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Original Article

A novel intervention for wound bed preparation in severe extremity trauma: Highly concentrated carbon dioxide bathing

Masakatsu Hihara*, Tomoki Himejima, Kota Takeji, Maako Fujita, Michika Fukui, Yuki Matsuoka, Toshihito Mitsui, Atsuyuki Kuro, Natsuko Kakudo

Department of Plastic and Reconstructive Surgery, Kansai Medical University, Osaka, Japan

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ABSTRACT

Introduction: In severe extremity trauma involving large tissue defects, early closure (e.g., free-flap surgery) of the defects is an essential step for good functional reconstruction; however, in some cases, early closure may be difficult. Highly concentrated carbon dioxide bathing, used to improve blood flow in ischemic limbs and skin ulcers, can also be applied in wound bed preparation for severe limb trauma.

Patients and Methods: The three cases in this study required an average of 13 weeks of highly concentrated carbonated bathing, which led to significantly better wound bed preparation, even in the exposed bone and tendon regions.

Results: We successfully achieved good functional limb reconstruction in patients with deep burns and severe open fractures by reducing wound infection and facilitating good wound bed preparation.

Conclusions: Highly concentrated carbon dioxide bathing was sufficient to prevent frequent wound infections, even in severe extremity trauma involving large soft-tissue defects such as deep crush burns and Gustilo Anderson classification ≥3b open fractures of the extremities. To our knowledge, such interventions have not been

* Correspondence author at: Masakatsu Hihara, M.D. PhD., Department of Plastic and Reconstructive Surgery, Kansai Medical University, 2-5-1, Shin-machi, Hirakata, Osaka 573-1010, Japan, TEL: +81 72-804-0101; FAX: +81 72-804-2031.
E-mail address: hiharams@hirakata.kmu.ac.jp (M. Hihara).

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reported in the past and are valuable as new procedures for wound bed preparation in severe extremity trauma from both cost and wound infection control perspectives.

Introduction

Highly concentrated carbon dioxide bathing has been clinically applied to ischemic limbs and skin ulcers[1,2]; however, there have been no reports on using such treatments for severe limb trauma involving large tissue defects. We here report the use of highly concentrated carbon dioxide bathing for severe limb trauma to verify the effectiveness of wound bed preparation.

Patients and Methods

Case 1[3]

A man in his 40s sustained a heat press injury when his right hand was caught in a roller heated to 180°C for crimping fabric products for approximately 30 s. The palmar skin was severely indurated owing to deep burn damage, and the active motion of the fingers was severely limited (Figure 1). From the day after the injury, a 15-min hand bath in highly concentrated carbon dioxide bathing at 37°C (AS Care®; Asahi Kasei Medical Co., Ltd., Tokyo, Japan) was performed daily to gradually eliminate necrotic tissue and continue finger rehabilitation (Figure 2). Four weeks after the injury, palmar necrotic tissue was completely eliminated, and sufficient granulation tissue had grown; therefore, the patient underwent skin grafting using plantar glabrous skin grafts (Figure 3). A year after the injury, the color, texture, and skin extensibility of the grafted skin were acceptable, and the intrinsic muscles

Figure 1. The palmar skin was severely indurated due to deep burn damage, and the active motion of the fingers was severely limited.

Figure 2. A 15-min hand bath in highly concentrated carbon dioxide bathing at 37°C (AS Care®; Asahi Kasei Medical Co., Ltd., Tokyo, Japan) was performed daily to gradually eliminate necrotic tissue and continue finger rehabilitation

Figure 3. Four weeks after the injury, the patient underwent skin grafting using plantar glabrous skin grafts.

and mechanisms of the fingers functioned normally without any residual damage. The treatment was completed with full restoration of hand function (Figure 4).[3]

Case 2

A man in his 20s sustained an open fracture of the left calcaneal region with degloving skin while riding a motorcycle in a traffic accident (Figure 5). After open reduction and internal fixation, necrosis of the calcaneal skin progressed, exposing most of the calcaneus and the fixation pin. Four weeks after injury, a 15-min foot bath in highly concentrated carbon dioxide bathing (AS Care®) at 37°C was performed daily to gradually eliminate necrotic tissue (Figure 6). Twenty-two weeks after the injury, necrotic tissue removal was completed, and sufficient granulation tissue had formed around the calcaneal base; therefore, a distally based sural flap was used to reconstruct the heel area (Figure 7). Ten months after the injury, the patient walked with normal shoes, although sensory disturbance in the sole of the foot persisted (Figure 8).

