Test file: A Clinical Study on the Application of Hyperbaric Oxygen Therapy in Hand Surgery Trauma

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Abstract

Background: Traumatic injuries to the hand, including crush injuries, avulsions, devascularizations, and complex fractures with soft tissue compromise, present significant surgical challenges due to compromised tissue perfusion, edema, and high risk of infection and necrosis. Hyperbaric Oxygen Therapy (HBOT), which involves breathing 100% oxygen at pressures greater than one atmosphere absolute (ATA), is an adjunctive treatment proposed to enhance wound healing in such complex scenarios by maximizing tissue oxygenation. Objective: This study aimed to evaluate the clinical efficacy and outcomes of adjunctive HBOT in the management of acute traumatic hand injuries requiring surgical intervention. Methods: A prospective, randomized controlled trial was conducted involving 80 patients with severe traumatic hand injuries (Gustilo-Anderson type IIIB/C open fractures, severe crush injuries with devitalized tissue, or replantation/revascularization cases). Patients were randomly assigned to the Standard Care Group (n=40), receiving surgical management (debridement, fixation, vascular repair, flap coverage as needed) and conventional post-operative care, or the HBOT Group (n=40), receiving standard surgical care plus an adjunctive HBOT protocol (2.4 ATA for 90 minutes, twice daily for 5 days, then once daily for a total of 20-30 sessions). Primary outcomes included wound healing rate, time to complete wound closure/graft take, flap survival rate, and infection rate. Secondary outcomes encompassed functional recovery (Total Active Motion - TAM, grip strength), analgesic requirement, and length of hospital stay. Results: The HBOT group demonstrated statistically superior outcomes. The incidence of major post-operative complications (flap/graft failure, deep infection, osteomyelitis) was significantly lower (15% vs. 37.5% in the control group, $p<0.05$). Time to complete wound closure or successful graft/flap take was reduced by an average of 4.2 days ($p<0.01$). Flap survival rates were 94% in the HBOT group compared to 82% in controls ($p<0.05$). Functionally, the HBOT group showed significantly greater TAM recovery at 3-month follow-up ($p<0.01$) and required fewer opioid analgesics in the first post-operative week ($p<0.05$). Conclusion: Adjunctive HBOT significantly improves wound healing, reduces complication rates, and enhances functional recovery in patients with severe traumatic hand injuries. It serves as a valuable adjuvant to meticulous surgical technique by modulating the ischemic-reperfusion injury, controlling edema, and augmenting neovascularization, thereby optimizing conditions for tissue survival and repair.

Keywords: Hyperbaric Oxygen Therapy; Hand Trauma; Crush Injury; Replantation; Flap Survival; Wound Healing; Ischemia-Reperfusion Injury; Adjunctive Therapy.

1. Introduction

The hand is a complex anatomical and functional unit, and its traumatic injuries can lead to devastating consequences for patients' quality of life and vocational capacity [1]. Severe injuries such as high-energy crush wounds, degloving injuries, traumatic amputations, and complex open fractures are characterized by extensive soft tissue damage, vascular compromise, and significant contamination [2]. The primary surgical goals are to debride devitalized tissue, restore skeletal stability, repair vital structures (tendons, nerves, vessels), and provide durable soft tissue coverage, often through local or free flaps [3]. However, the post-injury pathophysiology—marked by tissue hypoxia, severe edema, and an intense inflammatory response—creates a hostile microenvironment that can jeopardize surgical outcomes, leading to flap failure, infection, and nonunion [4].

Hyperbaric Oxygen Therapy (HBOT) is a therapeutic modality that has found application in conditions where tissue hypoxia is a limiting factor for healing [5]. By breathing 100% oxygen under increased atmospheric pressure (typically 2.0-2.5 ATA), the oxygen dissolved in the plasma is dramatically increased, overcoming the limitations of hemoglobin-bound oxygen delivery [6]. The resulting supraphysiological oxygen tension exerts multiple beneficial physiological effects: it enhances fibroblast proliferation and collagen synthesis, promotes angiogenesis, exhibits bacteriostatic effects against anaerobes, and reduces edema by inducing vasoconstriction without compromising oxygen delivery to hypoxic tissues [7, 8]. Importantly, HBOT modulates the ischemia-reperfusion injury cascade by downregulating neutrophil adherence and reducing lipid peroxidation, a critical factor in salvaging marginally perfused tissue after revascularization [9].

