Journal of the Mechanical Behavior of Biomedical Materials 78 (2018) 292–297

Contents lists available at ScienceDirect

Journal of the Mechanical Behavior of Biomedical Materials

journal homepage: www.elsevier.com/locate/jmbbm

Comparison of ballistic impact effects between biological tissue and gelatin

Yongxi Jin[a,b], Ruimin Mai[b], Cheng Wu[a,*], Ruiguo Han[a,b], Bingcang Li[c]

[a] State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 10081, PR China
[b] Science and Technology on Transient Impact Laboratory, Beijing 102202, PR China
[c] Research Institute of Surgery, Daping Hospital/State Key Laboratory of Trauma, Burns and Combined Injury, Third Military Medical University, Chongqing 400042, PR China

ARTICLE INFO

Keywords:
Gelatin
Muscle
Simulant
Penetration
Energy transfer
Temporary cavity

ABSTRACT

Gelatin is commonly used in ballistic testing as substitute for biological tissue. Comparison of ballistic impact effects produced in the gelatin and living tissue is lacking. The work in this paper was aimed to compare the typical ballistic impact effects (penetration trajectory, energy transfer, temporary cavity) caused by 4.8 mm steel ball penetrating the 60 kg porcine hind limbs and 10 wt% gelatin. The impact event in the biological tissue was recorded by high speed flash X-ray machine at different delay time, while the event in the gelatin continuously recorded by high speed video was compared to that in the biological tissue. The collected results clearly displayed that the ballistic impact effects in the muscle and gelatin were similar for the steel ball test; as for instance, the projectile trajectory in the two targets was basically similar, the process of energy transfer was highly coincident, and the expansion of temporary cavity followed the same pattern. This study fully demonstrated that choosing gelatin as muscle simulant was reasonable. However, the maximum temporary cavity diameter in the gelatin was a little larger than that in the muscle, and the expansion period of temporary cavity was longer in the gelatin. Additionally, the temporary cavity collapse process in the two targets followed different patterns, and the collapse period in the gelatin was two times as long as that in the muscle.

1. Introduction

Muscle tissue is the main part of the human body, and the effect of projectile penetrating the muscle is always a focus in wound ballistics (Liu et al., 1991; Kneubuehl et al., 2011). Janzon (Janzon and Seeman, 1985), Berlin (Berlin et al., 1988), Ma (Feng et al., 1988; Fu et al., 1988) and Liu (Liu et al., 1988) demonstrated that muscle damage is closely related to the typical ballistic impact effects (energy transfer, temporary cavity) by war wound analysis and biological experiments, and they also revealed the interaction mechanism of projectile penetrating the muscle. Because of the ethical constraints and inhomogeneity of biological tissues, many tissue simulants (such as gelatin, glycerin soap) are used in the study of wound ballistics as substitutes for muscle. Gelatin is translucent in nature meaning a projectile's behavior and the exact path and placement of projectiles can be easily viewed and analyzed, so gelatin is widely used as muscle simulant. However, work in the open source literature which compares ballistic impact effects produced in gelatin and living tissue is limited.

Harvey et al. (1962) firstly recommended using gelatin in ballistic experiment, and it was found that similar penetration depths were produced in gelatin compared to those measured in soft tissue. Fackler et al. (1984a, 1984b) and Fackler and Malinowski (1985) carried out ballistic experiment by using gelatin block (4 °C/10 wt%) and a single hind swine leg together with a 10 wt% gelatin block as target respectively, the results showed that the 10 wt% gelatin produced penetration depths that were within 3% of living porcine muscle, and they also demonstrated that the temporary cavity diameter produced in the gelatin was within 8% of living porcine muscle by citing unpublished data. Based on the results of above research, the gelatin block (4 °C/10 wt%) standard and the evaluation method of wound profile were established. By now, Fackler's results were widely cited in the following study as the main basis for choosing gelatin as muscle simulant.

However, only the penetration depths in the two targets were observed in the previous researches, and the experimental data were scattered and limited (e.g. 5 swine was used in Fackler's experiment). Moreover, the biological test was complicated to be carried out, as well as the quantitative ballistic impact parameters were difficult to be obtained, so the comparative analysis of the typical ballistic impact effects (penetration trajectory, energy transfer, temporary cavity, etc.) in the two targets has not been conducted. The aim of the work in this paper was to compare the typical ballistic impact effects (penetration trajectory, energy transfer, temporary cavity) caused by 4.8 mm steel ball

* Corresponding author.
E-mail address: chengwubit@163.com (C. Wu).

https://doi.org/10.1016/j.jmbbm.2017.11.033
Received 8 July 2017; Received in revised form 15 November 2017; Accepted 21 November 2017
Available online 24 November 2017
1751-6161/

penetrating into the porcine hind limbs and 10 wt% gelatin. The event in biological tissue was recorded by high speed flash X-ray machine at different delay time, while the event in gelatin continuously recorded by high speed camera was compared to that in the biological tissue.

2. Material and methods

2.1. Material

2.1.1. Biological targets

The double hind limbs of living swine were chosen as the biological target because the mechanical properties of muscle tissue in vivo are quite different from those in vitro (Duck, 1990; Yamada, 1970). The weight of swine was 60 ± 5 kg, and the maximum thickness of the double hind limbs was about 250 mm. The experimental procedures were conducted in accordance with the protocols approved by the Third Military Medical University Institutional Animal Care and Use Committee. The swine were anesthetized with intravenous pentobarbital injection (40 mg/kg of body weight) (Li et al., 2014; Ning et al., 2012), and the operations were done according to the requirements of human anesthesia during the experiment, such as making the swine feel not pain (stimulating eyelashes without reaction, stimulating the tail of swine without swaying), maintaining the body temperature, heartbeat, breathing and blood pressure stability during the whole process, keeping the fluent respiratory tract (clearing the secretions in time). The swine were euthanized in the state of anesthesia after the experiment being completed. 14 living swine of the same batch were used to obtain comprehensive data of the ballistic impact effects of the muscle tissue (penetration history, the evolution of temporary cavity).

