


Crush Injuries & Other Acute Ischemia


Michael B. Strauss, MD, AOFAS, FUHM



Traumatic Ischemias & 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



Traumatic Ischemias

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



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

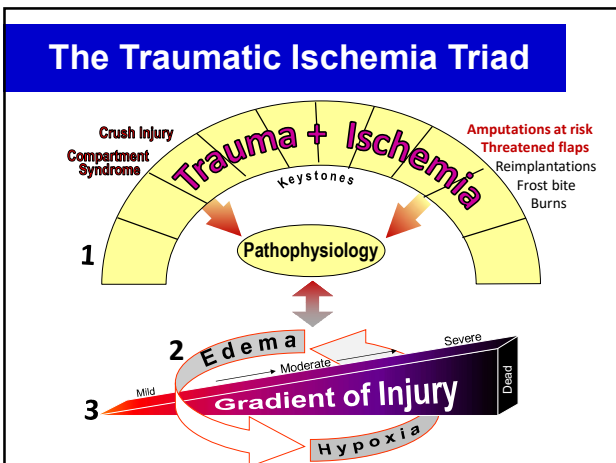
Objectives

By the end of this talk you will

- **Appreciate** the spectrum of the **Traumatic Ischemias** 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 TI Care



Tissue Injury & Death

Acute Tissue Death

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

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

Tissue viability

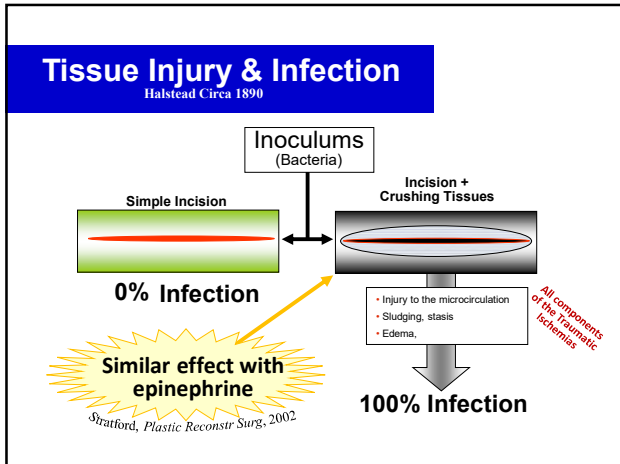
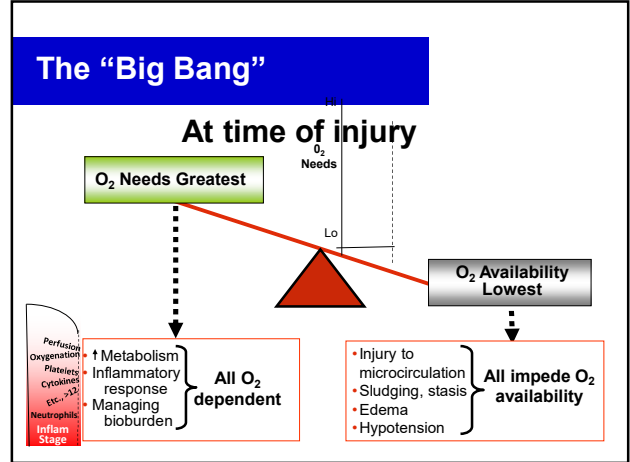
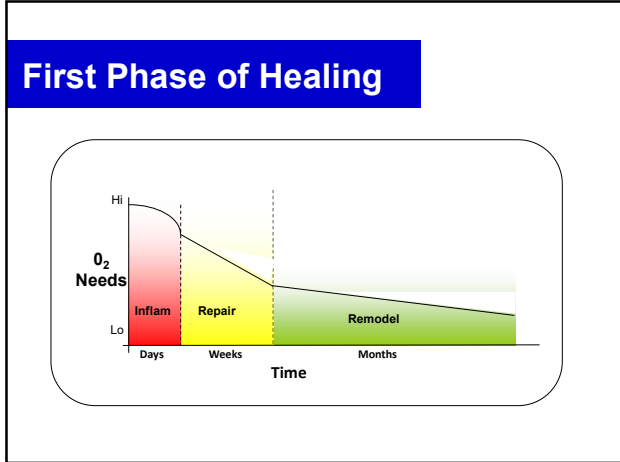
Secondary Injury

