Characteristics and mechanisms of extremity injuries caused by mine blasts in shoals

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ABSTRACT

BACKGROUND: The characteristics of explosion in water are different from those in air and vary in different water depths. It is important to investigate the characteristics and mechanisms of extremity injuries caused by mine blasts in shoals.

METHODS: A total of ninety New Zealand rabbits were randomly divided into four groups put in different depths of water (land group, midpoint of the thigh in the shoal 1 group, the xiphoid process in the shoal 2 group, and control group). Electric detonators simulating mines were placed under the rabbits' right hindpaw. After detonation, the animals were subjected to morphological examination.

RESULTS: The lower third of the calf was almost completely destroyed by the mine blast on land, and only the rabbits' feet and ankles were destroyed in shoals. The skeleton, artery and sciatic nerve were injured more seriously in shoals than those on land.

CONCLUSION: Mine blasts in shoals caused less disruption of the soft tissue than those on land. However, the skeleton was more seriously damaged in shoals since the pressure wave was transmitted with greater intensity and had a stronger shattering effect on the skeleton. Furthermore, the characteristics of extremity injuries varied according to water depths.

Keywords: Biomechanics; explosion; extremity injury; morphology; shoal.

INTRODUCTION

Amphibious warfare is one of the most important naval combat tactics. A large amount of mines placed in shoals may cause mass casualties during beach landing stage.[1,2] The wave of an underwater blast with high-pressure encompasses a larger area than that in air because water is 800 times denser than air and is non-compressible.[3] Blast wave in water propagates rapidly, with a slow rate of dissipation, and has greater potential for injury than in air.[4] Additionally, as the detonation products dissolve into water after mine blasts in shoals, the characteristics of injuries may be different from those observed on land. Finally, water depth is an important parameter affecting the efficiency of the wave generation procession,[5] and thus the characteristics of blast wave and the movement of combustion gas may vary according to the water depth.

The aim of the present study was to investigate the characteristics and mechanisms of extremity injuries after explosion in shoals.

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MATERIALS AND METHODS

Ethical Approval of the Study Protocol

This study was approved by the Science and Technological Committee and the Animal Use Care Committee of the Third Military Medical University. All animal studies were performed in accordance with the guide for the care and use of laboratory animals of the Third Military University (Chongqing, China).

Groups and Animal Preparation

A total of ninety New Zealand rabbits (2.10~2.40 kg) were randomly allocated into three experimental groups: (1) 6 animals in the control group for pathologic examination; (2) 48 animals (16 animals in the land, shoal1 and shoal2 group, respectively) were used to study the characteristics of extremity injuries and high-speed photography; (3) 36 animals (12 animals in the land, shoal1 and shoal2 group, respectively) were used to examine the biomechanics of injuries. All animals were anesthetized with intravenous injection of pentobarbital (30mg/kg) through the ear marginal vein.

Animal Model

This experiment was performed in a water tank (length 120 cm, width 120 cm, height 60 cm), with soil covered on the bottom. For the land group, there was no water in the tank. For the shoal1 group, the water height reached the midpoint of rabbits' thigh. For the shoal2 group, the water height reached xiphoid process. The anesthetized animals were secured in a special designed metal holder whose height could be adjusted to make sure the double feet reach the ground. The fore-and-aft clearance of the bilateral hindpaws was 11 cm, and the space between the left and right hindpaws was 9 cm. The RDX paper electric detonators (600 mg, 845Factory, Chongqing, China) were used to simulate mine. The detonators were placed under the rabbits' right hindpaws and ignited electronically. All wounds of the rabbits were sutured and bandaged immediately after detonation. Water temperature was maintained at 20±2°C, and room temperature at 22±2°C. Plots of the blast event duration were obtained by high-speed photography (Red Lake HG-LE, USA) through a window of the tank.

