs

Hi

Lo

Days

Weeks

Months

Time

Inflam

Repair

Remodel

Equivalent to a cytokine storm

- Platelets
- Chemokines
- Cytokines (EGF, FGF, PDGF, TGF)
- Histamine
- Hyaluronic Acid
- Laminins
- Prostaglandins
- Other clotting mediators
- Neutrophils

Sub-acute Tissue Death

2nd component of the Traumatic Injury Triad

Hypoxia

Ischemia

Edema

- ↑ O₂ diffusion distance
- Collapse of microcirculation

- Interferes with metabolism
- Inhibits cell functions
- Leaks intracellular fluid

A Self-perpetuating Cycle

O₂ Diffusion & Gradients

Normal

Edema

Capillary

Capillary

Capillary

Capillary

Gradient

Gradient

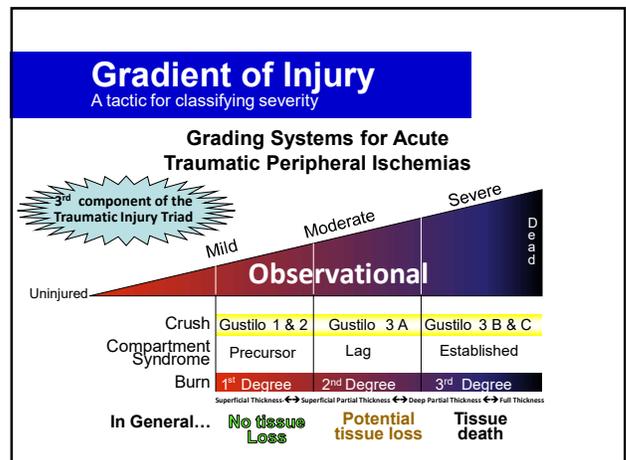
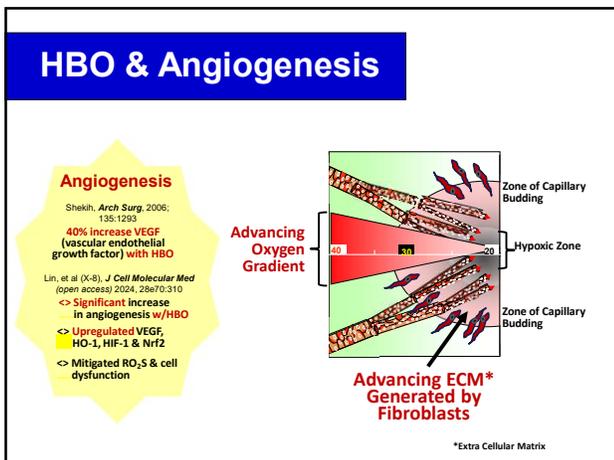
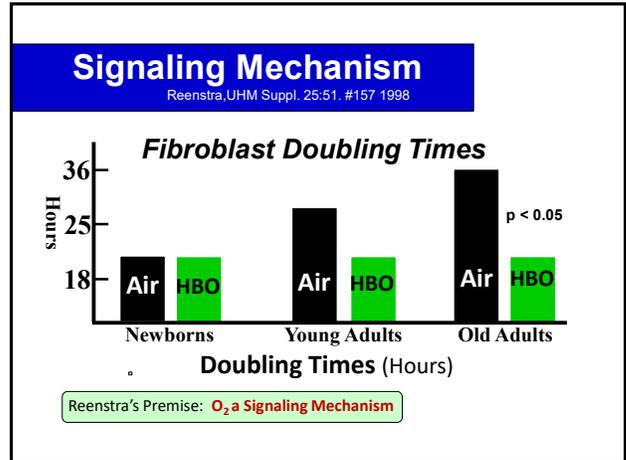
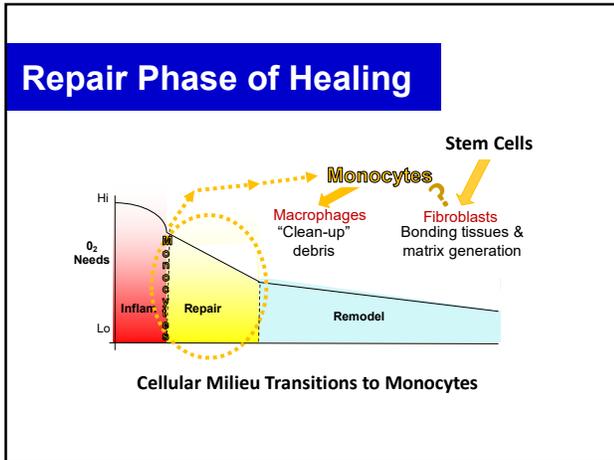
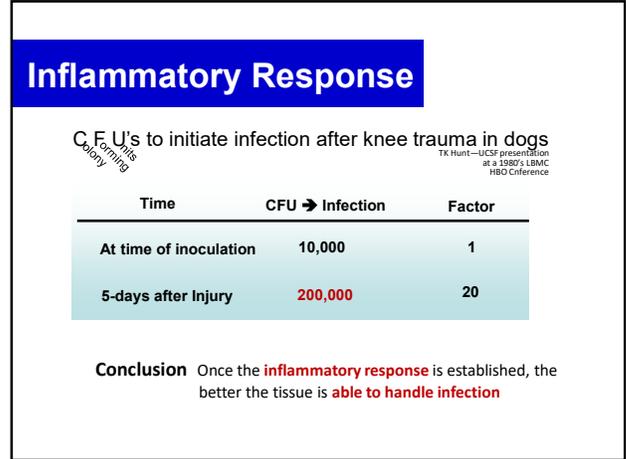
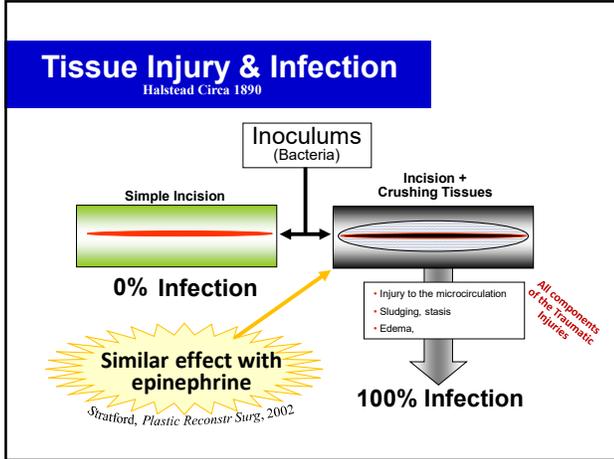
Gradient