- Reperfusion injury
- Infection
- Ischemia ==> Non-healing wounds, deformity, pain

Car versus Pedestrian

Speed (MPH)	Deaths (%)	Factor
20	5	
30	45	
40	85	8x
40		17x

*Dependent on the tissue



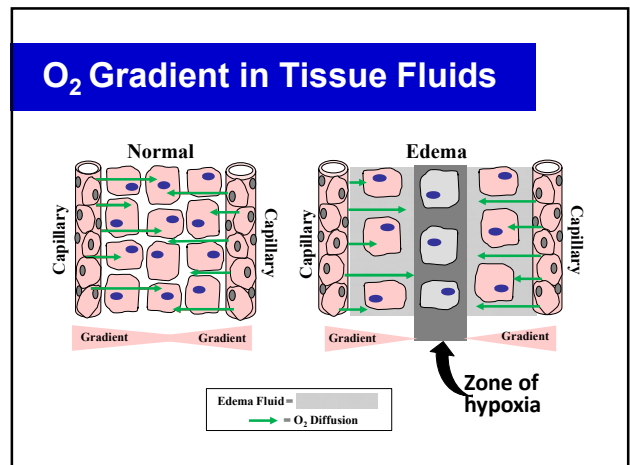
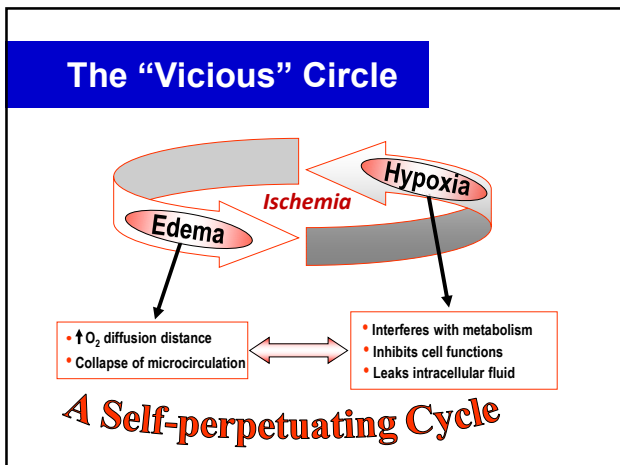
Inflammatory Response

