Efficacy of Body Armor in Protection against Blast Injuries using a Swine Model in a Confined Space with a Blast Tube

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Research

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Abstract

Background

Regarding blast injuries, fatal damage leading to immediate death is considered due to shock-lung, respiratory arrest, or circulatory failure induced by a neurological reflex, such as the severe vagal nerve reflex. It has not yet been determined whether a bulletproof vest protects against or aggravates shock-lung or the neurological reflexes considered to be fatal in the super-acute phase after an explosion.

Purpose

The purpose of this study was to clarify whether a bulletproof vest would protect the body in a pig blast model using a blast tube built at National Defense Medical College, which is the first such blast tube in Japan.

Methods

Seventeen pigs were divided into two groups: the body armor group (n = 6) and the non-body armor group (n = 11). Pigs underwent tracheal intubation with IV and A lines were secured to measure vital signs were checked and collect blood samples. Then, under intravenous anesthesia, the pigs were tightly fixed in the left lateral position on a table and exposed from the back neck to the upper lumbar back to the blast wave and wind with or without body armor, with the driving pressure of the blast tube set to 3.0 MPa. We checked the vital signs, collected blood samples, and observed the pigs for 3 hours after injury.

Results

When the surviving and dead pigs were compared, blood gas analyses revealed significant differences in PaO2, PaCO2, and pH in the super-early phase. In addition, all pigs injured by the blast wave and wind had lung hemorrhage, and 14 of 17 pigs had intra-abdominal hemorrhage with splenic injury. All 6 animals in the body armor group and 6 of the 11 animals in the control group survived for 3 hours after injury. Respiratory arrest immediately after exposure to the blast wave and wind was considered to influence the outcome in our pig model.

Conclusions

Respiratory arrest within several minutes after injury influenced the mortality of pigs. Body armor may have the beneficial effect in protecting against respiratory arrest immediately after an explosion.

Introduction

In recent years, terrorism-related bombings have become more frequent in the world, and the number of casualties from explosions has increased significantly [1–4]. More than sixty thousand US soldiers have been killed or injured during wartime in Iraq and Afghanistan [5]. Fortunately, there have been few terrorist bombings in Japan; however, Japan should not underestimate the risk of a bomb attack [6] because Japan will hold major events, such as the Tokyo Olympics and Paralympic Games in 2020. In addition, it is necessary for us to consider the means of protecting Japan Self Defense Force personnel who have the potential to be exposed to explosions during overseas missions.

Explosion-related injuries are classified into primary blast injury induced by the shock wave, secondary blast injury from penetrating wound caused by flying debris, tertiary blast injury caused by blunt trauma from the blast wind, and quaternary blast injury caused by burns [7–11]. Among these injuries, fatal damage leading to immediate death is considered to occur due to shock-lung, respiratory arrest, or circulatory failure induced by neurological reflexes such as severe vagal nerve reflex [12, 13].

It has been scientifically debated whether a bulletproof vest (body armor) designed to protect the trunk from damage caused by bullets protects against organ damage, such as lung hemorrhage induced by shock waves from explosions [14, 15]. It has not yet been determined whether a bulletproof vest protects against or worsens shock-lung or the neurological reflexes that are considered to be fatal in the super-acute phase after an explosion.

The purpose of this study was to clarify whether a Japanese bulletproof vest would protect the living body in a pig blast model using a blast tube built at the National Defense Medical College, which is the first such blast tube in Japan.

Methods

Establishment of the blast tube

In Japan, we did not have an appropriate model of blast injury because of strict ethical restrictions on animal experiments. Ten years ago, we established a novel small animal model of blast injury using a laser-induced shock wave at the National Defense Medical College (NDMC). Some original articles [16–21] had already been published in international scientific journals; however, these studies only involved small animals (e.g., mice and rats). We needed to establish a medium-sized animal model in order to apply the findings of the studies to human patients.

In 2017, we established a blast tube, which is a device that induces blast injury based on air pressure differences, in conjunction with IHI Corporation (Tokyo, Japan) in the NDMC Research Institute. The development of the blast tube was funded using the budget for Advanced Research on Military Medicine. This blast tube, which was the first of its kind in Japan, enables basic studies on blast injury to be conducted using medium-sized animals. The blast tube established in our institute has a blast pressure-generating area, control area, and measurement area with a Schlieren instrument and a high-speed camera (Fig. 1). The length of the blast tube is 7.5 m, and the diameter of the outlet window is 40 cm. Data are automatically recorded in a computer system. The driving pressure of this blast tube can be set to 5.5, 3.0, 1.5, 1.0, or 0.5 MPa. In our experiment, the driving pressure was set to 3.0 MPa based on a previous study by Bass et al. [22)]. This driving pressure was selected because we predicted that the mortality rate of the animals would be approximately 50% based on the data published by Bass et al. and our preliminary data on the static peak pressure and the duration produced through the outlet window of the shock tube (Fig. 2).

