Traumatic Injuries & Hyperbaric Oxygen

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 O_2 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

A little "Heads-up"!!!

…a lot of information

…for expediency key info on the slides is highlighted

References on the slides are provided for later retrieval

The bottom line…we'll be "moving" through 84 slides at a rapid pace

Objectives

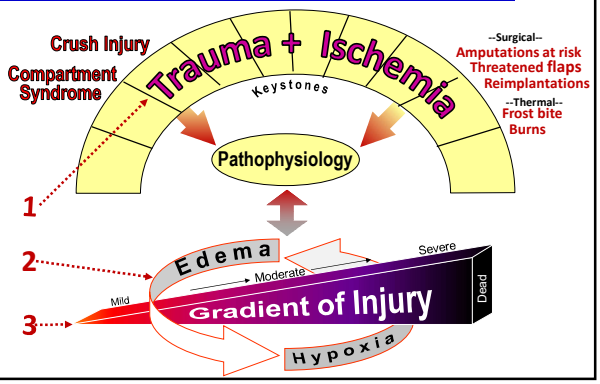
By the end of this talk you will

- **Appreciate** the spectrum of the **Traumatic Injuries** with special emphasis on crush injuries & compartment syndromes
- **Be aware of** their **pathophysiology** & **severity** classifications
- **Know** why & when **to use HBO** for them

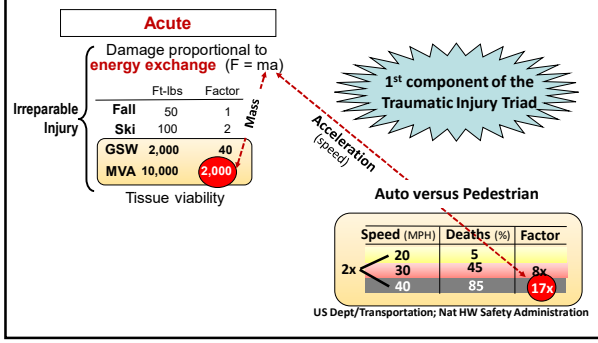
Introduction

- 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 **Traumatic Injury** Care