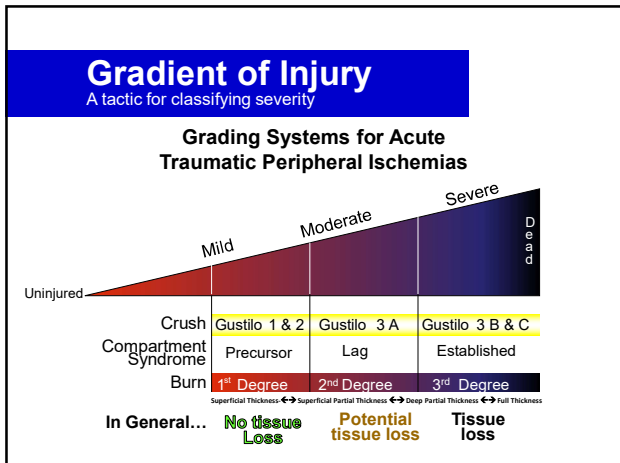
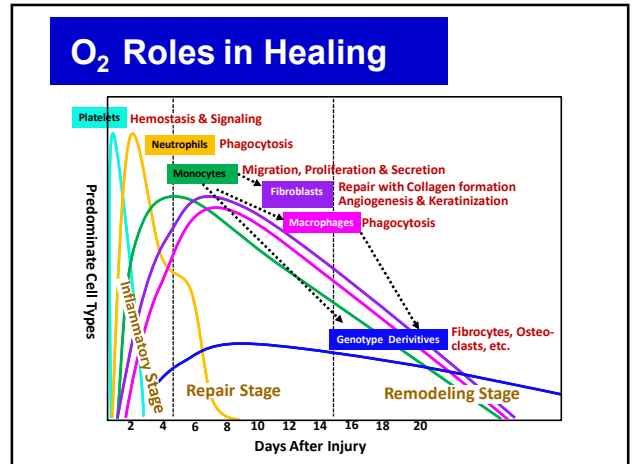
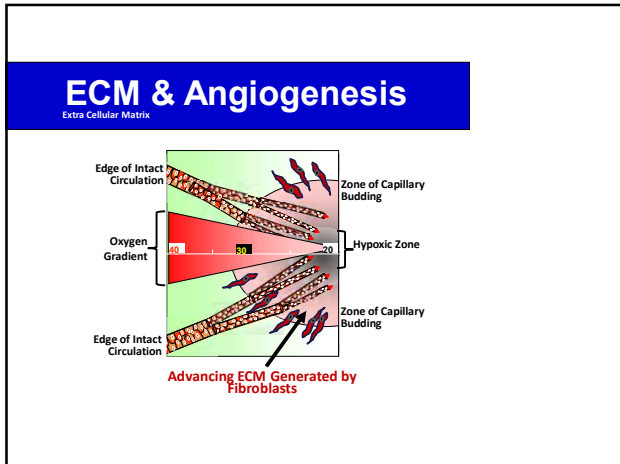
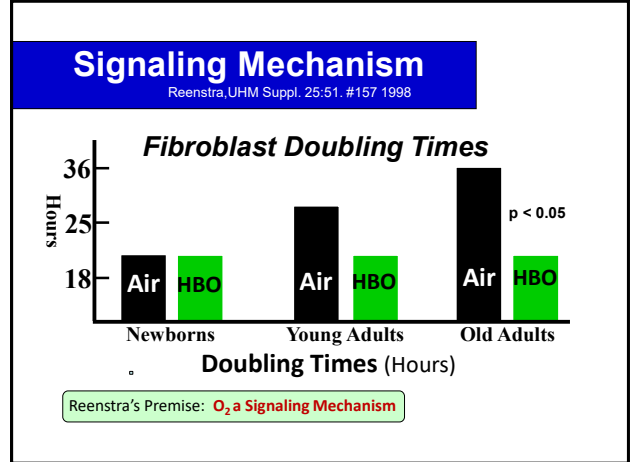
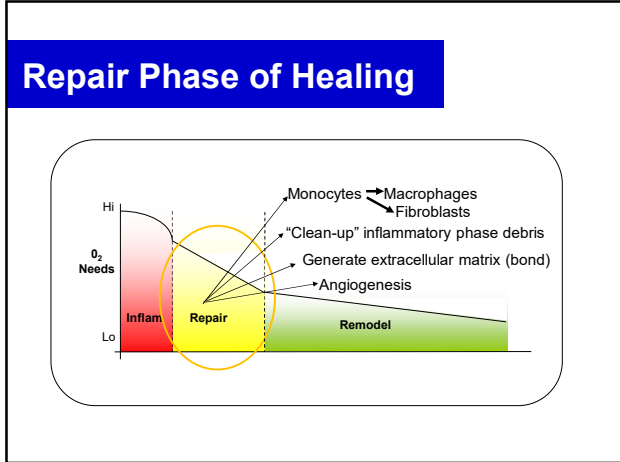
CFU's to initiate infection after knee trauma in dogs