Animal Experiments

Seventeen male hybrid pigs (age, 10–12 weeks; mean body weight, 38 kg), were used in these experiments. Before the experiments, each animal was housed in an individual cage in a room with a room 12:12 hour light: dark cycle and an ambient temperature of 24°C. The animals were fed standard laboratory pig chow and had ad libitum access to water. Seventeen pigs were divided into two groups: the body armor group (n = 6) and non-body armor group (n = 11).

The design of our animal study is shown in Fig. 3. All animals were anesthetized with ketamine hydrochloride (75 mg/kg sci) and xylazine hydrochloride (45 mg/kg sci). In the animal experiment room, we secured an intravenous line via the subcutaneous auricular vein and administered ketamine hydrochloride (25 mg/kg iv) and xylazine hydrochloride (15 mg/kg iv) every 30 minutes, intravenously. Normal saline was intravenously administered (30 mL/h) to maintain the intravenous line before injury. In addition, we performed tracheal intubation, and secured an arterial line via the femoral artery to collect blood samples (each 5 mL at pre-injury, and 5 min, 1 h, 2 h, and 3 h post-injury) to measure circulatory blood cell counts and perform blood gas analyses, and to check the vital signs before injury. We brought a pig to the room of the blast tube, and then fixed it tightly in the left lateral position on the table in the measurement area. The back of the neck to the upper lumbar back (mainly chest dorsal back) was then exposed to the blast wave and wind. We adjusted the central axis of the blast tube and the center of the chest dorsal back in the left lateral position to the same height. The average distance from the outlet window of the blast tube to the chest dorsal back of the pig was 65 cm (non-body armor group; 65–67 cm, body armor group; 60–65 cm). Immediately after the induction of the blast injury, we observed the respiratory condition and vital signs, and then collected heparinized artery blood for a blood gas analysis at 5-minutes post-injury. The animal was then returned to the animal experiment room and we checked the vital signs and collected blood samples every 1 hour and observed the animals for 3 h after injury. Surviving pigs were sacrificed at 3 h post-injury. Normal saline was intravenously administered (60 mL/h) without fluid resuscitation after injury. At sacrifice, the animals were again anesthetized with ketamine hydrochloride (150 mg/kg iv) and xylazine hydrochloride (90 mg/kg iv), and we macroscopically checked for organ damage in the intrathoracic and intra-abdominal spaces and collected lung tissue specimens from the left lower lobe for pathological examination.

The body armor worn by the pig was the bulletproof vest 2, which was previously worn by Japan Self-Defense Force personnel. We tried to make the human body armor worn by the pig as tight as possible. The bulletproof vest 2 was designed and deployed for a short period of 3 months in 2003, immediately before Japan Self-Defense Forces were dispatched to Iraq. The vest used ceramic plates (size: 35 × 30 cm) capable of stopping bullets. Body armor with ceramic plates were used in this study.

Measurements

Lung damage induced by blast injury was confirmed histologically using hematoxylin and eosin staining. A blood gas analysis of heparinized arterial blood was conducted using a Vetstat blood gas tester (IDEXX Laboratories, Inc., Japan). The circulatory blood count was determined using a multi-item automatic blood cell counter for animals (Sysmex TMC Corp., Tokyo, Japan).

Animals received complex trauma induced by shock and reflected waves. In the test room where an anesthetized pig was fixed in place, we measured and produced calculative pressure images based on the propagation of blast waves. The numerical analysis was performed with a home-made axisymmetric two-dimensional Eulerian code, WAF-2D, in which the weighted average flux (WAF) method was used as the Reimann solver. Shock capturing was implemented by the adaptive mesh method, with an initial mesh size of 5 mm to detect the precise locations of the blast waves. An axisymmetric computational domain comprising a high-pressure chamber of radius 160 mm and length 500 mm, a low-pressure channel of radius 160 mm and length 5800 mm, a nozzle of radius 200 mm (at the exit) and thickness 5 mm, and a test room of radius 1400 mm and length 2780 mm was developed for the analysis. The initial pressure ratio between the high-pressure chamber and the low-pressure channel (P4/P1) was 22.5. The pressure inside the low-pressure channel (P1) was 101.3 kPa, which is the standard atmospheric pressure. The pressure inside the high-pressure chamber (P4) was set to produce shock waves with the same incident shock Mach number obtained from the previous experiment.

Statistical Analyses

All values are expressed as the mean ± standard error. The survival rates of the two groups were compared by Fisher's exact test. The vital signs (systolic blood pressure, pulse, and SpO2), circulatory blood count values (hemoglobin and hematocrit), and blood gas analysis results (PaO2, PaCO2, and pH) were compared between the two groups by a repeated measures ANOVA. P values of < 0.05 were considered to indicate statistical significance.