Despite its mechanistic rationale, the integration of HBOT into standardized protocols for hand trauma remains inconsistent, with evidence primarily drawn from case series and small cohort studies [10, 11]. This study was designed to provide higher-level evidence through a randomized controlled trial to systematically evaluate the clinical impact of adjunctive HBOT on hard endpoints such as tissue survival, infection control, and functional recovery in severe hand trauma.

2. Methods

2.1 Study Design and Participants

A single-center, prospective, randomized controlled trial was conducted over a 24-month period. Approval was obtained from the institutional review board. Eligible patients were adults (18-65 years) presenting within 12 hours of sustaining a severe traumatic hand injury, defined as: Gustilo-Anderson type IIIB or IIIC open fractures, major crush injuries with substantial devitalized tissue, or complete/partial amputations requiring microvascular replantation or revascularization. Exclusion criteria included: pre-existing chronic limb ischemia, severe chronic obstructive pulmonary disease (contraindication for HBOT), inability to provide informed consent, or isolated tendon/nerve injuries without significant soft tissue or vascular compromise.

2.2 Randomization and Groups

Eighty eligible patients were randomized using computer-generated sealed envelopes into two groups:

Standard Care Group (Control, n=40): Underwent immediate and definitive surgical management (thorough debridement, fracture fixation with plates/external fixator, vascular/nerve/tendon repair, and immediate or delayed flap coverage as indicated) followed by standard post-operative care (elevation, antibiotics, analgesia, conventional wound care).
HBOT Group (Intervention, n=40): Received identical surgical management plus a standardized adjunctive HBOT protocol.

2.3 Hyperbaric Oxygen Protocol

HBOT commenced within 24 hours post-operatively. The protocol consisted of treatments in a multiplace chamber at 2.4 ATA for 90 minutes of 100% oxygen breathing, interspersed with brief air breaks to mitigate oxygen toxicity risk. The initial phase involved two sessions per day for the first 5 days, followed by one session per day, for a total of 20-30 sessions based on clinical response.

2.4 Outcome Measures

Patients were assessed daily during hospitalization and at scheduled follow-ups (2 weeks, 6 weeks, 3 months, 6 months).

Primary Outcomes:

1. Wound Healing/Complication Rate: Time to complete epithelialization, successful split-thickness skin graft (STSG) take, or flap survival. Major complications recorded included flap/graft failure (>20% necrosis), deep surgical site infection, and osteomyelitis.
2. Infection Rate: Based on clinical signs and positive culture requiring intervention.

Secondary Outcomes:

1. Functional Recovery: Total Active Motion (TAM) of digits, measured with a goniometer; grip strength using a Jamar dynamometer.
2. Analgesic Use: Total morphine milligram equivalents (MME) consumed in the first 7 post-operative days.
3. Hospital Length of Stay (LOS).

2.5 Statistical Analysis

Data analysis was performed using SPSS 25.0. Continuous variables were compared using independent t-tests or Mann-Whitney U tests. Categorical variables were analyzed using Chi-square or Fisher's exact test. A p-value of <0.05 was considered statistically significant.

3. Results

3.1 Baseline Characteristics

Both groups were well-matched for age, gender, injury mechanism (predominantly industrial crush and saw injuries), injury type distribution, and time from injury to surgery.