Imaging Examination

All animals underwent CT scanning at 5 h after detonation, and their injuries were diagnosed and analyzed by the bone window, soft-tissue window and reconstruction image. Digital subtraction angiography (DSA) was performed after CT scanning as following procedures: Using sterile techniques, the left femoral artery was exposed, dissected and cannulated with a 4F sheath (1.35 mm, Cordis Corporation, USA). A bolus of heparin (100 U/kg) was delivered through the sheath. A micro-guide wire (0.89 mm, Terumo Corporation, Japan) was propelled into the abdominal aortic branches through the sheath under fluoroscopy (General Electric Company, USA). Next, the 4F catheter (135°, 1.35 mm, Cordis Corporation, USA) was inserted to the right common iliac artery and the femoral artery through the sheath under fluoroscopic guidance. DSA was performed by an injection of 8 ml iodinated contrast material (Ultravist, Bayer Vital GmbH, Germany).

Pathologic Examination

Animals were killed by an overdose of pentobarbital after 6-hours of observation. The sciatic nerve was harvested from the inferior margin of piriformis to the bifurcation of the tibial nerve and common peroneal nerve. The sciatic nerve was embedded in paraffin and sectioned at 5 μm thickness. The deparaffinized sections were stained routinely with haematoxyline and eosin (Chemical Reagent Factory, Shanghai, China) and examined under a light microscope (Ixz50, Olympus, Japan). The sciatic nerve was assessed in a blind manner. At the same time sciatic nerve injury was scored according to the categories in Sunderland's protocol.[6] The scores of three random areas in each section per animal were recorded for averaging. The soleus, gastrocnemius, and tibialis anterior muscle were also examined.

Biomechanical Recording System

Three pressure transducers (Decheng, Xi'an, China) were used for biomechanical test. One was located at the right calf muscle, 8 cm from the detonator, the other one was located at the left calf muscle, 20 cm from the detonator, and the last one was located at the right thigh muscle, 16 cm from the detonator. Signals were acquired with a TST6150 (Chengdutest, Chengdu, China) and analyzed with DAP6.01. Sampling rate of the data acquisition system was 200 kHz. The signal frequency spectrums were analyzed by the fast fourier transform linear spectrum. An infinite impulse response filter was used to filter the signal with the cut-off frequencies at 100 kHz.

Statistical Analysis

All data were expressed as the mean ± standard error or percentage. Chi-squared test was performed to handle the categorical data. Quantitative data were compared by one-way analysis of variance. The sciatic nerve histologic injury score was expressed as box-and-whisker plot and then subjected to analysis of variance by the Kruskal-Wallis nonparametric test. The means were expressed within 95% confidence interval, and alpha value was set at 0.05.

RESULTS

Anatomic Characteristics of the Injury

The lower third of the calf was almost completely destroyed in the land group, with the soft tissue often stripped off the bone until exposure of the fascial planes and tibia (Fig. 1a). In the shoal groups (Fig. 1b), only the foot and ankle were destroyed, without the exposure of tibia. After skin incision, thigh muscle contusion was found at the water-air interface in the shoal1 group (Fig. 1c). Bilateral tibia fractures and right femur fracture occurred in the shoal2 group (Fig. 1d).

Pathologic Manifestation

In the control group (Fig. 2a), the nerve fibers were arranged regularly, with the axon's layout in compact and orderly pattern. After the explosion on land, the axons exhibited slight degeneration. The perineurium became loose, so the nerve fiber compartment was broadened (Fig. 2b). There were nerve fiber degeneration, nerve fiber compartment enlargement and breakage, blood vessel expansion and congestion in