The Traumatic Injury Triad

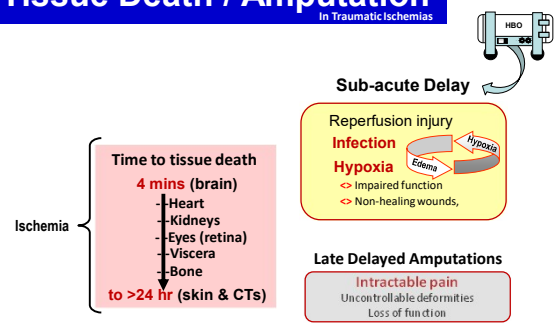


Tissue Injury & Death

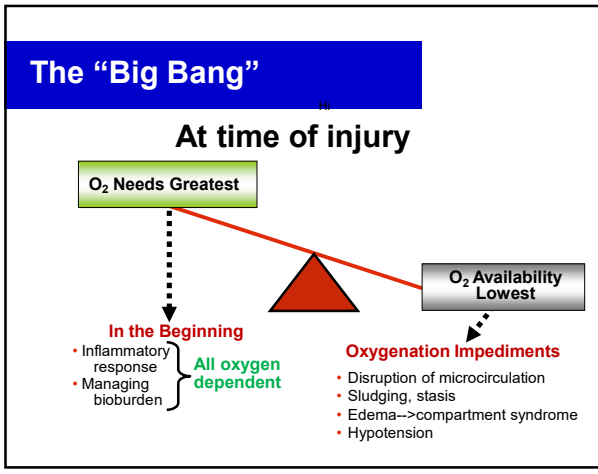


Tissue Death / Amputation

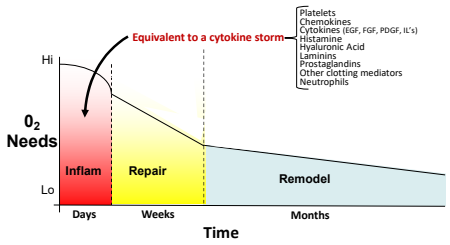
In Traumatic Ischemias



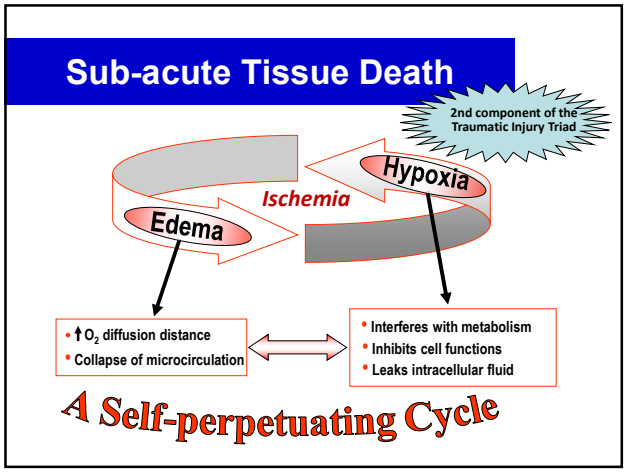
The "Big Bang"



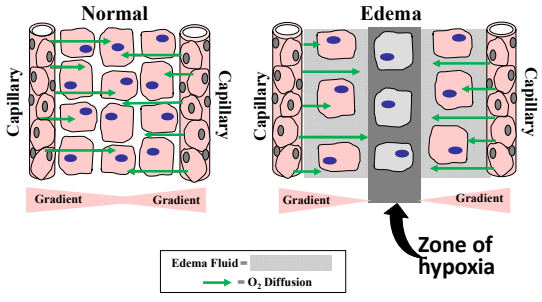
Metabolic Activity in Healing



Sub-acute Tissue Death

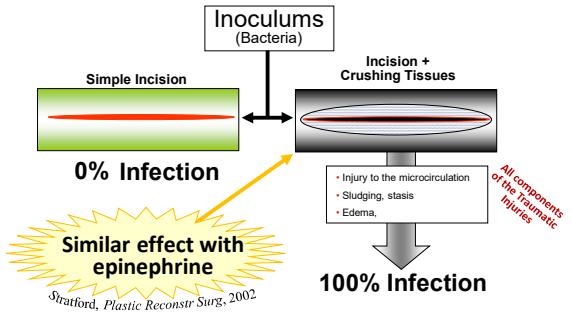


O_2 Diffusion & Gradients



Tissue Injury & Infection

Halstead Circa 1890



Inflammatory Response

C F U's to initiate infection after knee trauma in dogs

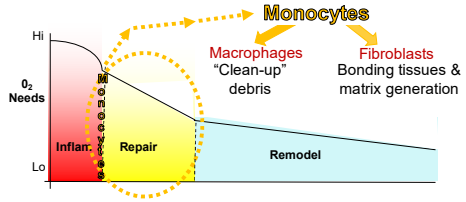
Colony Forming Units

TK Hunt—UCSF presentation at a 1980's LBMC HBO conference

Time	CFU ➔ Infection	Factor
At time of inoculation	10,000	1
5-days after Injury	200,000	20

Conclusion Once the **inflammatory response** is established, the better the tissue is **able to handle infection**

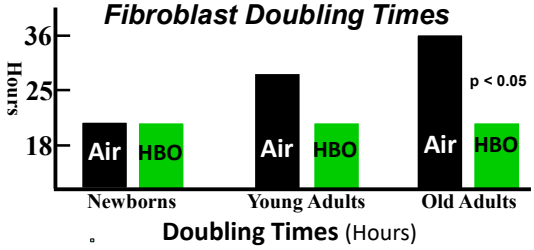
Repair Phase of Healing



Cellular Milieu Transitions to Monocytes

Signaling Mechanism

Reenstra,UHM Suppl. 25:51. #157 1998



Reenstra's Premise: O_2 a Signaling Mechanism

HBO & Angiogenesis

Angiogenesis

Shekih, *Arch Surg*, 2006; 135:1293

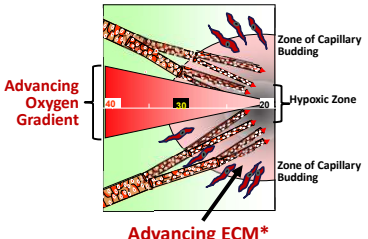
40% increase in vascular endothelial growth factor (VEGF) with HBO