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

forming colony





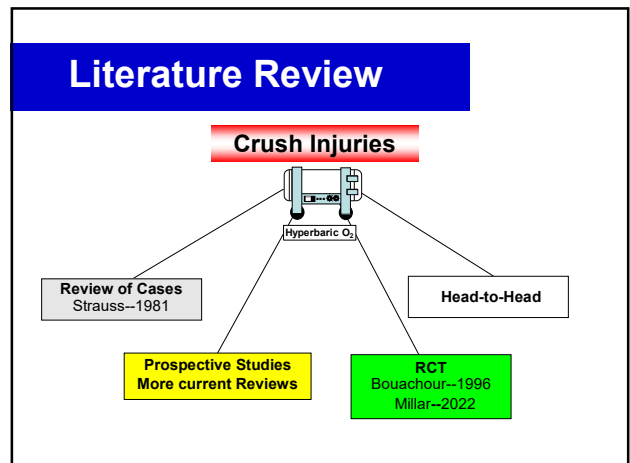
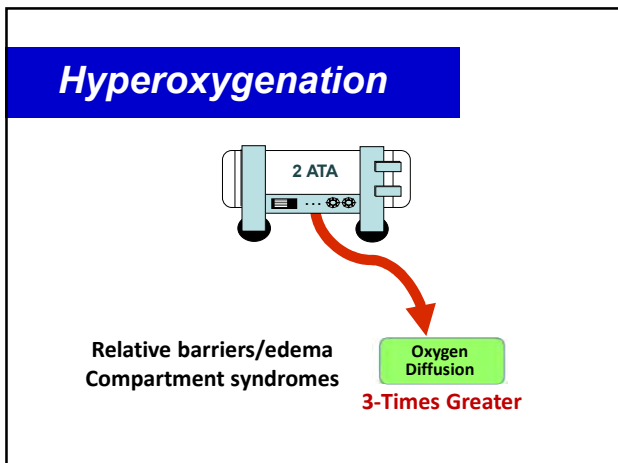
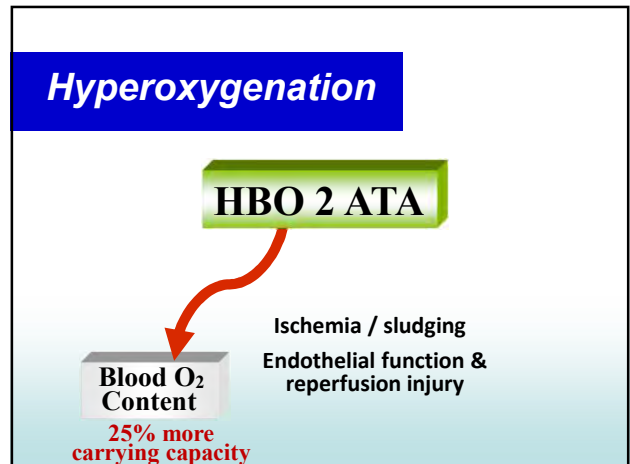
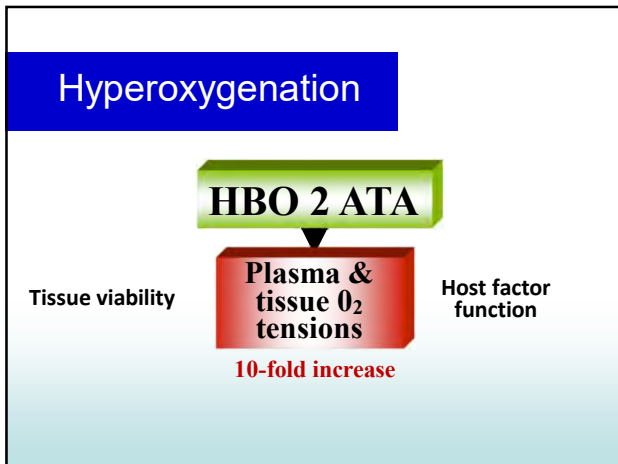
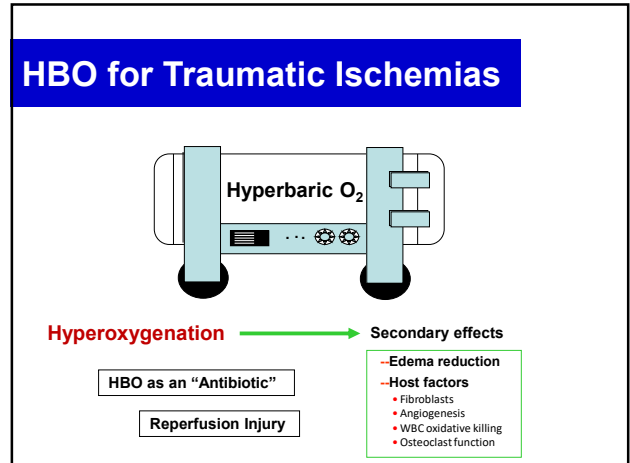
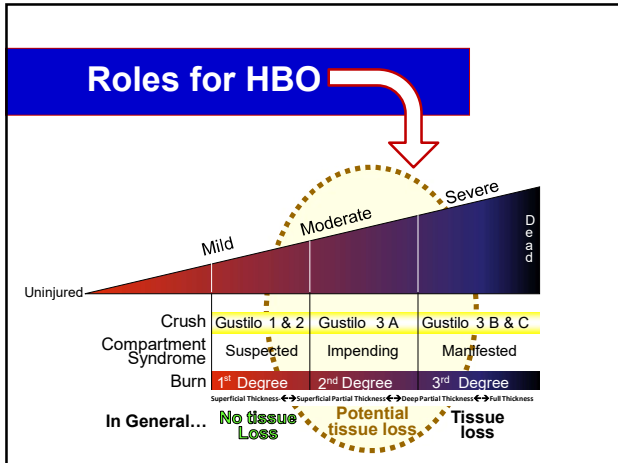
Gustilo – 1979 & 1984