Results

The parameters and results of the experiments using 17 pigs (body weight, distance from outlet window to dorsal chest back of each pig, use of body armor, organ damage, and outcome at 3 h post-injury) are summarized in Table 1. There was no significant difference in the body weight of pigs; however, there was a significant difference ($p < 0.001$) in the distance from the outlet window between the body armor and non-body armor groups. It was concluded that the positions of pigs were the same, but that the distances differed due to the thickness of body armor. All pigs injured by the blast wave and wind had lung hemorrhage, and 14 of the 17 pigs had intra-abdominal hemorrhage with splenic injury. All 6 animals in the body armor group and 6 of 11 animals in the control group were alive at 3 hours after injury. There was a significant difference in the survival rate between body armor and non-body armor groups.

Eight pigs in the two groups suffered respiratory arrest immediately after exposure to the blast wave and wind; 3 pigs spontaneously recovered from respiratory arrest and survived for 3 hours after injury. As a result, all pigs in the body armor group survived for 3 hours. Respiratory arrest immediately after exposure to the blast wave and wind was considered to influence the outcomes in our pig model (Table 2).

The changes in the vital signs, hemoglobin and hematocrit values, and blood gas analyses results of the surviving pigs with and without body armor are shown in Figs. 4, 5, and 6, respectively. These parameters did not differ between the two groups to a statistically significant extent. In contrast, Fig. 7 demonstrates significant differences in the blood gas analysis results (PaO_2, $PaCO_2$, and pH) of the surviving and dead pigs.

Figure 8 shows a computer-generated pressure image created based on the real sizes of the shock tube and test room and the measured pressures in a confined space. Figure 8(1)– (7) shows the time-resolved development of the blast waves discharged from the nozzle into the test room. The color indicates the overpressure: red indicates ≥ 30.4 kPa (130% of the initial pressure), and blue indicates ≤-30.4 kPa (70% of the initial pressure), generated by the blast waves. As shown in Fig. 8(1), at $t = t0$, the incident shock wave propagated inside the low-pressure channel arrived at the middle section of the nozzle. As shown in Fig. 8(2), at $t = t0 + 1.00$ ms, the incident shock wave was discharged from the nozzle, and the strong shock wave along the center axis propagated into the test room, generating vortexes beside the nozzle (indicated by blue). At $t = t0 + 3.35$ ms, the diffracted shock waves reached the wall of the test room (Fig. 8(3)). At $t = t0 + 4.75$ ms, the shock waves reflected from the wall of the test room appeared, and the incident shock waves reached the right side (of the wall) of the test room (Fig. 8(4)). At $t = t0 + 10.00$ ms, the shock waves reflected from the right side (of the wall) interfered with the shock waves reflected from the upper side of the test room and the jet of the nozzle (Fig. 8(5)). As shown in Fig. 8(6), at $t = t0 + 15.00$ ms, the shock waves were reflected from the right side of the wall toward the opposite wall of the test room, experiencing interference with the reflected waves from the upper wall and jet. Finally, the overpressure inside the test room increased (in the entire region) due to the multiple reflected blast waves. According to the numerical results, in the test room, the incident shock waves directly produced a strong impulse on the test object followed by multiple impacts caused by a large number of reflected shock waves.

Macroscopic views of blast-lung in the non-body armor group are shown in Fig. 9. Hemorrhage was seen on the surface of the bilateral lungs. This was noted on all lungs of animals injured by the blast wave and wind. Lung hemorrhage was also noted in all animals of the body armor group (data not shown). Micrographs after hematoxylin and eosin staining of blast-lung tissue specimens from the non-body armor group and body armor group are shown in Figs. 10 and 11, respectively. The severity of lung hemorrhage was similar in the two groups.

Discussion

In this study, pigs with bulletproof vests (body armor) had significantly higher survival rates than pigs without bulletproof vests. Moreover, all of the dead pigs in this study had respiratory arrest immediately after exposure to the blast wave and wind. Only pigs with spontaneously recovered breathing survived for 3 hours. All of the pigs that did not recover from respiratory arrest died within one hour of injury. Thus, it was clear that the occurrence of respiratory arrest, which appears to be a neurological reflex that occurs immediately after injury, is significantly involved in the 3-h outcome. We hypothesized that the body armor reduced the incidence of neurological respiratory arrest and protected the pig's life by lessening the insult induced by the blast wave and wind. At any rate, the body armor significantly improved the survival rate, and it was considered to be beneficial to the living body in terms of life support in the super-acute phase after an explosion.