Lin, et al (X-8), *J Cell Molecular Med (open access)* 2024, 28e70.310

<> **Significant** increase in angiogenesis **w/HBO**

<> **Upregulated** VEGF, HO-1, HIF-1 & Nrf2

<> Mitigated RO_2S & cell dysfunction

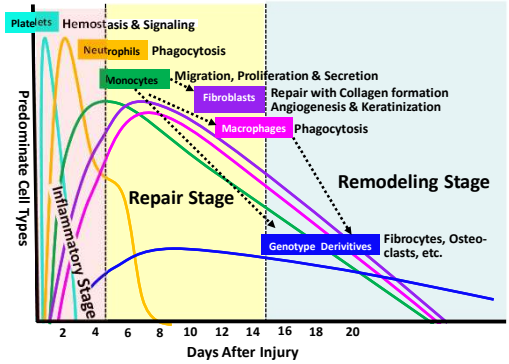


*Extra Cellular Matrix

The Message

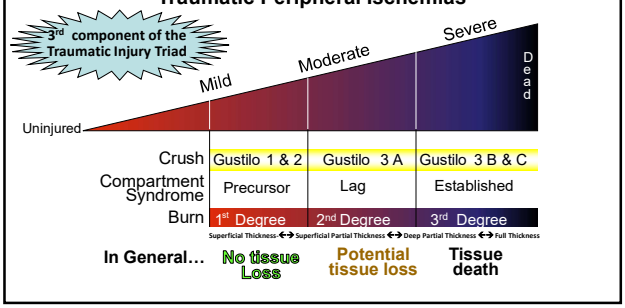
Specific cell types predominate for each stage of healing

Oxygen is essential for the function of each cell type



Gradient of Injury
A tactic for classifying severity

Grading Systems for Acute Traumatic Peripheral Ischemias

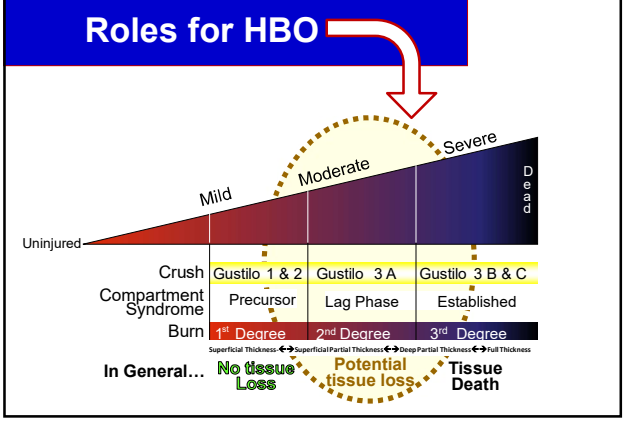


Gustilo – 1979 & 1984

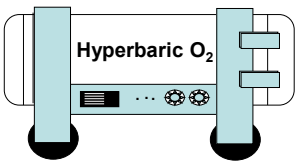
Open-fracture, Crush Injury

	Grade	Findings	Outcomes
J Bone Jt Surg, 1979; 58:453	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**
J Trauma, 1984; 24:742	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**

Roles for HBO



HBO for Traumatic Injuries



Hyperoxygenation → **Secondary effects**

HBO as an "Antibiotic"

Reperfusion Injury
Perturbs Neutrophil Adhesion

- **Edema reduction**
- **Host factors**
  - Fibroblasts
  - Angiogenesis
  - WBC oxidative killing
  - Osteoclast function