2.1.2. Gelatin

The gelatin target in this work followed Fackler model (4 °C/10 wt %). Gelatin with a Bloom strength of 250 was used to manufacture the gelatin block, and its preparation is detailed in Jussila (2001). The gelatin block dimensions of 30 cm × 30 cm × 30 cm is chosen according to the Chinese Military Standard. This size is also close to the dimension of double hind limbs of swine used in the experiment (Wen et al., 2017; Luo et al., 2016). Liquid gelatin at 60 °C was put into a 30 cm × 30 cm × 30 cm mould. The filled mould was left to set at room temperature (about 20 °C) for 12 h, then was placed in a refrigerator (4 °C) for 24 h. The test was conducted within 3 min of taking the block from the refrigerator to reduce the experimental error caused by temperature change.

2.1.3. Projectile

0.45 g steel balls with diameter of 4.8 mm were used as projectiles in the experiments. The influence from projectile yaw and deformation is avoided because the steel balls are not affected by yaw nor will deform on or after impact. The balls were secured in a polymeric sabot before being fitted into a 7.62 mm × 53 mm cartridge case for firing. The impact velocity was controlled at 1150 ± 5 m/s, so it was considered that the impact velocity of each projectile was well consistent.

2.2. Methods

2.2.1. Biological tissue experiment

The swine samples were placed in the supine position on the test bench with the hind limbs tied together without gap, and were arranged 5 m downrange from the end of the muzzle to the thickest part of double hind limbs. A 7.62 mm smoothbore ballistic gun was used to fire steel ball. Each sample was only shot by one steel ball to avoid the influence of existing wound channel on the ballistic impact effects. The impact velocity was recorded using a laser screen target XGK-2002 (Manufactured by Xi'an Technological University). The impact event was recorded using the high speed flash X-ray machine Scandiflash 450. Its X-ray generator was placed beside target, and the X-ray direction

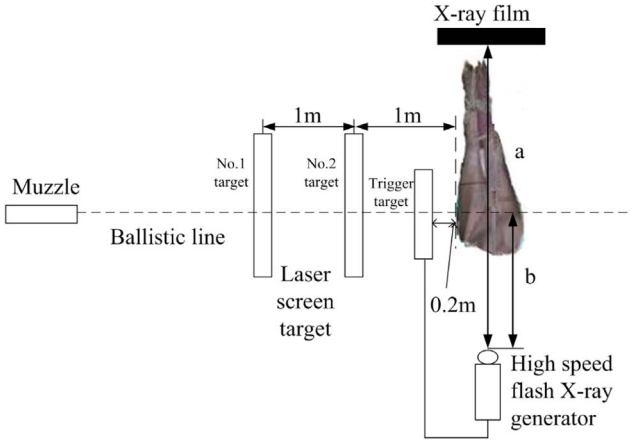

Fig. 1. The setup of biological experiment.

was perpendicular to the direction of ballistic trajectory. A digital X-ray film was set on the other side of target, and three lead blocks was placed on the film as scale. In addition, a tinfoil was placed 0.2 m in front of target to trigger the high-speed flash X-ray machine, and the images at different time were obtained by adjusting the trigger time. The setup of biological experiment was illustrated in Fig. 1.

The image process software was used to measure the penetration depth (from the entry to the steel ball) and temporary cavity diameter in the muscle based on the scale. The actual value was obtained by the measured value multiplied by the ratio b/a (where, a was the distance between the generator and the X-ray film, and b was the distance between the generator and the ballistic line, as shown in Fig. 1).

2.2.2. Gelatin experiment

The gelatin block was placed 5 m downrange from the end of the muzzle. A 7.62 mm smoothbore ballistic gun was used to fire steel ball. The laser screen target XGK-2002 (Manufactured by Xi'an Technological University) was used to record the impact velocity. The impact process was recorded using a FASTCAM SA-X2 high speed video (20,000 fps, 10 μs exposure time and 1024 × 640 frame resolution). The gelatin block was illuminated from the back using a high power LED light source. A scale was used to allow the high speed video footage to be calibrated. The gelatin experimental setup was shown in Fig. 2.

The Photron FASTCAM Viewer (Ver.351) was used to analyze the high speed footage. Each image was calibrated by using a known length visible in the image, converting pixels present in the image to a dimension in millimeters. Once calibrated, it was possible to take measurements that included the temporary cavity diameter and penetration depth (from the entry to the steel ball in the gelatin block).

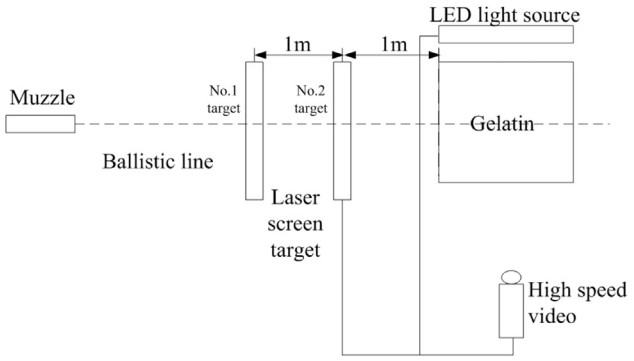

Fig. 2. The setup of gelatin experiment.