Phillips et al. reported that wearing an army ballistic jacket was not beneficial for protecting against shock wave damage to the chest [1)]. Their study involved basic blast injury experiments using sheep. Although there were numerous differences in the conditions of their study and our own, they reached the opposite conclusions with regard to the lifesaving effect of wearing a bulletproof vest on blast injury. The length of the blast tube used by Phillips et al. was 36.6 m, and they applied shock waves and blasts to the right side of sheep placed in an open field. When the peak pressure was 420 kPa, which was the highest, 5 out of 6 sheep with bulletproof vests died, while only 2 out of 6 sheep in the non-body armor group died. According to Phillips et al., it was considered that the pressure in the vest increased and that blast-lung was exacerbated. However, the results of the present study contradict the suggestion that wearing a bulletproof vest exacerbates blast-lung. The organ damage induced by a blast wave in a confined space may be worse than that induced in an open space due to wave reflection. We believe that wearing body armor had beneficial effects in the super-acute phase because it reduced the incidence of respiratory arrest and increased the survival rate.

In this study, we investigated mortality and organ injury when blast waves and wind were applied from the back of the neck to the upper lumbar back centering on the chest dorsal back during an explosion in a confined space. In the absence of respiratory arrest, all pigs survived for 3 hours after injury without resuscitation. When we raised the driving pressure of the blast tube to 5.5 MPa, the pigs exhibited not only respiratory arrest but also reduced blood pressure and cardiac arrest due to ventricular fibrillation immediately after injury (data not shown). Thus, we suggest that in the combat setting, survival is possible if respiratory and cardiac arrest do not occur immediately after an explosion. Wearing body armor may be beneficial to saving lives if an explosion occurs.

Limitations

The present study was associated with some limitations. First, this study simulated an explosion in a confined space, organ injury is likely to be more severe than that in an open space. Second, the organ damage and mortality may differ depending on the animal posture, body parts, and angle of exposure to the blast wave and wind. Third, the animal species differed from previous studies. In addition, there are anatomical and physiological differences between humans and animals. Finally, The fit of the body armor to the trunk was not ideal because it was designed for humans. Even so, the body armor had a protective effect against shock waves.

Conclusions

A blast tube was established in the National Defense Medical College Research Institute in 2017. The mortality rate of a swine model exposed to a driving pressure of 3.0 MPa was decreased in swine wearing body armor. In addition, respiratory arrest within several minutes after injury may have influenced the mortality of the pigs. We will conduct further studies to develop lifesaving systems that can be applied immediately after explosions and prevent early death caused by blast wave and wind.

Abbreviations

BLI: blast lung injury; MPa: megapascal; KPa: kilopascal; ms: millisecond; BP: blood pressure; BGA: blood gas analysis; PaO2: arterial blood oxygen partial pressure; PaCO2: arterial blood carbon dioxide partial pressure; SpO2: peripheral oxyhemoglobin saturation; Hb: hemoglobin; Ht: hematocrit; SD: standard deviation; WAF: weighted averaged flux; HE: hematoxylin-eosin; BW: body weight; LH: lung hemorrhage; IAH: intra-abdominal hemorrhage

Declarations

Ethical Approval and Consent to participate

All requests for animals and intended procedures in the present study were approved by the Ethics Committee of Animal Care and Experimentation, National Defense Medical College, Japan (permission numbers: 16067, 19041).

Consent for publication

Not applicable.

Availability of data and materials

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Y.S. is the primary investigator of this study and was thus responsible for all of the study processes. D.S. contributed to the study design, animal experiments, data collection, statistical analyses, data interpretation and writing of the manuscript. Y.Y. contributed to the animal experiments, and data collection. Y.K. contributed to the animal experiments, data collection and creation of the figures. M.F., Y.A., H.K. and S.Y. contributed to the animal experiments. Y.S. and H.T. contributed to the animal experiments, data collection and supplying materials and tools. T.M. and Y.O. contributed to the animal experiments, data interpretation and writing of the manuscript. M.N. contributed to the study design and writing of the manuscript.

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Tables

Due to technical limitations, Tables 1-2 are provided in the Supplementary Files section.