Hyperoxygenation

HBO 2 ATA

Plasma & tissue 0_2 tensions

Tissue viability

Host factor function

10-fold increase

Hyperoxygenation

HBO 2 ATA

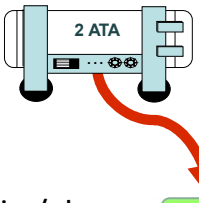
Blood O_2 Content

25% more carrying capacity

Ischemia / sludging

Endothelial function & reperfusion injury

Hyperoxygenation



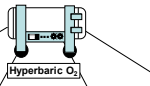
Relative barriers/edema
Compartment syndromes

Oxygen Diffusion

3-Times Greater

Literature Review

Crush Injuries



- Review of Cases Strauss--1981
- Head-to-Head
- Prospective Studies More current Reviews
- RCT Bouachour--1996 Millar--2022

Retrospective Review

Strauss ***HBO Reviews***, 1981

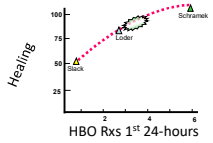
- Anecdotal & small case series (>700 patients)
- Military applications (600 cases from Soviet Union)
- Patients **"did better"** with HBO

- Fewer Complications
- Fewer surgeries for equally severe injuries
- Edema Reduction
- Injuries of similar magnitude would have had bad outcomes
- Survival of tissues that would have otherwise sloughed

Strauss--Retrospective

As subjective as the data was, **outcomes improved** as the **frequency of HBO** treatments increased

Author (Citation)	**1st day HBO Rxs**	**Good Outcomes**
Schramek (1977 ***J. Surg***; 64:644)	6	100%
Loder (1979, **Ann RC Surg**; 61:472)	3	80%
Slack (1966, ***Proc 3rd Intl Cong HB Med***;621)	1	59%



HBO Rxs 1st 24-hours

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

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

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

***Journal of Trauma*, 1996**

Gustilo grade 3 open fractures (Blinded, placebo)

	HBO 18 Patients	Control 18 Patients	p
Pº Healing	94% (17)	56% (10)	<0.01
Add'l Surg's	6% (1)	33% (6)	<0.05
Heal >40	88% (7/8)	30% (3/10)	<0.05

Bouachour—Outcomes
With Hyperbaric Oxygen

Primary Healing: 40% better than controls

Healing >40-years of age* 66% better than controls

***Chronological** age is subordinate to **biological age**

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

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 Within 12 days	25/58 (29%)	34/59 (53%)	0.01
Late Complications Up to 1-year Infection, non union	6/53 (11%)	18/52 (35%)	0.007
Quality of life	Significantly improved (based on 2 different scales) in HBO limb		

Quantifying Health

Wellness Score
~Apgar 10-point Newborn Scoring

Factor	2-Points	1-Point	0- Points
ADLs	Full	Some	None
Ambulation	Community	Household Minus ½ point if aids required	None
Comorbidities Other than neuro	None Significant	Impaired Which ever gives the lowest score	Decompensated
Inhibitors Smoking, steroids, immunosuppressors	None	Past Ditto comorbidities	Current
Neuro Deficits	None	Moderate	Severe
Scoring	7.5-10 Points	4-7 Points	0-3.5 Points
Interpretation	Healthy	Impaired	Decomp'd

HBO for Crush Injuries

Gustilo System w/Wellness Score

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

Wellness Score

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

Wellness Score in Action

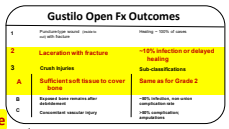
Nathe, K, et al., *J Ft & Ankle Surg*, 21 JUN 2024 (open access)