Figure 4. One year after the injury, the intrinsic muscles and mechanisms of the fingers functioned normally without any residual damage.

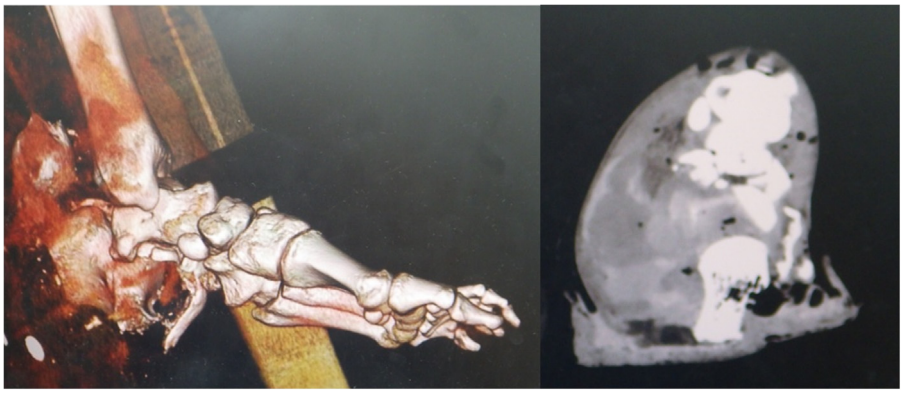

Figure 5. The patient sustained an open fracture of the left calcaneal region with degloving skin while riding a motorcycle in a traffic accident.

Case 3

A man in his 30s sustained an upper extremity open fracture while riding a motorcycle sandwiched between a truck and a roadside wall. The patient had bone defects of the lateral epiphysis of the humerus and neck of the radius and an extensive soft-tissue defect on the outer side of the elbow, approximately 40 cm in diameter (Figure 9). First, large tissue defects were packed using a right latissimus dorsi muscle flap and right pectoral skin flap, and external fixation of the right upper extremity was performed. Two weeks after injury, wound irrigation was continued with a highly concentrated carbonated spring bathing (AS Care®) at 37°C for 15 min once daily (Figure 10). Twelve weeks after the injury, sufficient granulation tissue developed around the elbow; therefore, full-thickness skin grafts were performed on the skin defect at the elbow (Figure 11). Six months after the injury, the patient still had a limited range of motion of the right elbow joint; however, hand function was fully preserved (Figure 12).

Results

Highly concentrated carbon dioxide bathing was sufficient to prevent frequent wound infections, even in severe extremity trauma involving large soft-tissue defects such as deep crush burns and

Figure 6. Four weeks after injury, a 15-min foot bath in highly concentrated carbon dioxide bathing (AS Care®) at 37°C was performed daily to gradually eliminate necrotic tissue.

Figure 7. Twenty-two weeks after injury, the removal of necrotic tissue was completed, and sufficient granulation tissue had formed around the calcaneal base; therefore, a distally based sural flap was used to reconstruct the heel area.

Gustilo Anderson classification ≥3b open fractures of the extremities. The three cases in this study required an average of 13 weeks of highly concentrated carbonated bathing, which led to significantly better wound bed preparation, even in the exposed bone and tendon regions. A good joint range of motion and shape was also obtained, exceeding the goals set after surgical interventions such as skin grafts and flaps.

Figure 8. Ten months after the injury, the patient walked with normal shoes, although sensory disturbance in the sole of the foot remains.