Figures

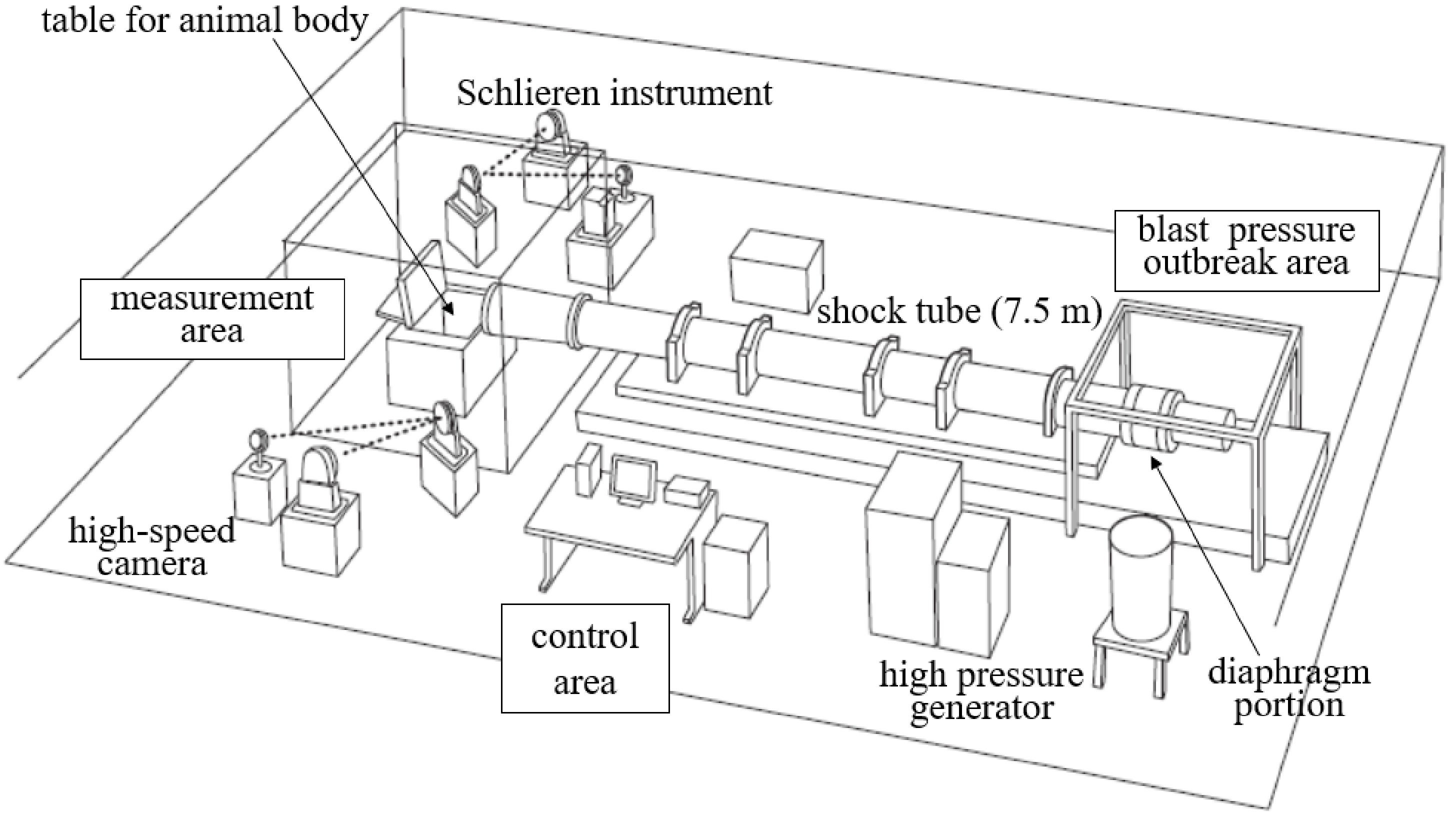


Figure 1

The appearance of the blast tube established at the National Defense Medical College. The blast tube established inside an institute building has a blast pressure-outbreak area, control area, and measurement area. The length of the blast tube is 7.5 m, and the diameter of the outlet window is 40 cm.