Gradient

Edema Fluid =

O₂ Diffusion

Zone of hypoxia

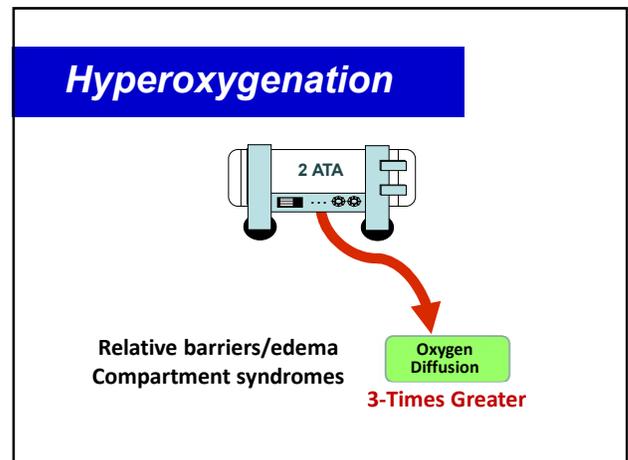
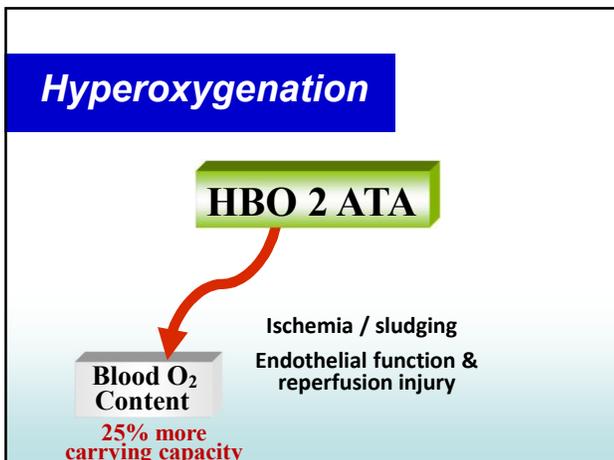
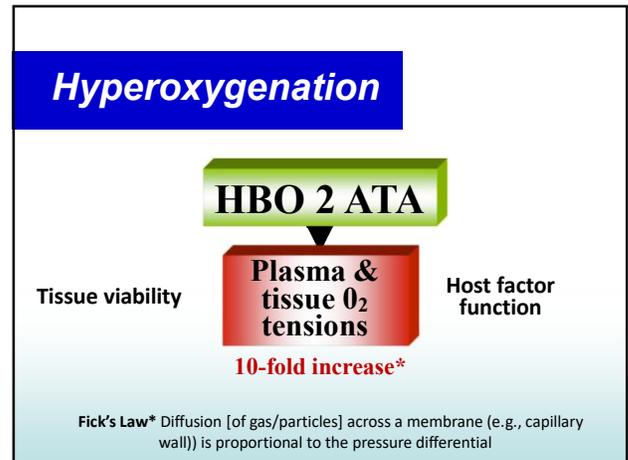
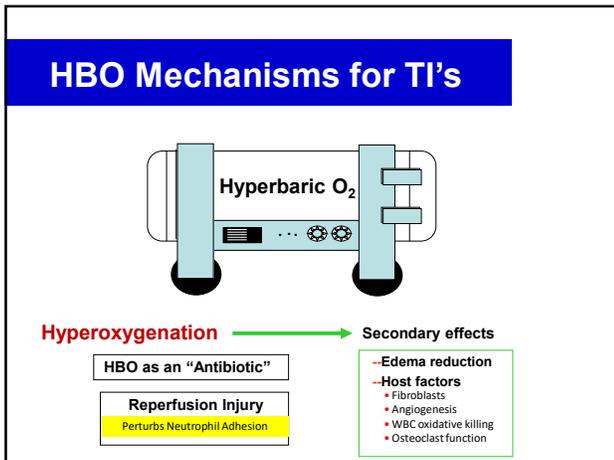
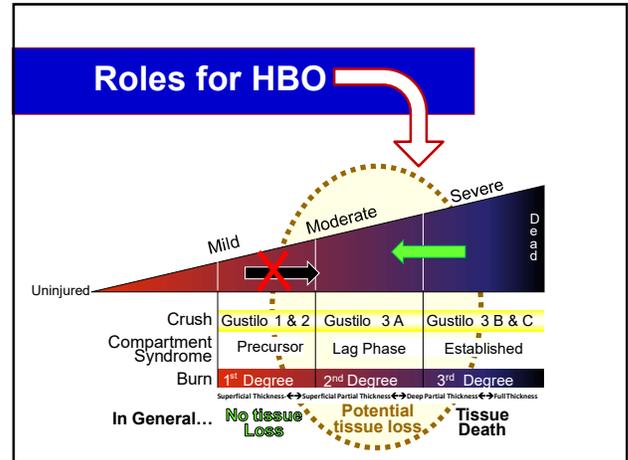