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**



Complications 34.6%

Wellness Score

ADLs
Mobility
Comorbidities
Inhibitors
Neuro deficits

Superficial Infections **15.4%**

Deep Infections **9.9%**

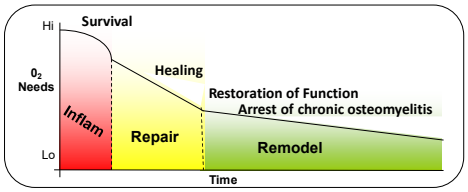
Amputations **9.3%**

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

HBO for Traumatic Injuries

Treatment Protocols & Peer Review

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



HBO for Traumatic Injuries

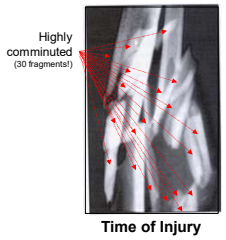
Treatment Protocols & Peer Review

Condition	HBO Rxs	Peer Review (# of Rxs)	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

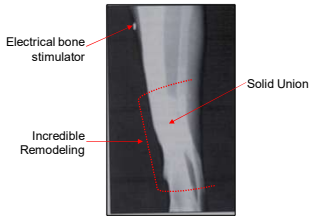
Clinical Correlations

Acute use of HBO

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



Time of Injury



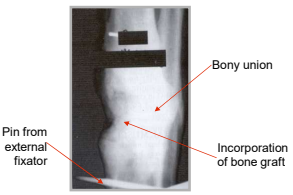
18 Months Later

Clinical Correlations

Delayed use of HBO

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

1 year post injury



18 months post-injury

After HBO + Surgery & Antibiotics

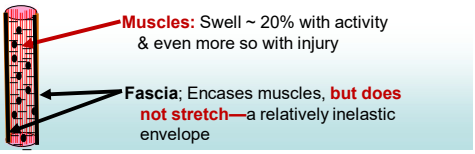
Transition Time

Crush Injury → Compartment Syndrome

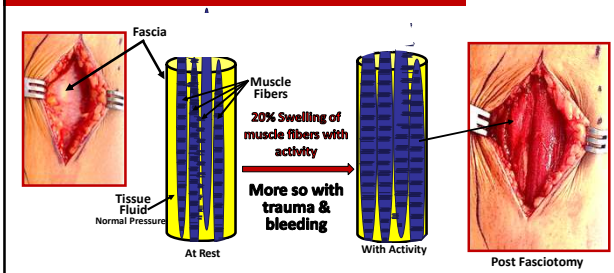
Conclusions & Perspectives

Compartment Syndromes

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



Muscle Swelling

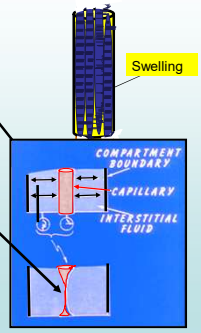


Pathophysiology

Swelling causes **pressure to increase** in the compartment

When swelling **exceeds the capillary perfusion pressure,** capillaries collapse

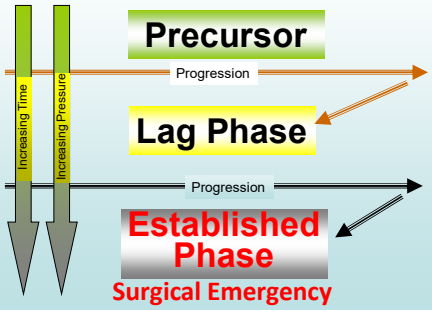
Perfusion to the compartment **ceases**



Perfusion Pressures

Pressure	Site
120 mmHg	Artery
60 mmHg	Arteriole
30 mmHg	**Capillary**
10 mmHg	Intra-compartmental
8 cm H_2O / 5.9 mmHg	Venous

Compartment Syndrome Evolution



Precursors

Index of Suspicion

Precursors

- Post-traumatic edema
- Obstruction of venous outflow
- Increased compartment contents (osteotomies, bone grafting)
- Decreased perfusion pressure (shock, arterial blockage)
- Snake bite
- Infiltrations
- Exercise