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 >50% complication; amputations
C	Concomitant vascular injury	

J Bone J Surg. 1979; 58:453

J Trauma. 1984; 24:742



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)	1 st day HBO Rx's	Good Outcomes
Schramek (1977 <i>J. Surg.</i> ; 64:644)	6	100%
Loder (1979, <i>Ann RC Surg.</i> ; 61:472)	3	80%
Slack (1966, <i>Proc 3rd Intl Cong HB Med</i> :621)	1	59%

Healing (%) vs HBO Rx's 1st 24-hours

More Current & Prospective Reviews

- 2005 Garcia-Covarrubias *Am Surg* 71(2):144-151
8 Of 9 (89%) of “qualified” reviews showed benefits of HBO
- 2014 Dauwe *Plast Reconstr Surg* 133(2):208e-215e
8 studies showed improved outcomes--aided wound healing by improving graft survival, ecchymosis resolution and TCOMs
- 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%)

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

Adjunctive hyperbaric oxygen therapy in the management of severe lower limb soft tissue injuries: a systematic review

Comments { 2/7 (29%) RCTs; 5/13 elements (38%) had statistical 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
P ^o 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 <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		

Quantifying Health

Wellness Score

~Aggar 10-point Newborn Scoring

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	Past <small>Site comorbidities</small>	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	↓	???
-C	↓	???	Amput.

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

HBO for Traumatic Ischemias

Treatment Protocols & Peer Review

Condition	HBO Rxs	Peer Review (# of Rxs)	Comments
Crush Injury, Other TI.	TID 1 st 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 Ischemias

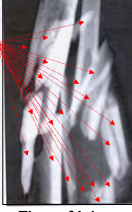
Treatment Protocols & Peer Review

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



Highly comminuted (30 fragments)

Time of Injury



Electrical bone stimulator

Incredible Remodeling


Solid Union

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



Non-union site

1 year post injury

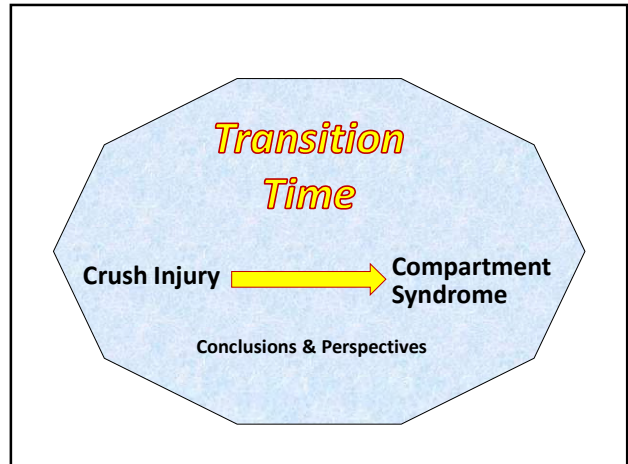


Bony union

Incorporation of bone graft

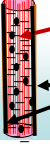
Pin from external fixator

18 months post-injury
After HBO + Surgery + Antibiotics



Compartment 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

Muscle Swelling



Fascia

Muscle Fibers


Tissue Fluid Normal Pressure

At Rest

20% Swelling of muscle fibers with activity

More so with trauma & bleeding

With Activity



Post Fasciotomy

Lag Phase

Factor	2-Points	1-Point	0-Points
ADLs	Full	Some	None
Activities	Community	Household	None
Consciousness	None	Significant	Impaired
Instability	None	Plant	Control
Neuro-Output	None	Moderate	Severe
Scoring	2-10 Points	1-2 Points	0-1 Points

Findings

Progression →

Clinical

- **Pain** in muscle compartment
- **Worse pain** with passive stretch
- **Swelling / tautness** feeling of the compartment

2 or more

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

Is there **anything** in between?