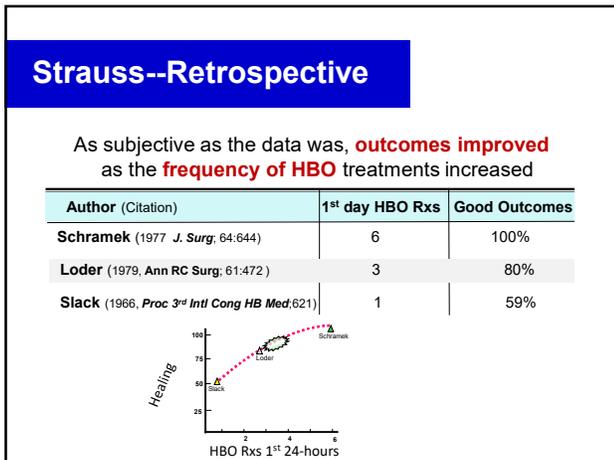
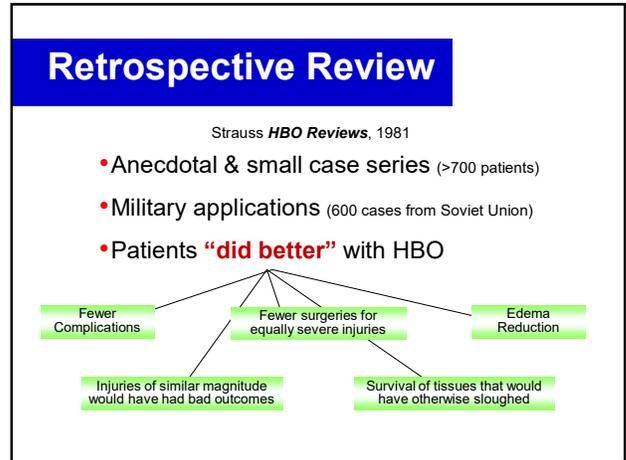
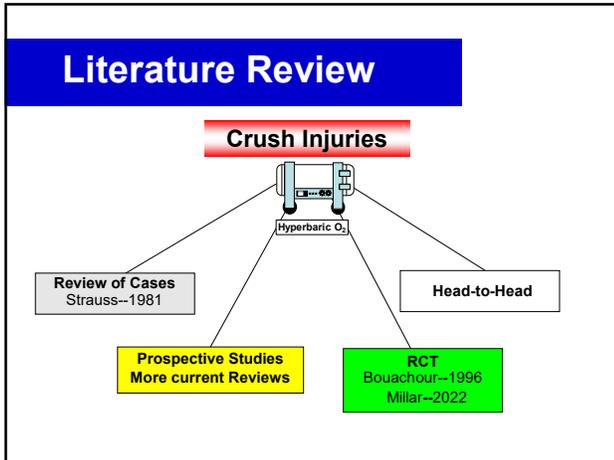
Gustilo – 1979 & 1984

Open-fracture, Crush Injury

Grade	Findings	Outcomes
1	Puncture-type wound (inside to out) with fracture	Healing ~ 100% of cases
2	Laceration with fracture	~10% infection or delayed healing
3	"Crush" Injuries	Sub-classifications
A	Sufficient soft tissue to cover bone	Same as for Grade 2
B	Exposed bone remains after debridement	~50% infection, non-union complication rate
C	Concomitant vascular injury	>50% complication; amputations

J Bone Jt Surg. 1979; 58:453
J Trauma. 1984; 24:742





Some Current Reviews

- Ortho** • 2005 Garcia-Covarrubias *Am Surg* 71(2):144-151
8 Of 9 (89%) of “qualified” reviews showed **benefits of HBO**
- Plas Surg** • 2014 Dauwe *Plast Reconst Surg* 133(2):208e-215e
8 studies showed **improved outcomes**-aided wound healing by improving graft survival, ecchymosis resolution and TCOMs
- Hand** • 2023 Chang *Wound Repair & Regen* doi:1111WRR.13134
72 patients (36 HBO 36 controls)with traumatic hand
Days for wound healing: 29.9 vs. 41 (p 0.03)
Benefits of early treatments (<72 hours)
--**Decreased hospital days**: 8.1 vs 15.5 (p 0.04)
--**Faster healing**: 28.7 vs 41.2 days (p 0.08)
--**Less surgeries**: 1.5 vs. 2.4 (p 0.06)

Most Recent...

- 2024 Kwee *Europ J Trauma & Emerg Surg*, Feb 2024
On-line: 10.1007/s00068-023-02426-2

7-Studies
229 Pts

HBO: 138 (60%) Controls: 91 (40%)

HBO in management of severe lower limb soft tissue injuries: a review

Considerations	Healing	Necrosis	Add'l Surgeries
HBO/Control (Mean %)	85/56 (20%)	14.5/43.8 (33%)	24.3/42.3 (28%)
Range (HBO)	62-100	0-29	0-67

Comments / Concerns { 2/7 (29%) RCTs; 5/13 elements (38%) had statistically significant findings
Quality of evidence mentioned, e.g., serious, low, moderate, or unclear
Deficient in pathophysiology / mechanism justifications for HBO

Caudle vs Matos

Gustilo 3-B & 3-C crush injury, fractures

Head-to-Head Contrasts

	Caudle-JBJS 1987 No HBO	Matos UHM-1999 With HBO
Amputation	13/62 (25%)	3/23 (13.8%)
Other unsatisfactory results	25/62 (40.3%)	0/23 (0%)
Complications	62.8%	13.8%

78% better outcomes with HBO

Bouachour--RCT

Gustilo grade 3 open fractures (Blinded, placebo)

Finding	HBO 18 Patients	Control 18 Patients	p	Improvement Factor
Po Healing	94% (17)	56% (10)	<0.01	38% better (Kwee 20%)
Add'l Surg's	6% (1)	33% (6)	<0.05	27% less (Kwee 28%)
Heal >40	88% (7/8)	30% (3/10)	<0.05	58% better

About 20% complication rate with HBO vs. 50% in controls

Bouachour—Outcomes

With Hyperbaric Oxygen

Healing >40-years of age* 58% better than controls

*Chronological age is subordinate to biological age with respect to healing

HOLLT Study--2022

Hyperbaric Oxygen for Lower Limb Trauma

Millar, et al x-13., Diving and Hyperbaric Medicine, 2022; 52(3):164-174

Open Fracture (non blinded) RCT

Considerations	HBO	Controls	p-value
Tissue Necrosis <small>Within 12 days</small>	25/58 (29%)	34/59 (53%)	0.01
Late Complications <small>Up to 1-year Infection, non union</small>	6/53 (11%)	18/52 (35%)	0.007

Quality of life Significantly improved (based on 2 different scales) in HBO limb

About 20% complication rate with HBO vs. 50% in controls

Quantifying Health

Ala Appgar 10-point Newborn Scoring

Wellness Score

Differentiating Biological from Chronological Ages

Factor	2-Points	1-Point	0- Points
ADLs	Full	Some	None
Ambulation	Community	Household <small>Minus 1/2 point if aids required</small>	None
Comorbidities <small>Other than neuro</small>	None Significant	Impaired <small>Which ever gives the lowest score</small>	Decompensated
Inhibitors <small>Smoking, steroids, immunosuppressors</small>	None	Prior use	Current
Neuro Deficits	None	Mild-to-Moderate	Severe
Scoring	7.5-10 Points	4-7 Points	0-3.5 Points
Interpretation	Healthy	Impaired	Decomp'd