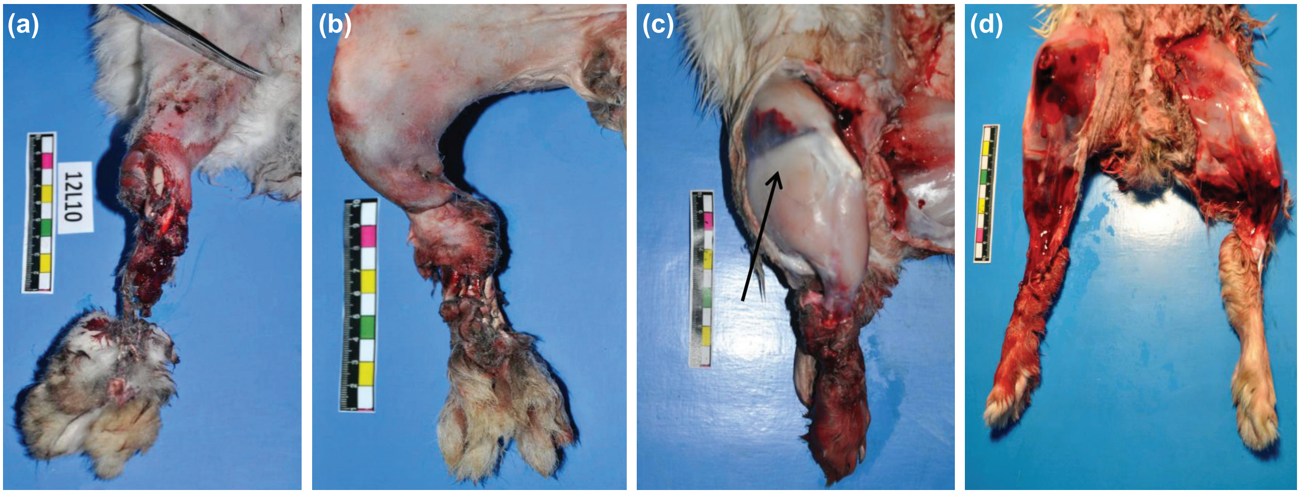
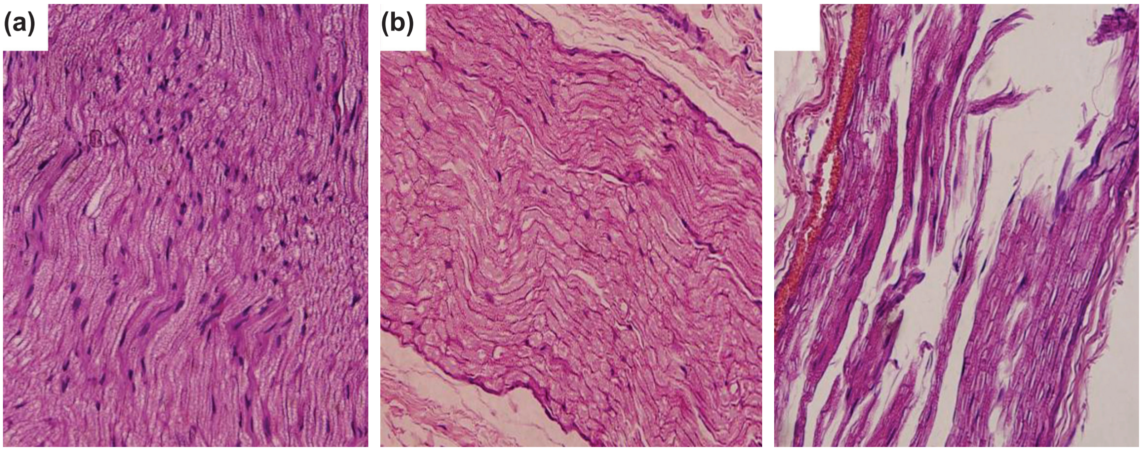


Figure 1. Anatomic characteristics of the limbs after simulated mine blasts in the three groups. Wound appearance in the land group **(a)**. Wound appearance in the shoal1 group and the shoal2 group **(b)**. Muscle hematoma at the water-air interface of the thigh in the shoal1 group **(c)**. Bilateral tibia fractures and right femoral fracture in the shoal2 group **(d)**.

the shoal1 group (Fig. 2c). It was observed that there were nerve fiber degeneration, breakage and disintegration in the shoal2 group (Fig. 2d). These changes are expressed in the box-and-whisker plot of the score data (Fig. 2e).