Management

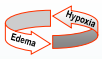
Observation

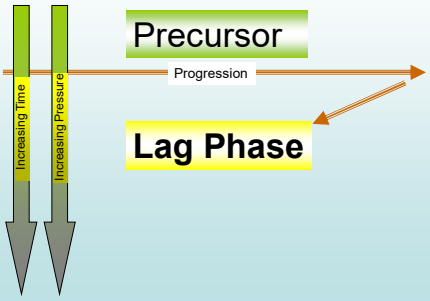
Significance

- **Pain** Magnified with passive stretch
- Paresthesias
- Paralysis
- Pallor
- Pulselessness

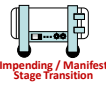
The 5 "p's"

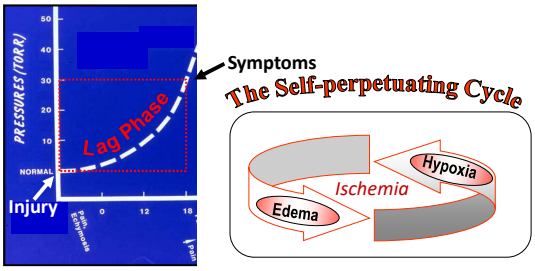
Self-perpetuation





Lag Phase





Lag Phase

Wellness Score

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

Findings

Progression

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

The Surgical Mentality!

No compartment syndrome

Lag Phase

Observe — Manometrics

Established Compartment syndrome

Fasciotomy

The Surgical Mentality!

No compartment syndrome

Lag Phase

Observe — Manometrics

Is there anything in between?

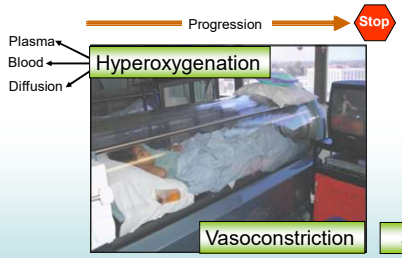
Established Phase

Fasciotomy

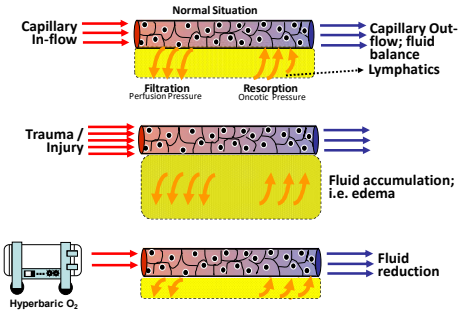
Hyperbaric Oxygen

Hyperbaric O_2

Lag Phase



Vasoconstriction with HBO

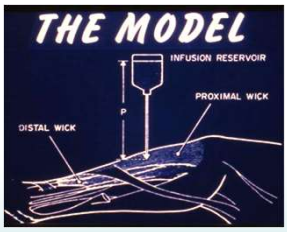


Canine Model

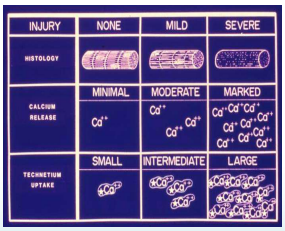
Hargins / Mubarak—San Diego

Impending

Hyperbaric O_2



The Model
8 Hour Infusions

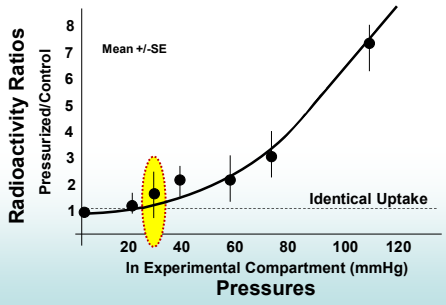


Documenting Injury
4 Days Later

Dog Study

Control results

Hyperbaric O_2



Dog Study

HBO arm

Hyperbaric O_2

Plasma

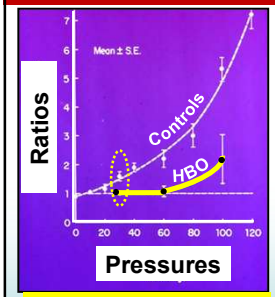
3 one hour HBO Rxs at 2 ATA over a 12 hour period