HBO for Crush Injuries

With consideration of Biological Age

	Healthy	Impaired	Decompensated
1	No HBO	No HBO	HBO
2	↓	HBO	↓
3-A	HBO	↓	??Amput
-B	↓	?? Amput.	↓
-C	↓	↓	↓

Wellness Score

Factor	2-Points	1-Point	0- Points
ADLs	Full	Some	None
Ambulation	Community	Household	None
Comorbidities	None Significant	Impaired	Decompensated
Inhibitors	None	Prior	Current
Neuro Deficits	None	Mild-to-Moderate	Severe
Scoring	7.5-10 Points	4-7 Points	0-3.5 Points

Wellness Score in Action

Nathe, K, et al., J Ft & Ankle Surg, 21 JUN 2024 (open access)

Multicenter Study (n = 162) NO HBO

Gustilo 2 (41%) & 3-A (39%) open ankle fractures

Literature: 10% complications

Older patients >60 chronological age vs. biological age

Gustilo Open Fx Outcomes

Grade	Classification	Sub-classifications
1	Location with Fracture	-10% infection or delayed healing
2	Crush Injuries	
A	Qualifies as both Grade 1 or Grade 2	Grade 1 or Grade 2
B	Requires amputation after 10% complication rate	10% infection, non-union, amputation rate
C	Consistent vascular injury	10% amputation, non-union, infection, neuro deficits

Complications 34.6%

- Superficial Infections 15.4%
- Deep Infections 9.9%
- Amputations 9.3%

Mortality at 1-year: Age (p=0.021) & Diabetes Mellitus (p=0.005)

HBO for Traumatic Injuries

Treatment Protocols & Peer Review

Condition	HBO Rx's	Peer Review (# of Rx's)	Comments
Crush Injury, Other TI.	TID 1 st 24 Hrs BID 2 Days Daily 5 Days	12	If deterioration noted with step down Rx's, resume previous schedule Similarly, for threatened flaps, failing amputations, etc.

HBO for Traumatic Injuries

Treatment Protocols & Peer Review

Condition	HBO Rx's	Peer Review (# of Rx's)	Comments
Reperfusion Injury	1 or 2	2	Minimal tissue trauma; replantations, free flaps transient, ischemia, after revascularizations, etc.,
Compartment Syndrome	2 or 3	3	Impending stage fasciotomy not required

Clinical Correlations

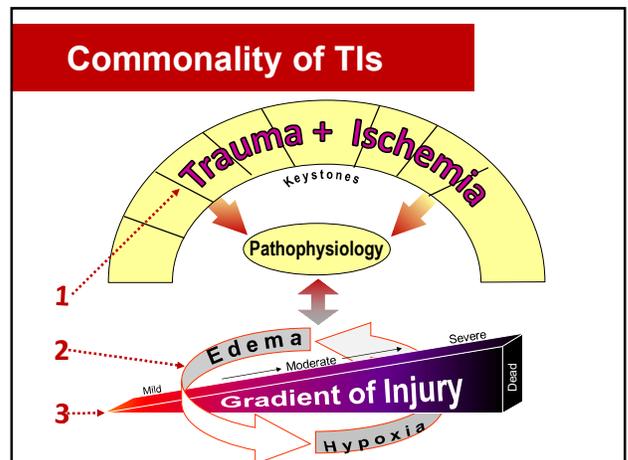
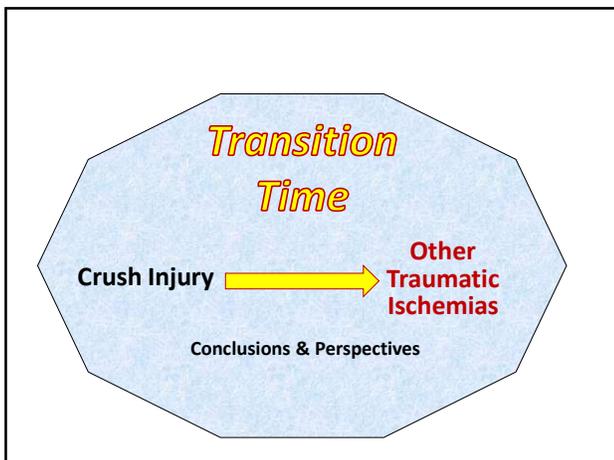
Acute use of HBO

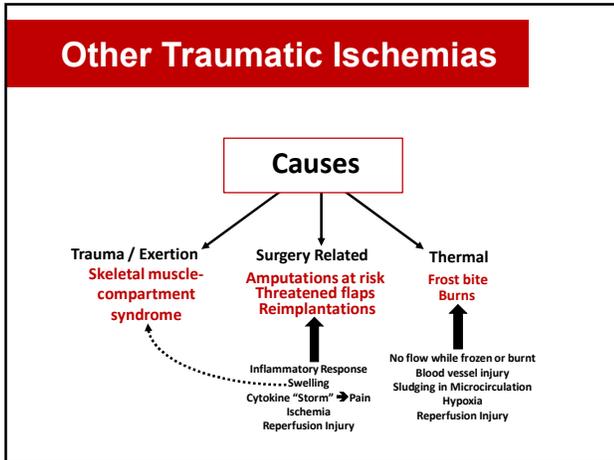
- 18 Year old male
- Mangled left leg (drum water extractor while working at a car wash)
- BKA proposed

Clinical Correlations

Delayed use of HBO

- 27 Year old male
- Crush/Fracture with septic nonunion after ~20 surgeries
- BKA requested by patient