Imaging Outcomes

CT revealed bone defects of the distal tibia in the land group, but no femoral and contralateral limb fractures (Fig. 3a). However, the closed tibial fracture of thirteen animals and closed femoral fracture of eleven animals were observed in the shoal1 group (Fig. 3b), which significantly differed from the land group (p<0.05). The closed tibia fracture of fourteen animals and the closed femoral fracture of seven animals were observed in the shoal2 group (Fig. 3c), which significantly dif-



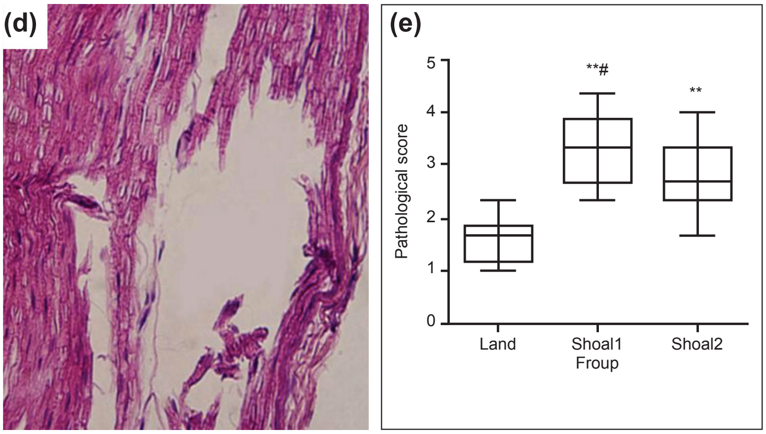


Figure 2. Photomicrographs of the sciatic nerve (H&E, ×400). Normal sciatic nerve histology in the normal control **(a)**. The morphological structure of the sciatic nerve changed in the land group **(b)**, shoal1 group **(c)** and shoal2 group **(d)**. The pathological scoring data of the sciatic nerve injuries are presented in a box-and-whisker plot (the boxes are constructed with 25% and 75% confidence intervals, with median and maximum or minimum individual values). **: p≤0.01 versus the land group, #: p≤0.05 versus the shoal 2 group **(e)**.