High pressure to generate injury

Dog Study

HBO arm—muscle injury

Hyperbaric O_2



Muscle Injury--Radioactivity

Muscle Histology

Control HBO

60 mmHg infusion pressure for 8-hours

Edema Reduction

Hyperbaric O_2

Clinical

Muscle Wet Weight Measurements

Muscle edema reduced by 20%

Vasoconstriction Effect

Shock Model

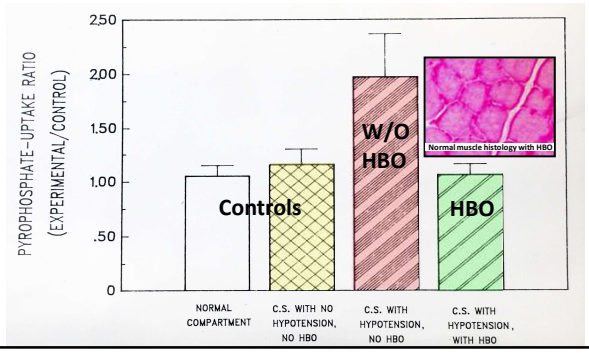
Dogs rendered **hypotensive by bleeding**

Infusion pressures of **30 mmHg** for 6-hours (vs. 8-hours) produced **muscle injury** in the control animals

3 one hour treatments over 12 hours

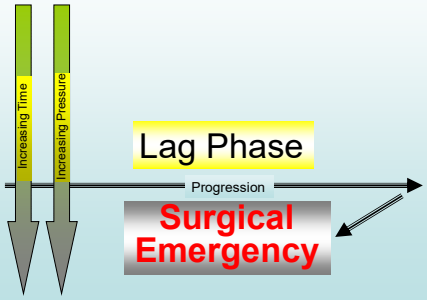
*Previous work by Hargens & Marbarak showed muscle injury threshold was 30 mmHg for 8-hours

Shock Model Results



Worsening Symptoms

Manifested



Pressure Dilemmas

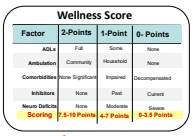
Criteria for fasciotomy

Established Stage

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

Surgical Emergency

Findings



Progression

Clinical

Plus 1 or more **2 or more major**

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

+/-

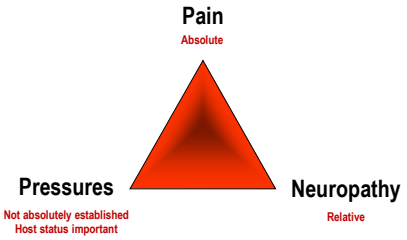
- Anesthesia
- Impaired or decompensated host
- Encephalopathy, myelopathy or neuropathy
- Hypotension
- Prolonged (greater than 4 hours) ischemia time

Manometrics

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

1 or more

Cardinal Signs for Fasciotomy



HBO is Not a Substitute for Fasciotomy

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

Neurological Residual & HBO

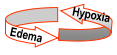
- 13-year-old ballet dancer & gymnast
- **Severe leg pain** plus **unilateral "drop foot"** (i.e. peroneal nerve palsy) after a strenuous combination of above activities.
- Pain resolved, but seen in ED 2-days later with on-going foot drop. **Pressures normal**; patient told she **did not have** a compartment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

After Thoughts…

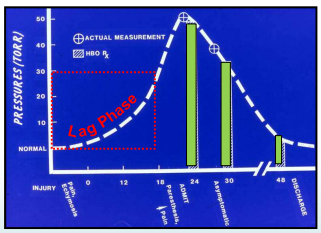
Manifested

- **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

Acute CompartmentSyndrome



- 17-Y/O **heathy** 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)