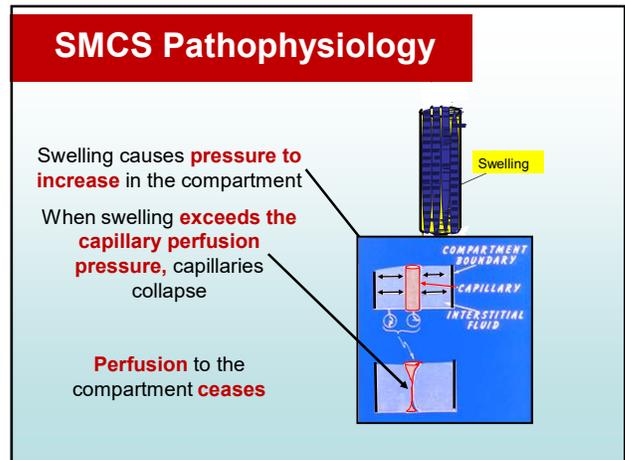
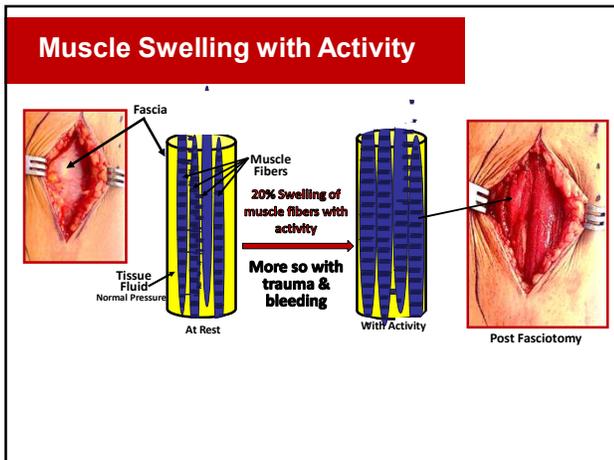


Skeletal Muscle Cmnt. Syndromes

- **Inadequate perfusion** at the micro-circulation level—usually after trauma
- Excellent **justification** for the use of HBO

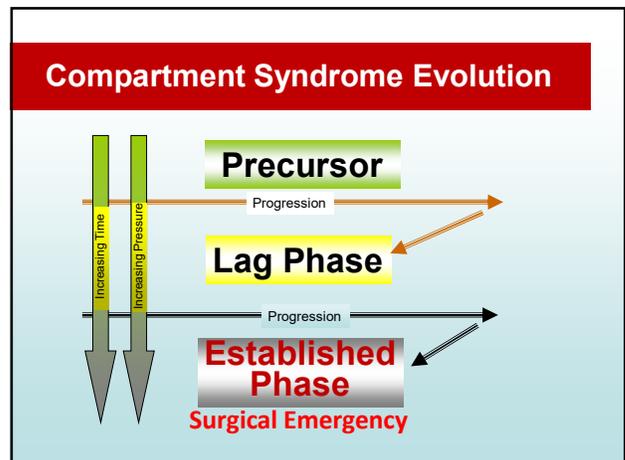
Muscles: Swell ~ 20% with activity & even more so with injury

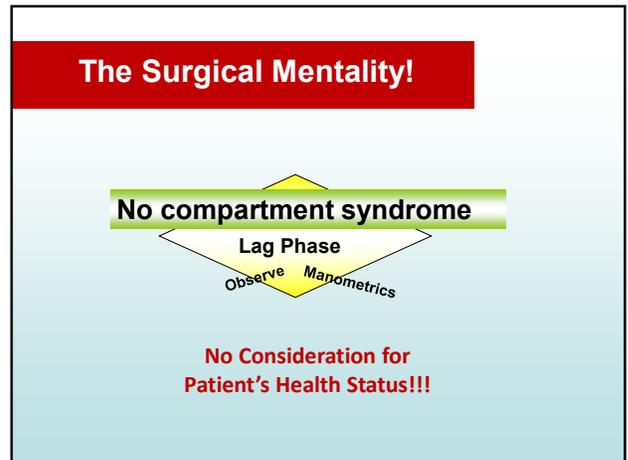
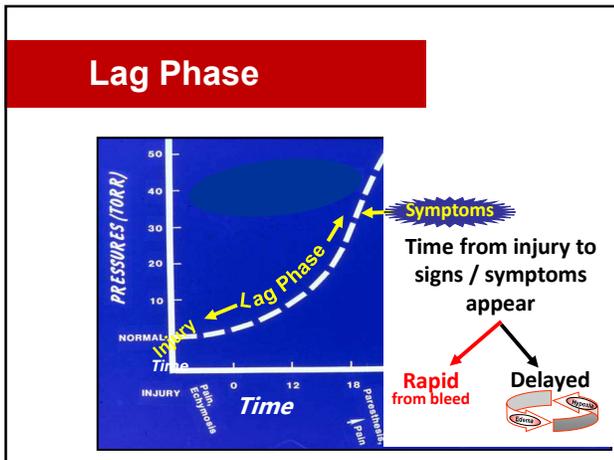
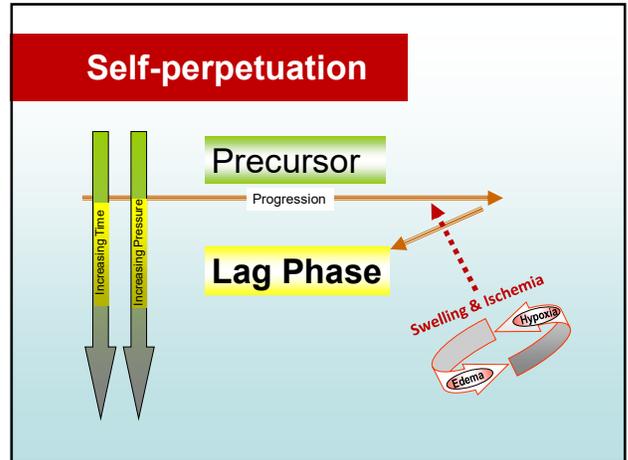
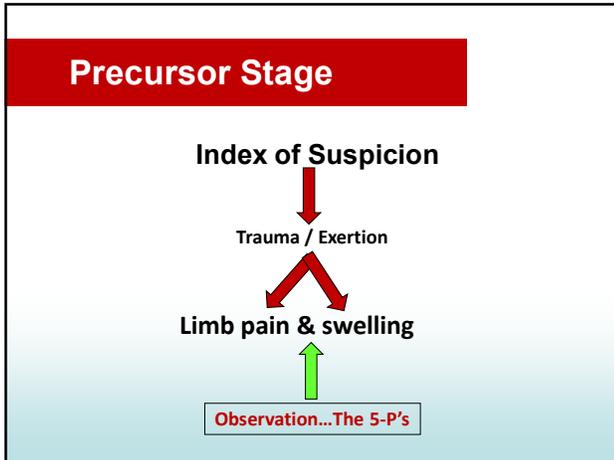
Fascia: Encases muscles, **but does not stretch**—a relatively inelastic envelope



Perfusion Pressures

Pressure	Site
120 mmHg	Artery
60 mmHg	Arteriole
30 mmHg	Capillary
10 mmHg	Intra-compartmental
8 cm H ₂ O / 5.9 mmHg	Venous