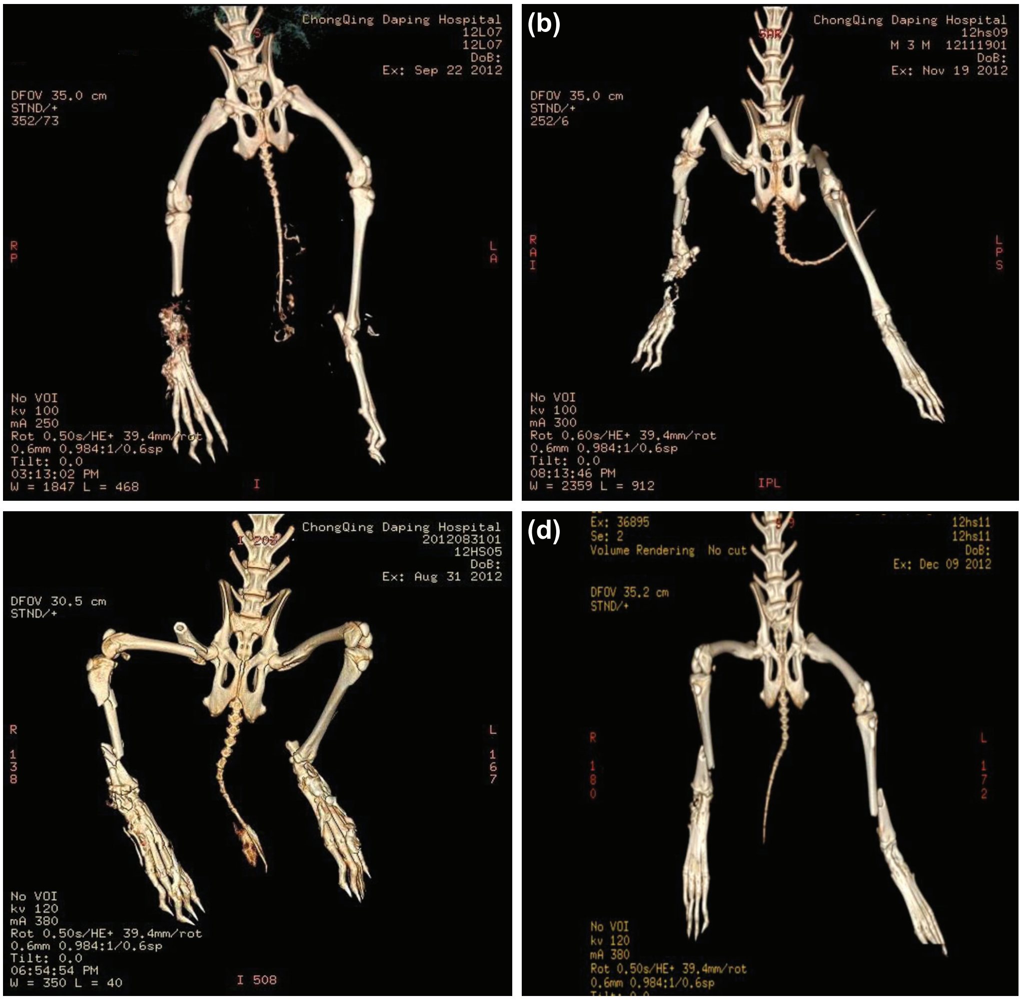


Figure 3. Images of the CT reconstruction after detonation. Bone defect of the distal tibia in the land group **(a)**. Comminuted tibial fractures and a femoral fracture of the right hindlimb in the shoal1 group **(b)**. Tibial fracture combined with an ipsilateral femoral fracture in the shoal2 group **(c)**. Bilateral tibial fractures in the shoal2 group **(d)**.

fered from the land group ($p<0.05$), but presented no significant differences compared with the shoal1 group. Additionally, contralateral tibial fractures of five animals were found in the shoal2 group (Fig. 3d). There was a significant difference ($p<0.05$) compared with zero occurrence in the shoal1 group.

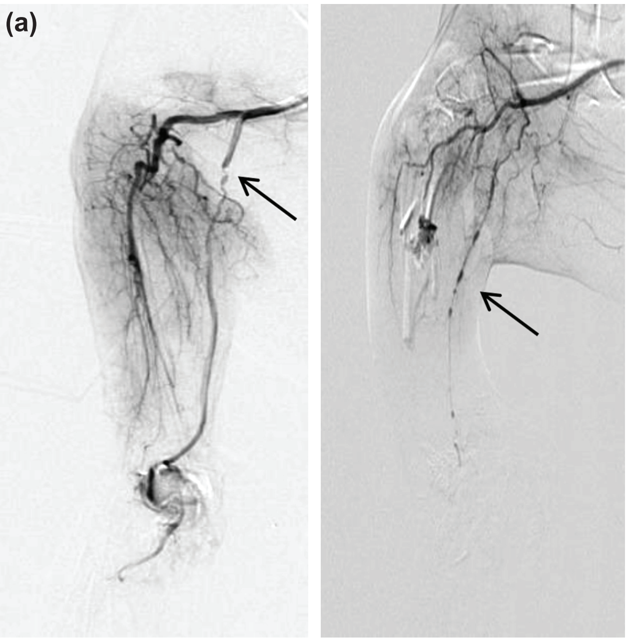
The DSA revealed vasospasm of the profunda femoris artery in the land group (Fig. 4a), but no rupture of the artery. In contrast, seven animals had anterior tibial artery ruptures and eight animals had posterior tibial artery ruptures in the shoal1 group (Fig. 4b), which were significantly different from the land group ($p<0.05$). In the shoal2 group, nine animals had posterior tibial artery ruptures, which were significantly different from the land group ($p<0.05$), but there was no statistical significance compared with the shoal1 group.

