Hyperbaric Oxygen Therapy as an Adjunct Therapy for Crush Injuries: A Case Series

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Statement of Purpose

To discuss the pathophysiology of crush injuries and the potential benefits of early administration of hyperbaric oxygen therapy (HBOT).

Literature Review

Crush injuries occur when a compressive or shear force of variable magnitude is applied for a variable amount of time to the body (1-4). There is a zone of primary injury, in which tissue may be nonviable, and a zone of secondary injury, which has variably injured and ischemic tissues (5). This zone of secondary injury is the result of ischemia, hypoxia, edema, and reperfusion injury. This can lead to a self-perpetuating injury which leads to more tissue damage, see Figure 1 (5-6). HBOT acts at the zone of secondary injury by using Boyle's and Henry's Law of physics to ultimately increase the amount of oxygen that reaches injured tissues (6-10).

Boyle's Law: $P1V1 = P2V2$

Henry's Law: $P = kC$

Under normal conditions at 1ata and 21% O2, the concentration of oxygen in plasma 0.31 mL O2/dL blood. Under hyperbaric conditions at 2ata and 100% O2, the concentration of oxygen in the plasma is 4.4 mL O2/dL blood (9). Figure 2 shows how HBOT targets all components of the zone of secondary injury ceasing this injurious cycle (5, 9).

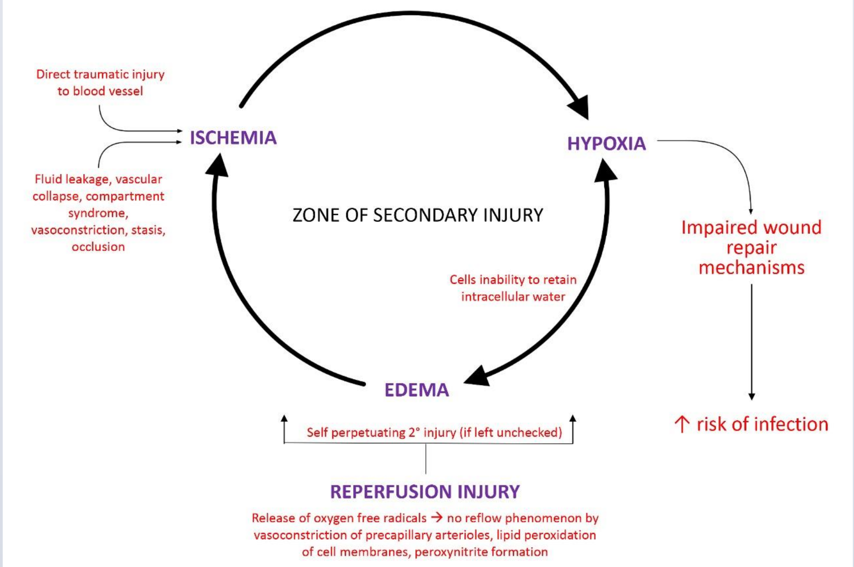

Figure 1. Zone of secondary injury as a result of a crushing injury and its effect on tissue.