Lag Phase

Findings

Clinical

- 2 or more
 - Pain in muscle compartment
 - Worse pain with passive stretch
 - Swelling / tautness feeling of the compartment
- Plus 1 or more
 - Hypesthesia
 - Impaired or decompensated host
 - Encephalopathy, myelopathy or neuropathy
 - Hypotension
 - Prolonged (greater than 4 hours) ischemia time

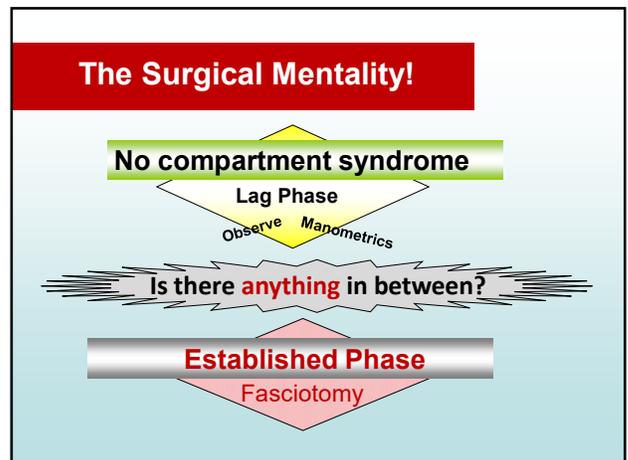
Manometrics

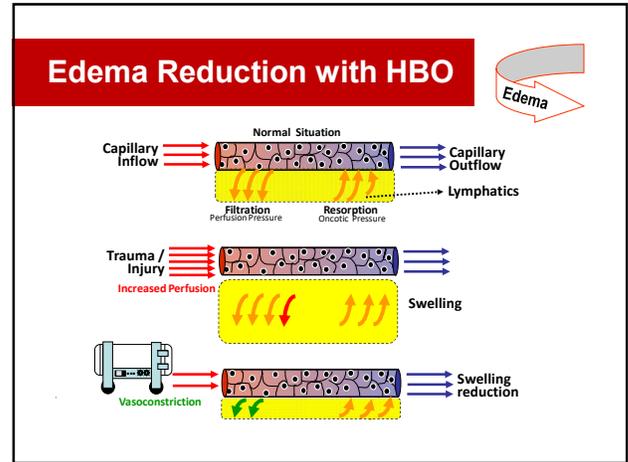
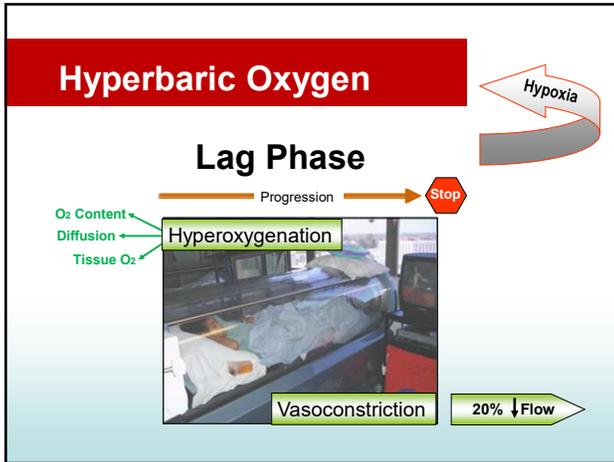
- Increasing pressures with serial repeats and / or
- ≤50 mmHg in a **Healthy Host**
- 30-40 mmHg in an **Impaired Host**
- 20-30 mmHg in a **Decompensated host** and / or **hypotensive patient**

+/-

Consider

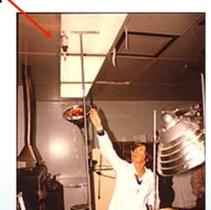
Wellness Score			
Factor	2-Points	1-Point	0-Points
ADLs	Full	Some	None
Activities	Community	Household	None
Communication	None Significant	Minimal	Decompensated
Neurological	None	Full	Complete
Neuro-Ortho	None	Medicare	Other
Scoring	7-5-10 Points	4-7 Points	0-3 Points