High-Speed Photographic Sequence

In the shoal1 group (Fig. 5a), the combustion gas ejected directly into the air without forming a bubble. The mine blast sprayed a lot of water column at 2 ms after detonation (Fig. 5b). In the shoal2 group (Fig. 5c), the explosive product and soil splashed around at 2 ms after detonation (Fig. 5d). The energy produced in water dissipated rapidly. A spherical bubble formed at 3 ms after detonation rose rapidly from the bottom (Fig. 5e) and emerged from the water after 57 ms. In the land group, the explosive flame hit the rabbits at 1 ms after detonation, and the gas jet flow and soil splashed at approximately 2 ms after detonation.

Biomechanical Records

Peak overpressure of the land group was much lower than those of the shoal groups at three different parts of extremity after detonation (Table 1), which meant that the destructive power of mine blasts did not reach these parts in the land group while remained considerably strong in the shoal groups. It was also noticed that the peak overpressure at three parts of the shoal2 group was significantly higher than that of the shoal1 group.



DSA images of right hindlimb after detonation. A profunda femoris artery spasm (arrow) and no ruptured arteries in the land group . Femoris artery plexus in the shoal groups , ruptured posterior tibial artery and profunda femoris artery resembling a “string of beads” (arrow).

DISCUSSION

High-energy mine blast injuries cause not only physical problems, but also psychological and social sequelae. Therefore, it is significant to understand the characteristics and mechanisms of extremity injuries caused by mine blasts in shoals.

In the present study, there were some differences between the land group and the shoal groups after the simulated mine blast in the characteristics of extremity injuries as follows:

Table 1. Comparison of peak pressure in three groups at different parts of extremity after detonation (Mean±SE, n=12)

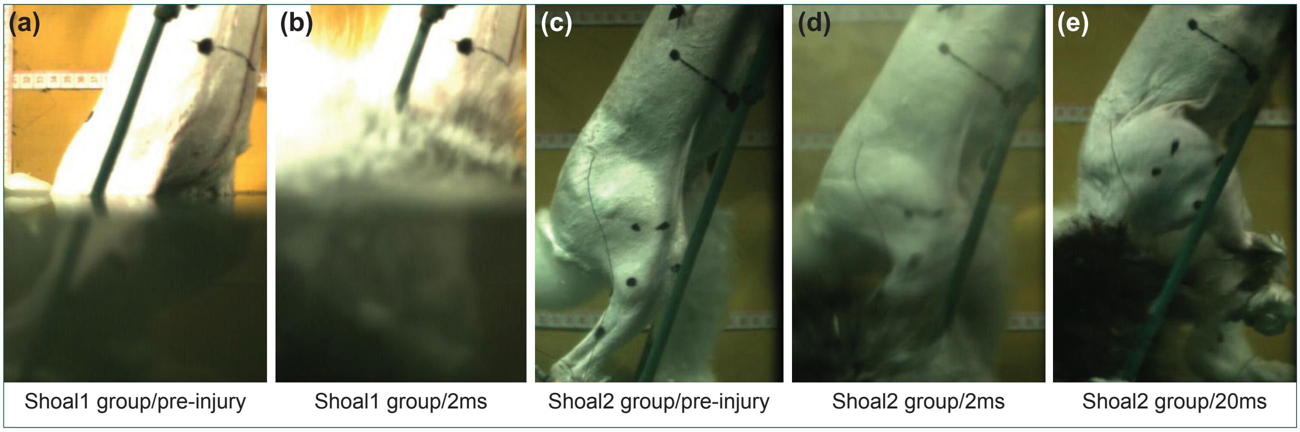
Group	Peak pressure (MPa)		
	Right calf	Right thigh	Left calf
Land	0.78±0.03*	0.14±0.01*	0.10±0.01*
Shoal1	63.85±2.15	28.63±0.66	21.46±0.71
Shoal2	73.53±2.21$^{\#}$	33.46±0.80$^{\#}$	25.08±0.82$^{\#}$

*p<0.05 for the land group compared with the shoal1 group and the shoal2 group.