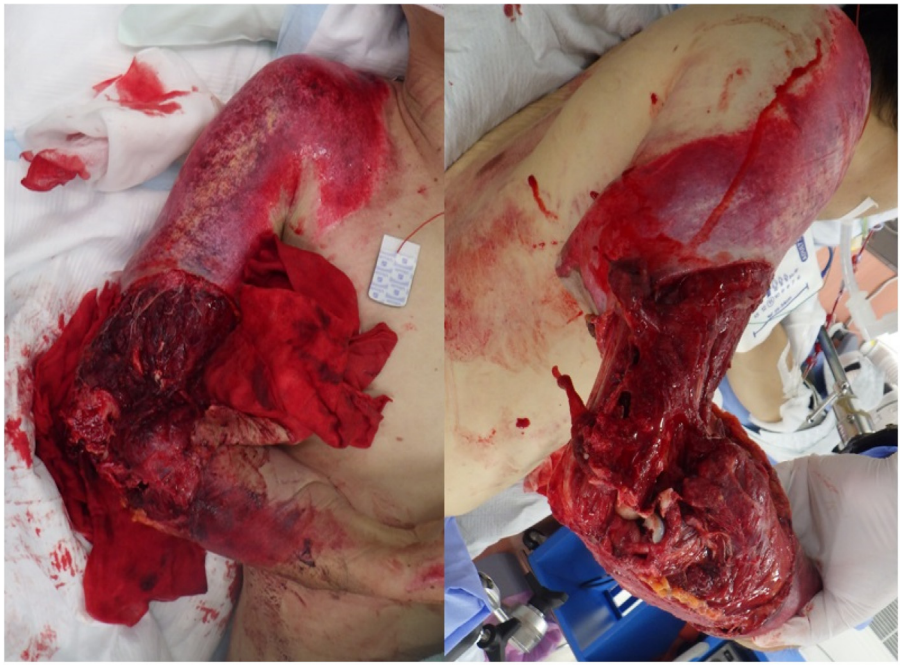

Figure 9. The patient had bone defects of the lateral epiphysis of the humerus and neck of the radius and an extensive soft-tissue defect on the outer side of the elbow, approximately 40 cm in diameter.

Discussion

In severe extremity trauma involving large tissue loss, early wound closure of the tissue defect is essential for good functional reconstruction.[4,5] However, early and reliable debridement is often difficult because of severe wound contamination and insufficient blood flow to the wound. There are also cases in which various patient-oriented factors (e.g., old age, multiple traumas, peripheral vascular disease, diabetes mellitus, etc.) make it difficult to perform early skin flap surgery. There is always a risk of prolonged infection due to inadequate debridement and skin flap necrosis due to the use

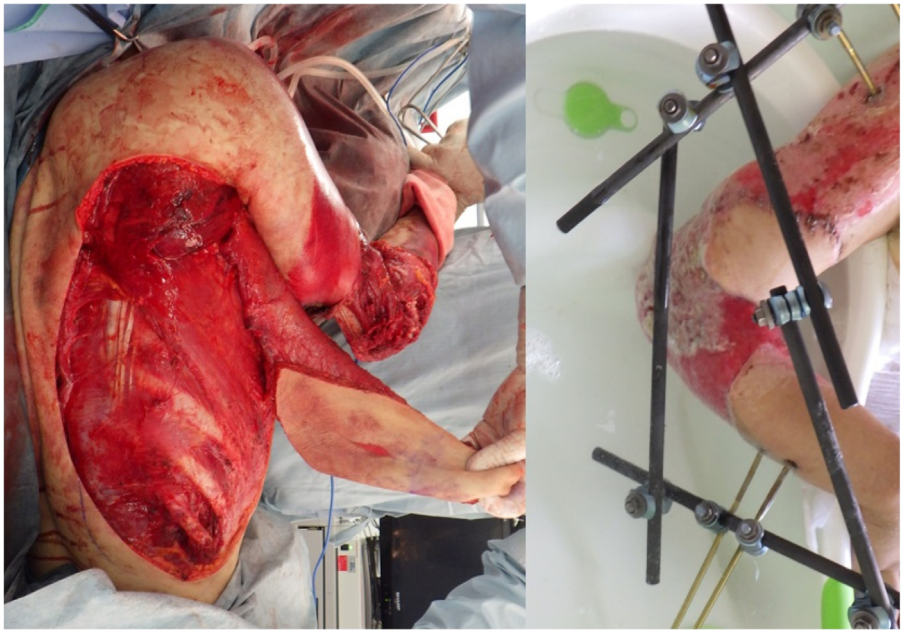

Figure 10. Large tissue defects were packed using a right latissimus dorsi muscle flap and a right pectoral skin flap, and external fixation of the right upper extremity was performed. Two weeks after injury, wound irrigation was continued with a highly concentrated carbonated spring bathing (AS Care®) at 37°C for 15 min once daily.

Figure 11. Twelve weeks after the injury, sufficient granulation tissue had developed around the elbow, and full-thickness skin grafts were performed on the skin defect at the elbow.

of damaged recipient vessels in haste to perform immediate surgery. It is also widely known that extremity reconstruction, especially after trauma, has a high-complication rate, including a high flap necrosis rate. Chronic osteomyelitis and cutaneous fistulas that complicate severe extremity trauma treatment are often caused by inadequate debridement, and the frequency of such complications is approximately 30%.[6,7] Therefore, facilitated wound granulation therapy using various techniques (e.g.,

Figure 12. Six months after the injury, the patient still had a limited range of motion of the right elbow joint, but the hand function had been fully preserved.

acellular dermal matrices or negative-pressure wound therapy [NPWT]) is commonly applied in combination with staged debridement for wound bed preparation.