Dog Study

HBO arm

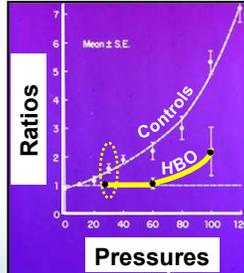



3 one hour HBO Rx's at 2 ATA over a 12 hour period

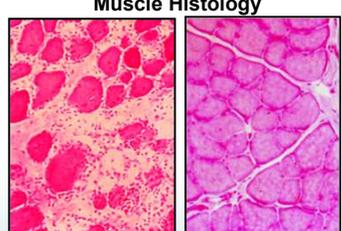
High pressure to generate injury

Dog Study

HBO arm—muscle injury



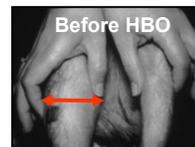
Muscle Histology



Control HBO

60 mmHg infusion pressure for 8-hours

Edema Reduction

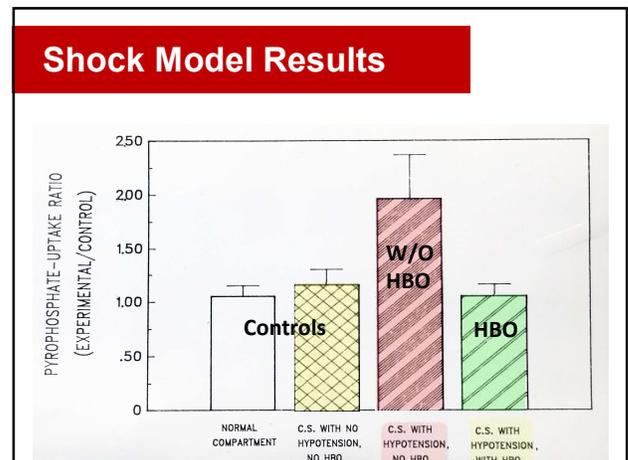


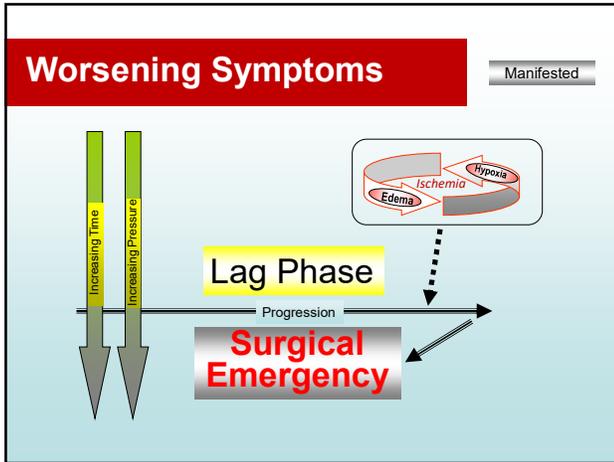

Muscle Wet Weight Measurements

Muscle edema reduced by 20%

Vasoconstriction Effect

Clinical





Pressure Dilemmas

Criteria for fasciotomy

Established Stage

Author (year)	Pressure for Fasciotomy
Whiteside(1975)	Less than 10-30 mmHg of diastolic blood pressure (DBP)
Matsen (1976)	40 mmHg
Mubarak (1978)	30 mmHg
Matsen (1980)	45 mmHg
Heckman (1993)	< 10-20 mmHg of DBP
Mateva (1994)	< 20 mmHg of DBP
McQueen (1996)	< 30 mmHg of DBP

No consideration for host status (circled in red)

Absolute Data are (circled in red)

Surgical Emergency

Findings

Progression

Clinical

- **Extreme** pain
- **Severe** pain with passive stretch
- **Marked** swelling / tautness of the compartment
- Compartment muscle **paralysis**

Plus 1 or more

- Anesthesia
- Impaired or decompensated host
- Encephalopathy, myelopathy or neuropathy
- Hypotension
- Prolonged (greater than 4 hours) ischemia time

Manometrics

- **>50 mmHg** in a **Healthy Host**
- **>30 mmHg** in an **Impaired ... Host**
- **>20 mmHg** in a **Decompensated/Hypotensive Host**

Wellness Score

Factor	2-Points	1-Point	0-Points
ADLs	Full	Some	None
Ambulation	Community	Household	None
Communication	None Significant	Impaired	Decompensated
Inhalation	None	Poor	Critical
Heart-Deficit	None	Mild/Moderate	Severe
Scoring	7-10 Points	4-7 Points	0-3 Points



Acute Compartment Syndrome

- 17-Y/O healthy male
- Water skiing injury to left calf
- 24 hour "lag" period
- HBO while awaiting OR availability

Pressure Measurements

Maxims about Compartment Syndromes

- HBO is **not a substitute** for fasciotomy in the **when urgent surgery required**, but may be considered while awaiting OR being available
- **No other interventions except for HBO mitigate rising compartment pressures** before a fasciotomy is required (i.e., during the lag phase)

HBO after Fasciotomy

One or more of the following

- **Ischemic** muscle
- **Demarcation** between viable & non-viable tissue is indistinct
- Major **swelling**
- Prolonged **ischemia time**
- **Threatened** skin flap or graft
- Residual **neuropathy**
- Markedly **impaired** and / or **decompensated** patient

Post-fasciotomy Residuals

Manifested
Post Fasciotomy

Immediate Post-op

After 10 days of HBO

- 5 year old male
- Sliver in elbow
- Clostridia in wound
- Compartment syndrome

Delayed Closure

SMCS-HBO Literature

7 "strong" studies

>50 "reports" ≠ Oriani

Laboratory Studies

- Strauss, Hargens, et al., Canine studies...very conclusive, *J Bone Joint Surg*, 1983, 1986, *J Ortho Res* 1986; **Plus 2 additional publications**
- Nylander, et al., Edema reduction, muscle preservation, *Plast Reconstr Surg*, 1985, *Ibid*, 1988, *Scandi J Plast Recon Surg*, 1989
- Bartlett, et al., Rabbit model...neuro recovery, *UHM*, 1998

Clinical Reports

- Strauss, Hart, *Clinical series in lag phase* with no subsequent fasciotomies, *Contemp Orthop*, 1989
- Oriani, several hundred clinical experiences without elaboration, *Handbk Hyperb Med* (Springer), 1996
- Fitzpatrick, et al., adjunctive treatment, case rept., *Mil Med*, 1998
- Kosugi, et al., 49 SMCS cases, 45 in lag phase before fasciotomy; **good results when HBO used as soon as clinically diagnosed**, *UHM*, 2014

Some Concluding Remarks

RBI (Rational based indications) for HBO

Hyperbaric O₂

Another 10-Point Scoring System!!!

Criteria	Strong Evidence (2 Pts)	Information is consistent with the assessment (1Pt)	No information, no benefit or possible harm (0 Pts)
Clinical experiences		1 1	
Mechanisms/Lab	2 2		
Literature / outcomes		1 1	
No other Rx's available	2	1 1/2	
RCT's; Head-to-head studies	2		0

Crush Injury = 7 ½ Points

Compartment Syndrome = 6 points

5 Points meets HBO criteria for a RBI

My New Perspectives

The **bone problem** is invariably **subordinate to the soft tissue injury**

Orthopaedic techniques & hardware is so advanced that rarely does bone management lead to less than adequate alignment & stability

The **seriousness of the soft tissue injury** is the **crucial consideration**

SURGICAL JUDGEMENT !!!

- ✦ ~ 30% better out comes with HBO
- ✦ Biological vs. chronical age factors into decision making

Linsey Tomp, USA Olympic skier with irreparable injuries to her leg fasciotomy & surgery

Now Super Athlete - New saved leg

Comments & Frustrations

Strauss & HBO

Traumatic Injuries



- Great potential
- Good evidence
- Major Logistic Challenges

Traumatologists

Que sera' sera'

Nothing in between

Egos, reluctance & lack of knowledge

HBO can nearly half the 50% complication rates

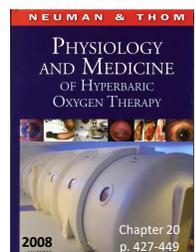
The *mechanisms* of HBO *mitigate the pathophysiology* of the traumatic Ischemias

Additional Resources



2025

"Preaching" to the Choir



2008

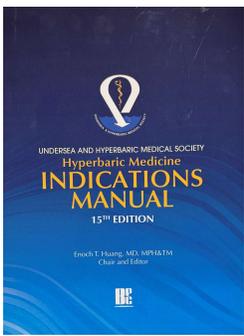
Chapter 20
p. 427-449

For the "Skeptics"

Crush Injury Chapters

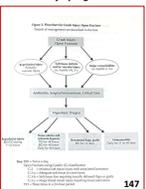
Similar subjects; different perspectives

HBO Committee Report



Part I. Chapter 6
Pages 137 -154

Crush Injury Algorithm



147

Compartment Syndrome Algorithm



148

For those who like algorithms...