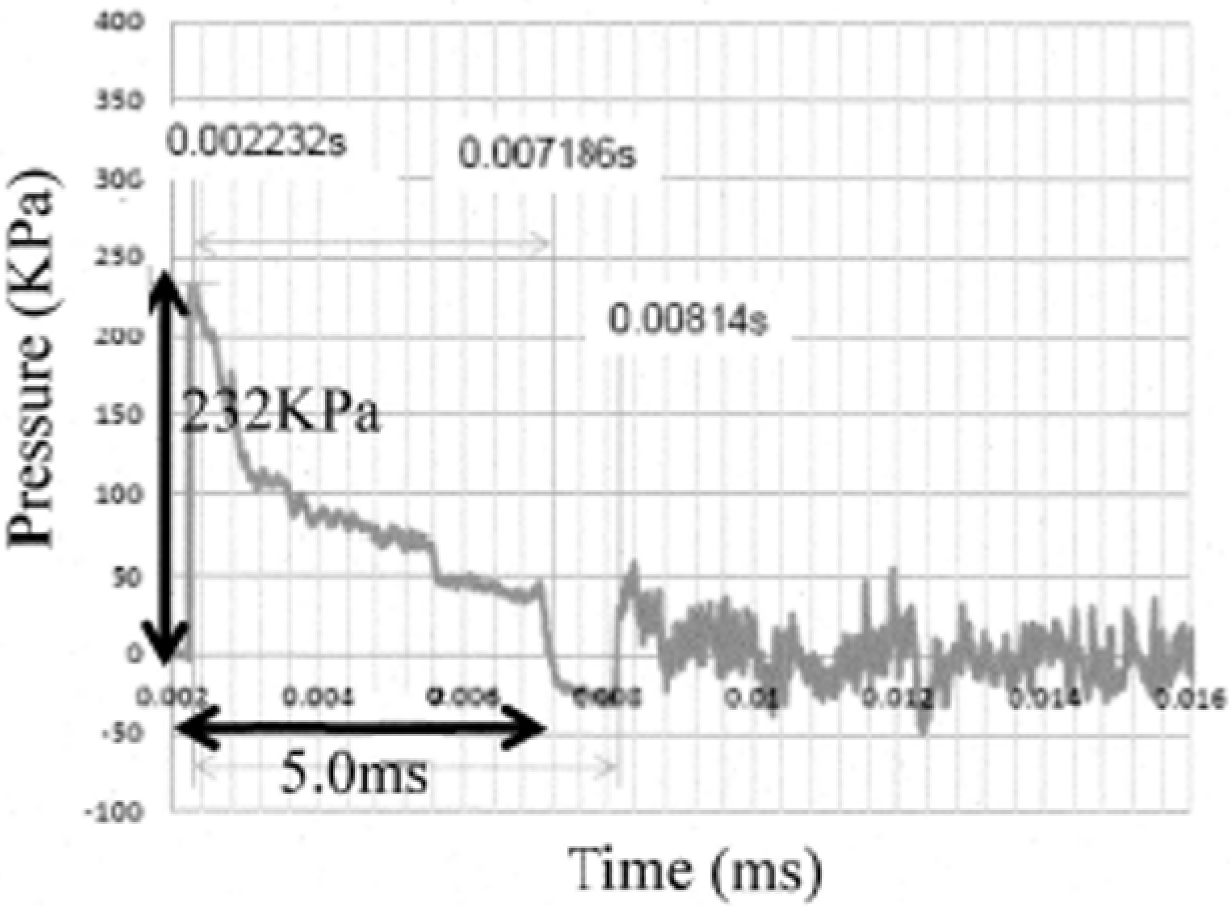


Figure 2

The peak static pressure and duration of action at the outlet window of the shock tube. Preliminary data on the static peak pressure and the duration produced through the outlet window of the shock tube were measured with 3.0 MPa set as the driven pressure.