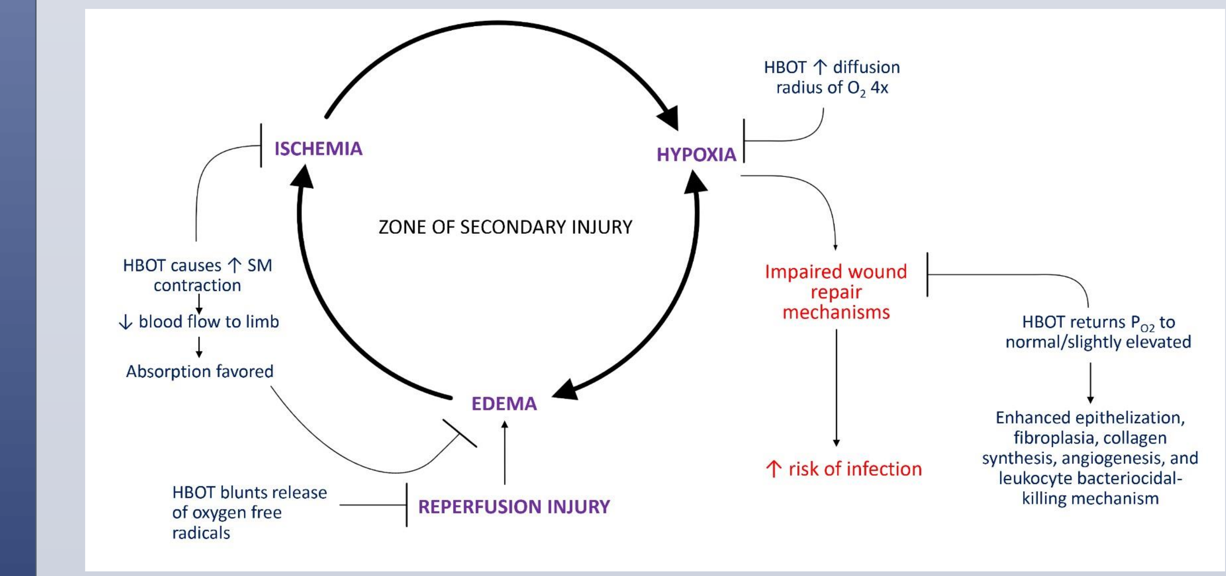

Figure 2. Effect of HBOT on the zone of secondary injury

Case Series

Our case series involves seven patients with varying injuries including closed and open fractures/dislocations, compartment syndrome, and simple/complex lacerations (see images 4-6). Patients were evaluated based on age, sex, smoking status, comorbidities, degree of injury, time to surgery, time to first HBOT, number of HBOT dives, time until healed, resulting amputation, and other complications (see Tables 1 and 2). Patient 7 underwent two hyperbaric oxygen dives and declined further treatment due to necessitating PE tubes and myringotomy.

Patient	Age/ Sex	Smoking status/Comorbidities	Mechanism/Injury
1	32 M	1 ppd x 8 years None	Forklift crushing injury, skin lacerations
2	23 M	THC occasionally None	Forklift crushing injury, multiple forefoot and midfoot fracture/dislocations
3	60 M	2 ppd x unknown years Sleep apnea	Steel pipe crushing injury, open hallux fracture
4	5 F	Never None	Crush by 30lb weight, open toe fractures, compartment syndrome
5	51 M	0.1 ppd x 33 years None	Forklift crushing injury, open toe fractures, compartment syndrome
6	26 F	Never None	Motor vehicle accident, open type II/III bimalleolar fracture
7	39 M	0.5 ppd x 12 years DMII, Idiopathic rhabdomyolysis	Pallet jack crushing injury, compartment syndrome

Table 1. Demographics and mechanism of injury for each patient. Packs per day = ppd

Patient	Time to OR/ Procedure	Time to HBOT/ # of Dives	Time to Healed	Complications
1	36D: hallux amputation	26H 15M 40 dives	60D FDS 96D FDOI	Dry gangrene, numbness
2	2H 24M: CRPP, I&D 63D: STSG	23H 31M 45 dives	37D FDS 100D FDOI	SSTI
3	1H 10M: I&D	22H 30M 20 dives	141D	None
4	1D 2H 40M: Fasciotomy	22H 30M 20 dives	106D FDOI	Required PE tubes/ myringotomy
5	3H 30M: I&D with wound vac application, fasciotomy 64D: Partial hallux amputation	22D 15 dives	56D FDS 120D FDOI	Flap necrosis
6	5H 11M: I&D and wound vac application 32D: STSJ	8D 4H 50M 3 dives	35D FDS 66D FDOI	None
7	7H 11M: Fasciotomy	1D 8H 26M 2 dives	24D	Required PE tubes/ myringotomy - declined

Table 2. Treatment details, outcomes, and complications. D = day. H = hour(s). M = minute(s). FDS = from date of surgery. FDOI = from date of original injury. CRPP = closed reduction percutaneous pinning. I&D = irrigation and debridement. STSG = split thickness skin graft.