Thank You

For inquires and/or suggestions

Email: [.MStrauss@MemorialCare.Org](mailto:MStrauss@MemorialCare.Org)

Inquiries: USA Phone 562 933-6960



Wound Care



Hyperbaric Medicine Program



Dive Medicine

Questions for Review



Hyperbaric O₂

What situations **justify HBO** for traumatic ischemias?

What are **similarities & differences** between crush injuries and other traumatic ischemias?

Why is HBO **not more utilized** for TIs?



A little Additional...

Much **Traumatic Ischemia** information has been presented.

The following questions & slides supplement information presented in today's talks

They have been used in **previous TI** presentations & publications

Additional Questions

1. Information from the following 7-supplement slides has been SPECIFICALLY DISCUSSED in today's presentation (slide 79) **T F**
2. Oxygen availability for cell functions IS ONLY NEEDED for the inflammatory phase of wound healing (slide 82) **T F**
3. Bouachour showed that tissue oxygen tensions DID NOT INFLUENCE healing rates of crush injury-fractures (slide 83) **T F**
4. It is not possible for an exertional compartment syndrome to coincide with a "full-blown" skeletal muscle-compartment syndrome (slides 84 & 85) **T F**
5. Almost ALL ORTHOPAEDIC SURGICAL DECISIONS are based on randomized control trials (slide 86) **T F**
6. RATIONAL BASED DECISIONS for using HBO in traumatic injuries is based entirely on experimental evidence (slide 87) **T F**
7. The use of Medicare DRGs (Diagnostic Related Groups) HAS BEEN A BOON for using inpatient HBO services (slide 88) **T F**

Answers

The following slides show why the answers are not true

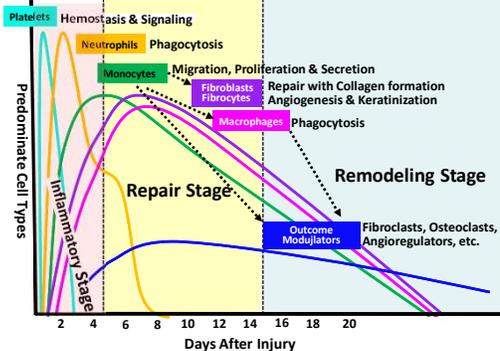
Roses are red, violets are blue
The answers mustn't be true

Each has merits worthy of extended discussions



The Message

Specific cell types predominate for each stage of healing
Oxygen is essential for the function of each cell type



Bouachour TCOM Indexes

Ratios of Injured vs. Uninjured Legs

Healed Legs
(vs Non-healed)
>0.9 (p = 0.05)

HBO Legs
(vs Controls)
>0.9 (p = 0.05)

Deductions: The **adequately oxygenated** fracture is the one that heals
HBO is an adjunct to oxygenating the fracture site

Neurological Residual & HBO

- 13-year-old ballet dancer & gymnast
- **Severe leg pain** plus unilateral "drop foot" (i.e. peroneal nerve palsy) after a strenuous combination of above activities.
- Pain resolved, but seen in ED 2-days later with on-going foot drop. **Pressures normal**; patient told she **did not have** a compartment syndrome
- **2nd opinion** delayed HBO consultation obtained.
- Foot drop resolved with a single HBO treatment

...A Case report paper in press

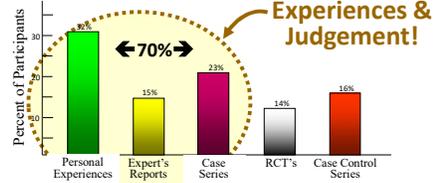
After Thoughts...

Manifested


- **Combination Problem**
 - Exertional compartment syndrome **pain resolved spontaneously**
 - **Acute compartment syndrome (ACS) residual** with peroneal nerve palsy...i.e. drop foot
- **Serendipity**
 - If the ACS had been recognized initially, a fasciotomy would likely have been done
 - The single HBO treatment **resolved** residual neuro problem
- **Later-on...**
 - Bilateral leg fasciotomies done
 - Patient able to resume activities without recurrent ECSs

Making Decisions

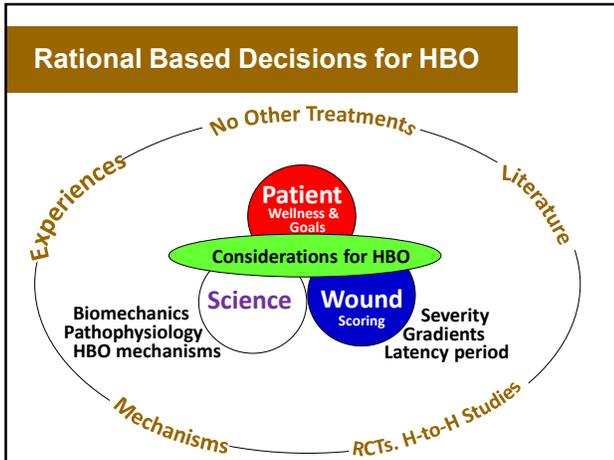
Evidence Used for Clinical Decision Making*
(American Orthopaedic Association)



Evidence Type	Percent of Participants
Personal Experiences	30%
Expert's Reports	15%
Case Series	23%
RCT's	14%
Case Control Series	18%

What is the primary type of evidence you use in your clinical decision-making?

*Schemitsch, EH, M Bhandari, MD McKee, et al., Orthopaedic surgeons: artists or scientists?, *J Bone Joint Surg*, 2009; 91:1264-73



Frustrations!

1977: ~30 HBO units in the USA; all treating wounds, **emergencies & medical problems of diving**

Reimbursements: Fee for service; **cognitive & support**

Today: Estimated 1500 HBO units in the USA; **BUT ONLY ABOUT ~70 (5%!!!)** are treating emergencies & medical problems of diving

Medicare Reimbursements: **Out-patient facilities only...**

DRGs (Diagnostic Related Groups) **DO NOT PROVIDE IN-PATIENT** payments for hyperbaric oxygen treatments