$^{\#}$p<0.05 compared between the shoal1 group and the shoal2 group.

1. Comprehensive tissue injuries of the calf and the tibia were presented after mine blast on land, while tissue injuries were usually confined to the foot and ankle in shoals.
2. The thighs and the contralateral limbs were also damaged in shoals after mine blasts.
3. The occurrence rate of closed fractures in the tibia and femoral shaft was significantly higher in shoals than on land.

The damaging effects of anti-personnel mine can be categorized as follows:[7] stress wave entering the limb, penetrating injuries from fragments, footwear and soil, dynamic overpressure load on tissue, shear produced by the flow of products, as well. After an anti-personnel mine detonation on land, the blast wave is directly transmitted to the limb, shattering the bone within 200 µs. In 1–2 ms post-detonation, the detonation products and environmental fragments contact the limb, causing destruction of the traumatized soft tissue.[7,8] When a mine blast occurs on land, the air surrounding the explosion is compressed and absorbs energy from the explosion. Moreover, the blast wave displaces immediately the surrounding air and generates high velocity air flow that can cause injury. On the contrary, water is non-compressible and much denser than air.[9] When a mine blast occurs in shoals, there is little absorption of energy from the explosion. The pressure wave is transmitted with a greater intensity and a lower rate of



Shoal1 group/pre-injury | Shoal1 group/2ms | Shoal2 group/pre-injury | Shoal2 group/2ms | Shoal2 group/20ms

Figure 5. High-speed photographs of pre and post detonation in the shoal groups. Photographs taken at pre-injury **(a)** and 2 ms **(b)** after the detonation in the shoal1 group. Photographs taken at pre-injury **(c)**, 2 ms **(d)** and 20 ms **(e)** after the detonation in the shoal2 group.

dissipation. Therefore, the blast wave is directly transmitted to the limb, causing a more severe shattering effect on bones than that of the land. Consequently, the closed fractures of tibial and femoral were frequent in the shoal groups, while zero occurrence in the land group. The results of biomechanical analysis also demonstrate this viewpoint. The peak overpressure record in the bilateral calves and right thigh was significantly higher in the shoal groups than that of the land group. The explosive products and soil dissolved in the water and moved more slowly than in the air, causing less disruption of extremity soft tissue in shoals. Tissue defect was usually confined to the foot and ankle after detonation in shoals.

The characteristics of extremity injuries differed between the shoal1 and the shoal2 group after the mine blast. Firstly, bilateral thigh muscle tissue contusions existed at the water-air interface in the shoal1 group, while such wound did not occur at this position in the shoal2 group. Secondly, contralateral tibia fractures were found in five animals in the shoal2 group, but none existed in the shaol1 group.

Explosion is a rapid chemical reaction that produces combustion gas. In the shoal2 group, a bubble of gas formed in the water at 3 ms after detonation. The bubble rapidly expanded in a sphere. This rapid expansion generated the first pressure wave mediated by water; thereby the releasing of destructive energy damaged the extremity. In the shoal1 group, the combustion gas did not form any bubble. Instead, the combustion gas ejected directly into the air and formed a water column. This water column carried a lot of energy and dissipated in the air. Under the water surface, the explosion released less energy onto the extremity in the shoal1 group than in the shoal2 group. Just as the biomechanical analysis finding, the peak overpressure record in each part of the extremity in the shoal2 group was significantly higher than that in the shoal1 group. This finding may explain the reason why contralateral tibial fractures were significantly more frequent in the shoal2 group than that in the shoal1 group.