3.2 Primary Outcomes

The HBOT group exhibited significantly better tissue viability outcomes. The composite rate of major complications was 15% (6/40) in the HBOT group versus 37.5% (15/40) in the control group ($p=0.022$). Specifically, complete flap survival was observed in 94% (17/18) of flap cases in the HBOT group versus 82% (14/17) in controls ($p<0.05$). The mean time to definitive wound

closure (either primary, via graft, or stable flap coverage) was 10.3 ± 2.8 days in the HBOT group compared to 14.5 ± 3.6 days in the control group ($p<0.01$). The incidence of deep infections requiring re-operation was also lower in the HBOT group (2 vs. 7 cases, $p<0.05$).

3.3 Secondary Outcomes

Functional recovery was accelerated in the HBOT group. At the 3-month follow-up, the mean TAM recovery percentage (compared to the contralateral uninjured hand) was 68% ± 12% in the HBOT group versus 55% ± 15% in the control group ($p<0.01$). Grip strength recovery followed a similar trend. Patients in the HBOT group required significantly less opioid analgesia in the first post-operative week (mean MME: 85 ± 30 vs. 112 ± 40, $p<0.05$). The mean hospital LOS showed a non-significant trend towards reduction in the HBOT group (14.2 vs. 16.5 days, $p=0.08$).

4. Discussion

This randomized controlled trial provides compelling evidence that adjunctive HBOT confers significant clinical benefits in the management of severe hand trauma. The observed reduction in major complications, particularly flap failure and deep infection, directly addresses critical challenges in hand surgery [12]. These findings are consistent with the established physiological principles of HBOT, which creates an optimal environment for healing in compromised tissues [13].

The primary mechanism by which HBOT likely contributed to improved flap survival is through the mitigation of ischemia-reperfusion (IR) injury. Following revascularization or in crush injuries, the reintroduction of oxygen can paradoxically generate a surge of reactive oxygen species (ROS), leading to endothelial damage and increased capillary permeability (no-reflow phenomenon) [9]. HBOT preconditions tissues and, when administered post-operatively, downregulates neutrophil β2-integrin-mediated adherence, thereby reducing inflammatory damage and preserving microcirculatory flow [14]. Furthermore, the enhanced oxygen diffusion gradient directly alleviates tissue hypoxia in the perfusion watershed zones of flaps and grafts, supporting cellular metabolism until neovascularization is established [15].

The accelerated wound healing and lower infection rates can be attributed to HBOT's role in bolstering host defense and promoting repair. High tissue oxygen tension is a critical co-factor for neutrophil oxidative killing of bacteria and enhances the efficacy of certain antibiotics [16]. Simultaneously, the sustained hyperoxia acts as a potent stimulus for fibroblast proliferation and collagen deposition, which is essential for graft incorporation and wound strength [17]. The reduction in post-operative analgesic requirements, a notable secondary finding, may be linked to HBOT's anti-inflammatory and edema-reducing effects, which decrease pressure on pain-sensitive structures [18].

From a health economics perspective, while HBOT adds direct treatment costs, its potential to reduce the need for complex revision surgeries (e.g., for flap failure or infection), shorten the time to wound closure, and improve long-term functional outcomes may lead to an overall reduction in long-term disability and healthcare utilization [19]. The trend towards shorter hospital stay, though

not statistically significant in this sample, supports this notion.

5. Limitations and Future Directions

This study has limitations, including its single-center design and the inherent difficulty in blinding caregivers to the treatment allocation. The HBOT protocol was intensive, and its cost-effectiveness requires formal analysis. Future research should focus on identifying specific injury subtypes that derive maximum benefit from HBOT, optimizing treatment timing and pressure/duration protocols, and investigating biomarkers (e.g., tissue oxygen measurements) to personalize therapy [20].

6. Conclusion

Adjunctive Hyperbaric Oxygen Therapy is a potent physiological intervention that significantly improves outcomes in severe traumatic hand injuries. By directly targeting the pathological hallmarks of trauma—hypoxia, edema, and reperfusion injury—HBOT enhances tissue viability, reduces infection, and facilitates faster functional recovery. Its integration into a multidisciplinary treatment protocol, alongside expert surgical management, should be considered for patients with high-risk hand trauma to maximize limb salvage and functional restoration.

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