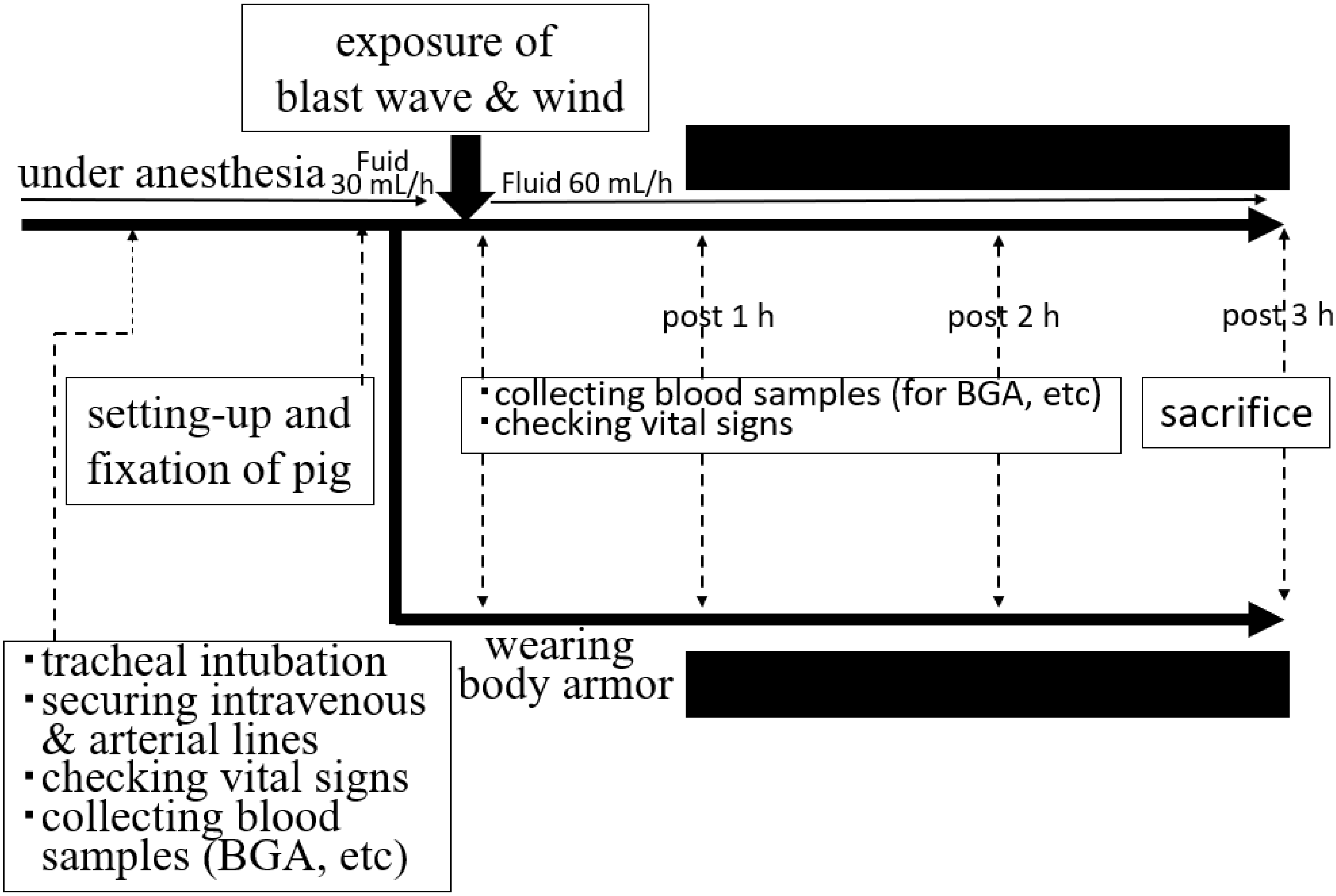


Figure 3

Study design using pigs. We performed tracheal intubation and secured an arterial line via the femoral artery to collect blood samples to measure circulatory blood cell counts and perform blood gas analyses and check the vital signs before injury. The pig was fixed tightly in the left lateral position on the table in the measurement area. The area from the back of the neck to the upper lumbar back (mainly chest dorsal back) was then exposed to the blast wave and wind. Immediately after the induction of the blast injury, we observed the respiratory condition and vital signs and then collected heparinized artery blood for a blood gas analysis at 5-minutes post-injury. Each animal had its vital signs checked and blood samples collected every hour, and animals were observed for 3 h after injury. Surviving pigs were sacrificed at 3 h post-injury.