The Frostbite Analysis Score (FAS) was calculated at initial examination by the treating surgeon (see Figures 3 and 4) to determine what the predicted amputation level would be without any treatment.

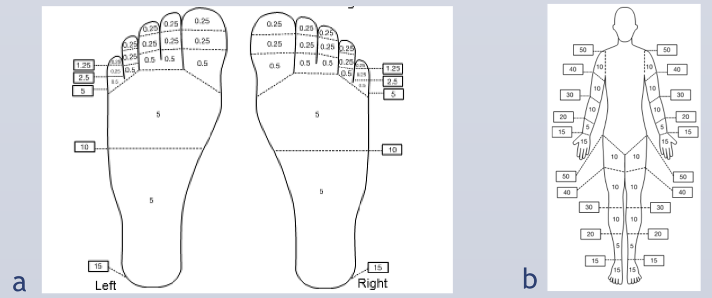

Figure 3a-b. Frostbite analysis score used to quantitate the potential amputation level patients might receive as a result of their injuries

Case Series Continued

Six of the seven patients underwent soft tissue fluorescence microangiography to determine the level of potential soft tissue damage. The Hyperbaric Oxygen physician then used these images to determine the FAS. These scores were then compared to the actual outcome of the patient (See Table 3 below). Images depicting select patients' initial injury, fluorescence microangiography images, and final outcomes can be seen in images 4-6.

Patient	Clinical Expertise FAS	Fluorescence Microangiography FAS	Final Outcome
1	1.00	1.00	Partial hallux amputation
2	15.00	0.00	STSG, no amputation
3	0.50	0.50	No amputation
4	3.00	3.00	Distal 4th and 5th toes autoamputated
5	1.00	0.50	Partial hallux amputation
6	15.00	0.00	STSG, no amputation
7	N/a	N/a	Healed

Table 3. FAS from the initial surgeon, hyperbaric physician, and final outcome of the patient

Figure 4a-d. (a, b) Patient 1's initial injury, (c) fluorescence microangiography image, and (d) final outcome

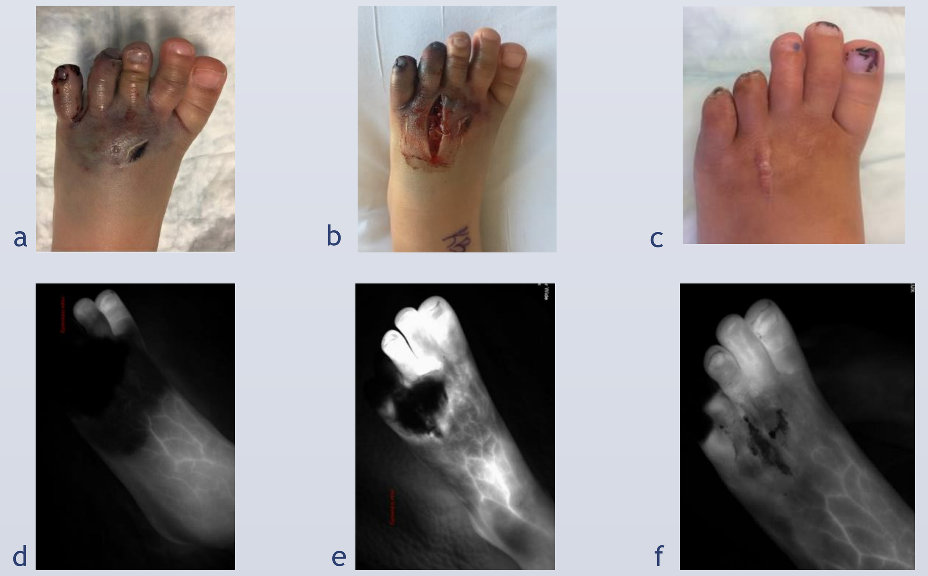

Figure 5a-f. Patient 4's initial injury (a), intermediate picture (b), and final outcome (c) with associated fluorescence microangiography images (d-f)