Post-fasiotomy Residuals

Manifested

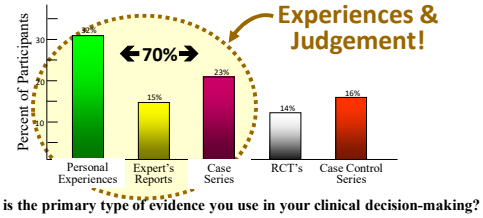
Post Fasciotomy

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

Some Concluding Remarks

Making Decisions

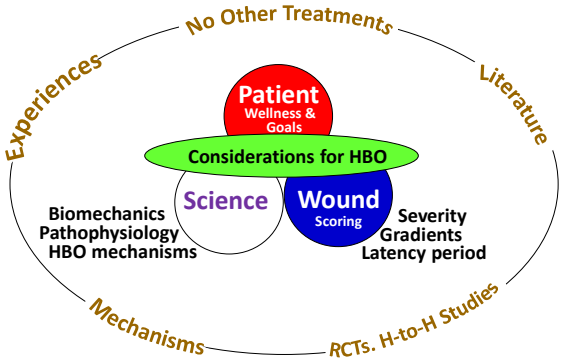
Evidence Used for Clinical Decision Making*
(American Orthopaedic Association)



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

Rational Based Decisions



RBI (Rational based indications) for HBO

Hyperbaric O_2

Another 10-Point Scoring System!!!

Criteria	Overwhelming 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 Rxs 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*** (orthopaedic) ***problem*** is ***subordinate to the soft tissue injury***

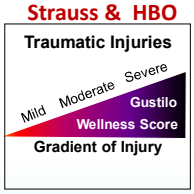
Orthopaedic techniques and hardware is so advanced that rarely does bone management lead to less than adequate alignment & stability

The ***extent / injury of the soft tissues*** is the ***crucial consideration*** in determining outcomes for traumatic ischemias

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

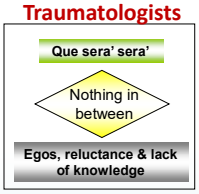
Comments & Frustrations

Strauss & HBO



- Great potential
- Good evidence

Traumatologists



- Major Logistic Challenges

We can do better than 50% complication rates

More Frustrations!

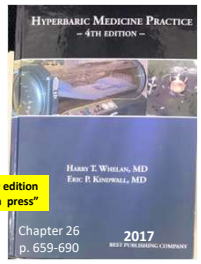
1977: ~30 HBO units in the USA; all treating wounds, **emergencies** & **medical problems of diving**

Reimbursements: Fee for service; cognitive & support

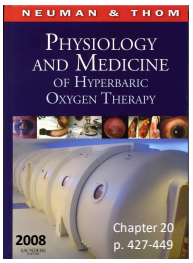
Today: Estimated 1500 HBO units in the USA; **but only +/- 70 (~5%!!!)** are treating emergencies & medical problems of diving

Reimbursements: Out-patient facilities only
DRGs (Diagnostic Related Groups) limit **IN PATIENT** payments for HBO

Additional Resources



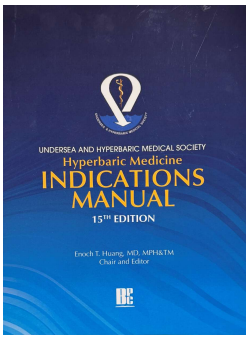
"Preaching" to the Choir



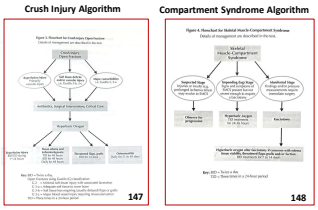
For the "Skeptics"

Crush Injury Chapters
Similar subjects; different perspectives

HBO Committee Report



Part I. Chapter 6
Pages 137 -154



For those who like algorithms…

Thank You

Time for questions?

Email: MStrauss@MemorialCare.org

Inquiries: USA Phone 562 933-6960

Hyperbaric Medicine Program

Dive Medicine

Questions

What situations justify using HBO for traumatic ischemias?

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

Why is HBO not more utilized for traumatic ischemias?