There have been a few reports on the efficacy of applying an artificial dermis to improve wound granulation[8]; however, there have been more negative reviews recently, especially in cases with large tissue defects, because of the potential to cause wound infection.[9,10] Some randomized controlled trials using NPWT have reported that the risk of wound infection was reduced by one-fifth and that wounds could be closed within an average of 3.7 days,[11] whereas others have reported a decreased wound area and reduced positive local infection rates.[12] Conversely, there have been reports of an increase in deep infection when NPWT is used for more than 7 days,[13] which is insufficient evidence to support the efficacy of NPWT for contaminated wounds,[14] and even statements against its use in patients with severe open fractures of the lower extremity, with no significant difference in surgical site infection.[15] Various expensive skin substitutes and wound dressings have also been developed; however, their effectiveness is currently limited.[16] NPWT with instillation and dwelling, which has the additional function of continuous wound cleansing, is gradually becoming more available.[17] This also has significant healthcare economic disadvantages. The reality is that treatments that do not consider costs and benefits are widespread, including continuing NPWT with inadequate debridement and using expensive extracellular matrix (ECM) products.[18] Therefore, researchers should return to the principles of wound care; in the case of contaminated and crushed wounds involving insufficient blood flow, daily “diligent wound cleansing” is probably still the most important task.

The fact that the procedure can be performed at home means that it does not require the intervention of a medical professional and significantly reduces the medical financial burden. The three patients required an average of 13 weeks of bathing, but the total cost averaged \$91 ($=13 \times 7 \times 1$) per case, leading to inexpensive and extremely good wound bed preparation, even in sites with exposed bone and tendon. NPWT in Japan can cost approximately \$2000 per month in medical procedure costs alone, even for wounds <100 cm^2 in size. Wound dressings and ECM products have also skyrocketed in price in recent years, with some materials costing as much as \$300 per cm^2.[19,20]

The main effects of highly concentrated carbonated bathing have been reported previously, including improved skin and muscle blood flow, decreased blood pressure, and amelioration of bradycar-

dia.[21] The clinical applications of highly concentrated carbon dioxide bathing for ischemic extremities, skin ulcers, and osteomyelitis have already been reported.[2,22,23] The biochemical mechanism involves the conversion of transdermally absorbed carbon dioxide to bicarbonate ions, which act directly on endothelial cells to increase nitric oxide (NO) production through endothelial NO synthase (eNOS) phosphorylation, a process considered to improve blood flow.[24] The optimal conditions for improving skin blood flow were as follows: carbon dioxide gas concentration, 1000–1300 ppm; water temperature, 37°C; bathing time, 15 min; and application interval, once daily.[1] This regimen is also acceptable for facilitating wound granulation during severe extremity trauma treatments. The disadvantage of this method is the prolonged treatment period; however, it has the great advantage of avoiding the inevitable risk of free-flap surgery, which is required even in the infectious stage, and downgrading the reconstructive ladder seems possible.[25,26]

Highly concentrated carbonated bathing tablets are commercially available in Japan at a low cost of approximately US $1 per day. From a medical economic point of view, this method should be added to the list of wound-healing procedures in the future.[2] However, the authors do not agree with blindly applying this method to patients with severe traumatic injuries for a long period, as it is essential for trauma specialists to set treatment goals according to the type of injury. Early and definitive debridement and wound closure with a free skin flap were performed in patients with potentially functionally detrimental scarring. Although careful attention must be paid when delivering prolonged treatment to specific joints to ensure safe and reliable reconstruction, this method can be advantageous for surgical downgrading and securing wound closure in select cases.

Conclusion

Highly concentrated carbon dioxide bathing is useful not only for treating ischemic limbs and skin ulcers but also as a novel method of wound bed preparation in severe extremity trauma from both cost and wound infection control perspectives.

Declaration of Competing Interests

The authors declare no conflicts of interest in association with the present study.

Limitations

The study was limited by its small sample size; all results were obtained from a single plastic surgeon. More cases and further studies are needed to confirm the statistical significance.

Funding

None declared.

Ethical approval

Not required.

Informed consent and patient details

Written informed consent was obtained from the patient for the publication of this case report and accompanying images.

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