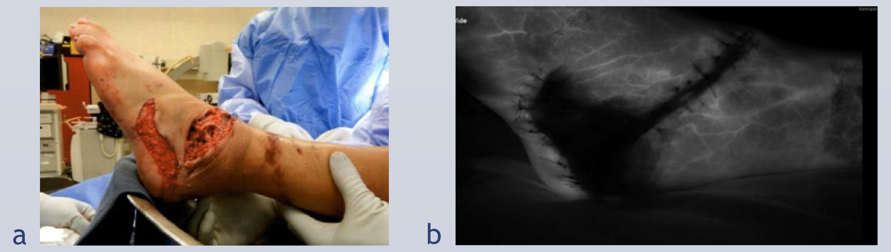

Figure 6a-b. Patient 6's initial injury (a) and associated fluorescence microangiography image (b)

Analysis and Discussion

Crushing related soft tissues injuries are difficult to treat due to the cyclic process called the zone of secondary injury (5, 9-10), whereby. tissues become edematous, hypoxic and often nonviable due to ischemia and reperfusion injuries (5). There is a limited amount of literature investigating the potential benefits of HBOT on crushing injuries.

In our study four of the seven patients healed their injuries without need for amputation. The remaining three patients had distal forefoot amputations that all healed. HBOT was an important adjunct in their treatment.

Bouachour et al performed the only double-blind randomized control study to date investigating crushing injuries and the use of HBOT. Patients suffering from crush injuries were randomly assigned to receive HBOT or placebo. Eighteen patients in the HBOT group received 100% O2 at 2.5 ata for 90-minute sessions for six days following the injury while eighteen patients in the placebo group received 21% O2 at 1.1 ata in order to feel an increase in pressure. They evaluated how many patients completely healed their injuries, the number of repeat surgeries, and the average time healing required. They found that the HBOT group had significantly more patients completely heal their injuries and required less repeat surgeries. There was no significant difference in the healing time between the two groups. They concluded that HBOT improves wound healing following crushing injuries and reduces the need for repeat surgeries (10). Stefanidou et al published a case report of a female patient who sustained an crushing injury with an associated open fracture to the right foot. Due to continued tissue ischemia, HBOT was initiated 72 hours after the injury to help demarcate the extent of tissue injury for amputation planning. However, after undergoing HBOT, amputation was no longer indicated, and she underwent surgical reconstruction with a vascularized cutaneous flap (11). Hong et al performed a retrospective review of 113 forklift-related crushing injuries of the lower extremity. They found that 40 of the patients required hospitalization and 35 required surgical intervention. Of the 113 patients, three required amputation. All amputations initially had open fractures. They reported 23 complications from wound infection, CRPS, flap complications, and equinus. None of their patients underwent HBOT (12).

Our study reports seven patients who sustained crushing injuries to the lower extremities. Five required emergent surgical intervention, three underwent repeat surgical debridement, and two eventually needed toe amputations. Six of the seven underwent HBOT. The average healing time was 65 days from their definitive surgery or 93 days from their original injury. Limitations to this study include the study size and its retrospective nature.

Analysis and Discussion (continued)

In conclusion, crushing injuries to the lower extremity can result in compartment syndrome, open fractures, and tissue necrosis (1, 3). Many of these injuries require emergent surgical intervention, repeat surgeries, and possible amputation. A self-perpetuating injury often occurs leading to increased nonviable tissue and possible need for amputation. Use of adjuvant HBOT can help improve tissue oxygenation, decrease oxygen free radicals and edema therefore decreasing the effect of secondary injury and possible need for future amputation.

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Financial Disclosures

None

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