↓

Compartment syndrome

↓

Fasciotomy

Hyperbaric Oxygen

Hyperbaric O₂

Lag Phase

Progression →

Stop

Plasma →

Blood →

Diffusion →

Hyperoxygenation

Vasoconstriction

20% ↓ Flow

Vasoconstriction with HBO

Normal Situation

Trauma / Injury

Hyperbaric O₂

Canine Model

Hargins / Mubarak—San Diego

Impending

Hyperbaric O₂

THE MODEL

The Model

8 Hour Infusions

INJURY	NONE	MILD	SEVERE
METABOLISM			
CALCIUM RELEASE	MINIMAL Ca ²⁺	MODERATE Ca ²⁺ Ca ²⁺	MARKED Ca ²⁺ Ca ²⁺ Ca ²⁺
TECHNIQUE OFFGAS	SMALL	INTERMEDIATE	LARGE

Documenting Injury

4 Days Later

Dog Study

Control results

Hyperbaric O₂

Radioactivity Ratios Pressurized/Control


In Experimental Compartment (mmHg) Pressures

Mean +/-SE

Identical Uptake


Dog Study

HBO arm




Hyperbaric O₂

Plasma




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



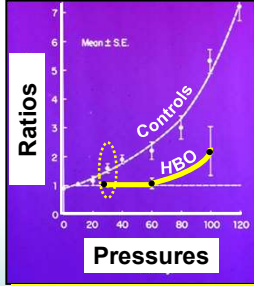
High pressure to generate injury

Dog Study

HBO arm—muscle injury

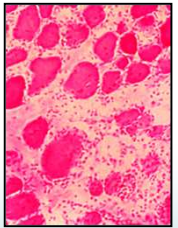
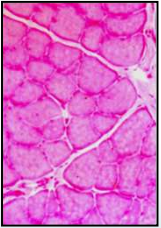


Hyperbaric O₂



Muscle Injury--Radioactivity


Muscle Histology

Control HBO


60 mmHg infusion pressure for 8-hours

Edema Reduction




Hyperbaric O₂

Before HBO



After HBO



Muscle Wet Weight Measurements

Muscle edema reduced by 20%



Vasoconstriction Effect

Clinical


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

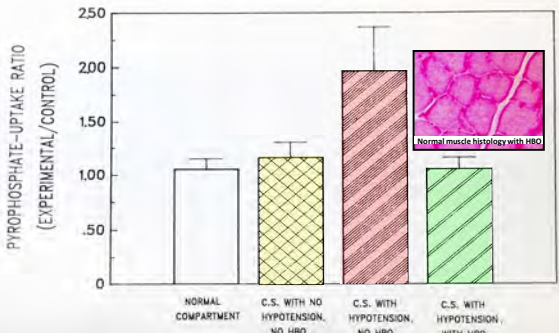



3 one hour treatments over 12 hours



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

Shock Model Results



Condition	Phosphate-Uptake Ratio (Experimental/Control)
NORMAL COMPARTMENT	1.0
C.S. WITH NO HYPOTENSION, NO HBO	~1.2
C.S. WITH HYPOTENSION, NO HBO	~2.0
C.S. WITH HYPOTENSION, WITH HBO	~1.1

Normal muscle histology with HBO

Worsening Symptoms

Manifested

Increasing Time

Increasing Pressure

Lag Phase

Progression

Established

Need for Fasciotomy

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

Absolute Delta "ps"

Established Stage

Wellness Score			
Factor	2-Points	1-Point	0-Points
ADLs	Full	Some	None
Activities	Community	Household	None
Comorbidity	None Significant	Present	Decompensated
Medications	None	Toler	Current
Neuro-Deficit	None	Moderate	Severe
Scoring	3-5 Points	1-2 Points	0-1 Points

Findings

Clinical

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

Plus 1 or more
2 or more major

- 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

Progression →

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 not demarcated
- 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

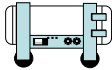
After Thoughts...