In the present study, the sciatic nerve exhibited nerve fiber breakage and partial nerve discontinuity because of the explosion shock waves in shoals. It is difficult to diagnose sciatic nerve injury if a casualty is exposed to a mine blast in shoals without any femoral fracture or sign of extensive soft tissues injury. Therefore, it needs to emphasize more on relieving pain and improving the prognosis in such situation. There are two appropriate levels for the amputations under knee. For non-salvageable foot injuries, with little involvement of the leg, an amputation may be performed through the middle third of the tibia, covered by a soleus muscle flap.[10] For an injury proximal to the foot, an amputation through the proximal tibia is performed, and the medial gastrocnemius may be used for closure over the bone end.[10,11] In our experiment, tissue defect usually confined to the foot and ankle in the shoal1 and shoal2 groups, therefore, a soleus muscle flap may be applicable for closure over the bone end after mine blast in shoals. Furthermore, serious arterial lesion may affect the amputation level for extremity injuries caused by mine blast in shoals.

Based on the above analysis, three conclusions can be drawn as follows: Firstly, explosive products and soil dissolve in water after explosions in shoals. The resistance of water is much stronger than that of air, so the spreading radius of the debris is shorter. Thus, mine blast in shoals causes less disruption of soft tissue than that on land. Secondly, the skeleton of the hind-limbs is damaged more seriously in shoals because the pressure wave is transmitted with greater intensity and has an intenser shattering effect on the bone than that on land. Finally, the characteristics of extremity injuries in shoal groups were different because of the various water depths causing different generation processes of blast wave.

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Conflict of interest: None declared.

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DENEYSEL ÇALIŞMA - *ÖZET*

Sığ sularda mayın patlamasının neden olduğu ekstremite yaralanmalarının oluş mekanizmaları ve karakteristik özellikleri

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AMAÇ: Suda mayın patlamasının karakteristik özellikleri havada patlamalardan farklı olup suyun derinliğine göre değişmektedir. Sığ sularda oluşan mayın patlamalarının neden olduğu ekstremite yaralanmalarının karakteristik özellikleri ve mekanizmalarını araştırmak önem taşımaktadır.
GEREÇ VE YÖNTEM: Toplam 90 Yeni Zelanda tavşanı dört gruba randomize edilip farklı derinliklerdeki suya bırakılmışlardır (kara grubu, uyluk kemiğinin yarısı derinlikteki su, Grup 1; ksifoit çıkıntıya kadar derin su Grup 2 ve kontrol grubu). Mayınları andıran elektronik patlatıcılar tavşanların arka patileri altına yerleştirildi. Patlama gerçekleştirildikten sonra tavşanlar morfolojik incelemeye tabi tutuldu.
BULGULAR: Karada mayınların patlatılmasından sonra tavşanların bacaklarının alt üçte biri hemen hemen yok olmuştu. Sığ sulardaki patlatmalar sonrası tavşanların yalnızca ayakları ve ayak bilekleri tahrip olmuştu. Karadakilere göre sığ sulardakilerin iskeleti, arterleri ve siyatik sinirleri daha ciddi derecede yaralanmıştı.
TARTIŞMA: Sığ sulardaki mayın patlamaları, karadaki patlamalara göre yumuşak dokuya daha az zarar vermiştir. Ancak, basınç dalgası daha yoğun biçimde iletildiği ve iskelete daha güçlü paramparça edici etki gösterdiği için sığ sulardaki patlamalarda iskelet daha ciddi derecede yaralanmıştı. Ayrıca ekstremite yaralanmalarında ekstremite yaralanmalarının karakteristik özellikleri suyun derinliğine göre değişmiştir.

Anahtar sözcükler: Biyomekanik; ekstremite yaralanması; morfoloji; patlama; sığ sular.

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