Manifested

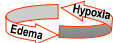
- **Combination Problem**
 - Exertional compartment syndrome **pain resolved spontaneously**
 - **Acute compartment syndrome (ACS) residual** with peroneal nerve palsy...i.e. drop foot
- **Serendipity**
 - If the ACS had been recognized initially, a fasciotomy would likely have been done
 - The single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

Maxims about Compartment Syndromes

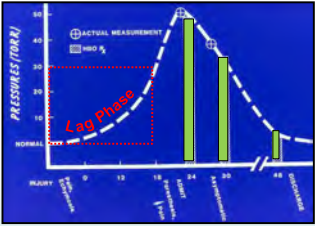
- HBO is **not a substitute** for fasciotomy in the **manifested stage**, but may be considered while awaiting OR
- No other interventions except for HBO mitigate rising compartment pressures** before a fasciotomy is required (i.e., during the lag phase)



Acute Compartment Syndrome




- 17-Y/O **heathy** male
- Water skiing injury to left calf
- 24 hour latency period**
- HBO while awaiting OR availability




Pressure Measurements

Post-fasciotomy Residuals




Manifested
Post Fasciotomy


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



Immediate Post-op



After 10 days of HBO

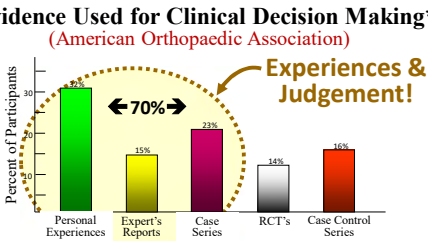


Delayed Closure

Some Concluding Remarks

Making Decisions

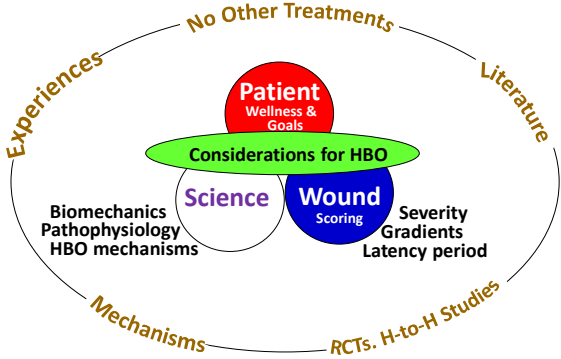
Evidence Used for Clinical Decision Making* (American Orthopaedic Association)




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




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 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** (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 / ischemia of the soft tissue injury** is the **crucial consideration** in determining outcomes for traumatic ischemias

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

Comments & Frustrations

Strauss & HBO

Traumatic Injuries



- Great potential
- Good evidence

Traumatologists

Que sera' sera'

Nothing in between

Egos, reluctance & lack of knowledge

• 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

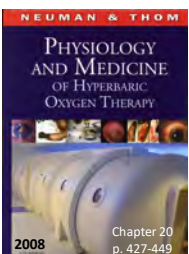
Today: ~1500 HBO units in the USA; **but only about 70** are treating emergencies & medical problems of diving
Reimbursements: Out-patient facilities only!!!

Additional Resources



Chapter 26
p. 659-690
2017
BEST PRACTICE GUIDANCE

"Preaching" to the Choir



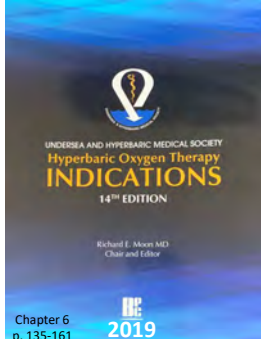
Chapter 20
p. 427-449
2008

For the "Skeptics"

Crush Injury Chapters
 Similar subjects; different perspectives

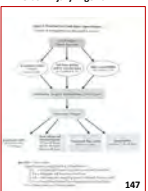
HBO Committee Report

Chapter 6
Pages 135 -151




Chapter 6
p. 135-161
2019

Crush Injury Algorithm



147

Compartment Syndrome Algorithm



148

For those who like algorithms...

Thank You

Time for questions?

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

Inquiries: USA Phone 562 933-6960



Wound Care



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?