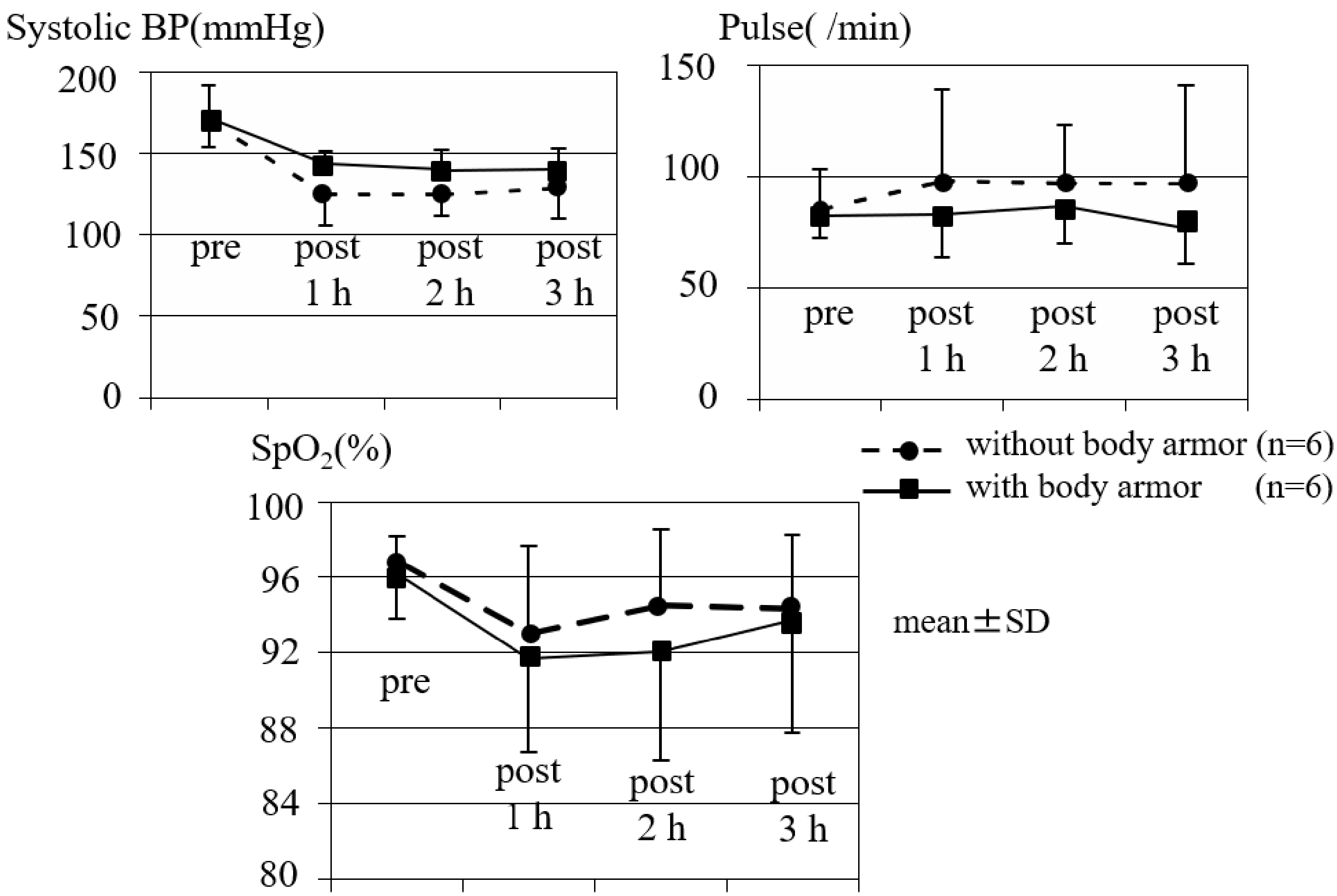


Figure 4

Changes in the vital signs in two groups with and without body armor among surviving pigs. The changes in the systolic blood pressure, pulse rate and SpO2 did not differ markedly between the two groups to a statistically significant extent.

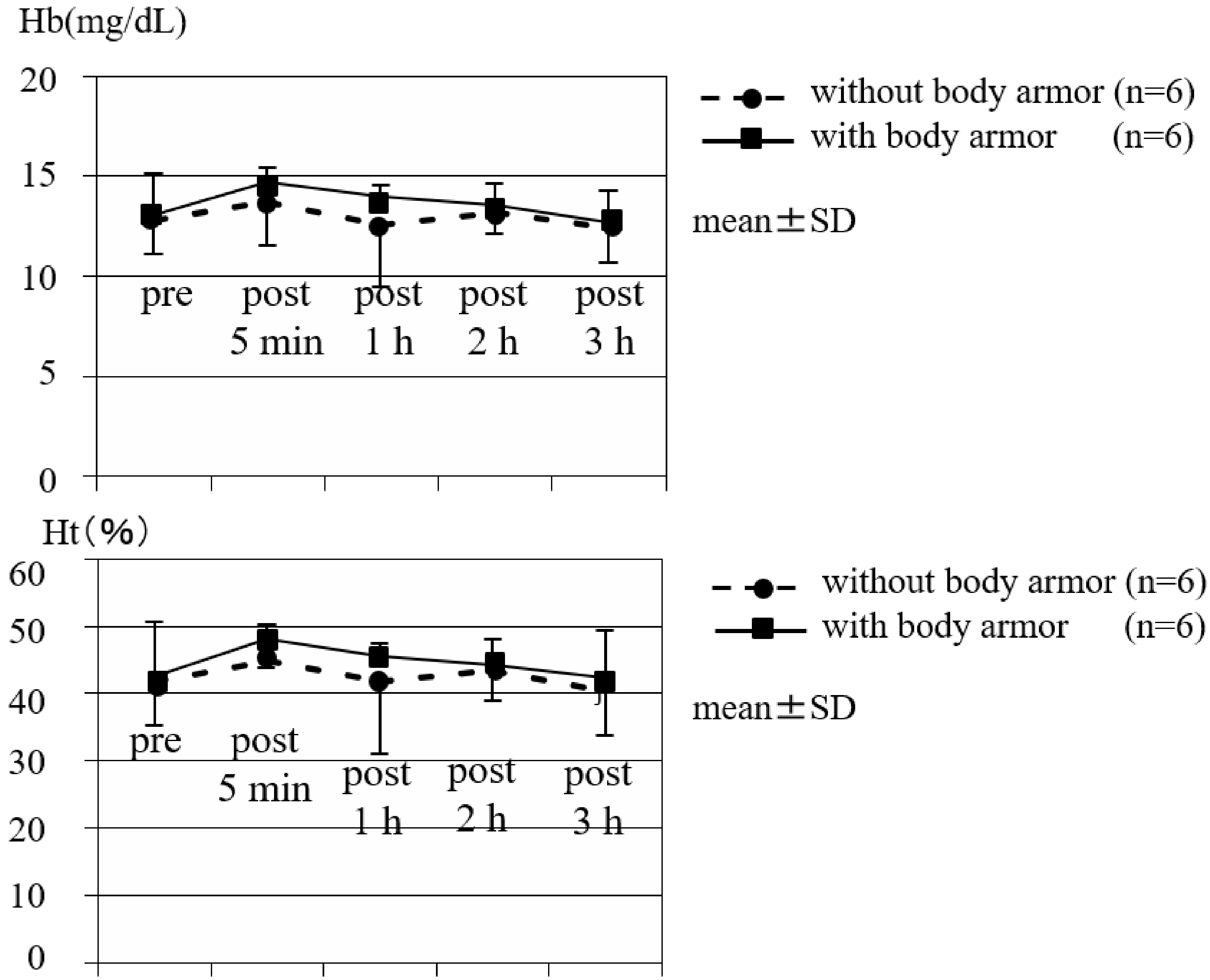


Figure 5

Hemoglobin and hematocrit values in the two groups with and without body armor among surviving pigs. The changes in these values did not differ markedly between the two groups.

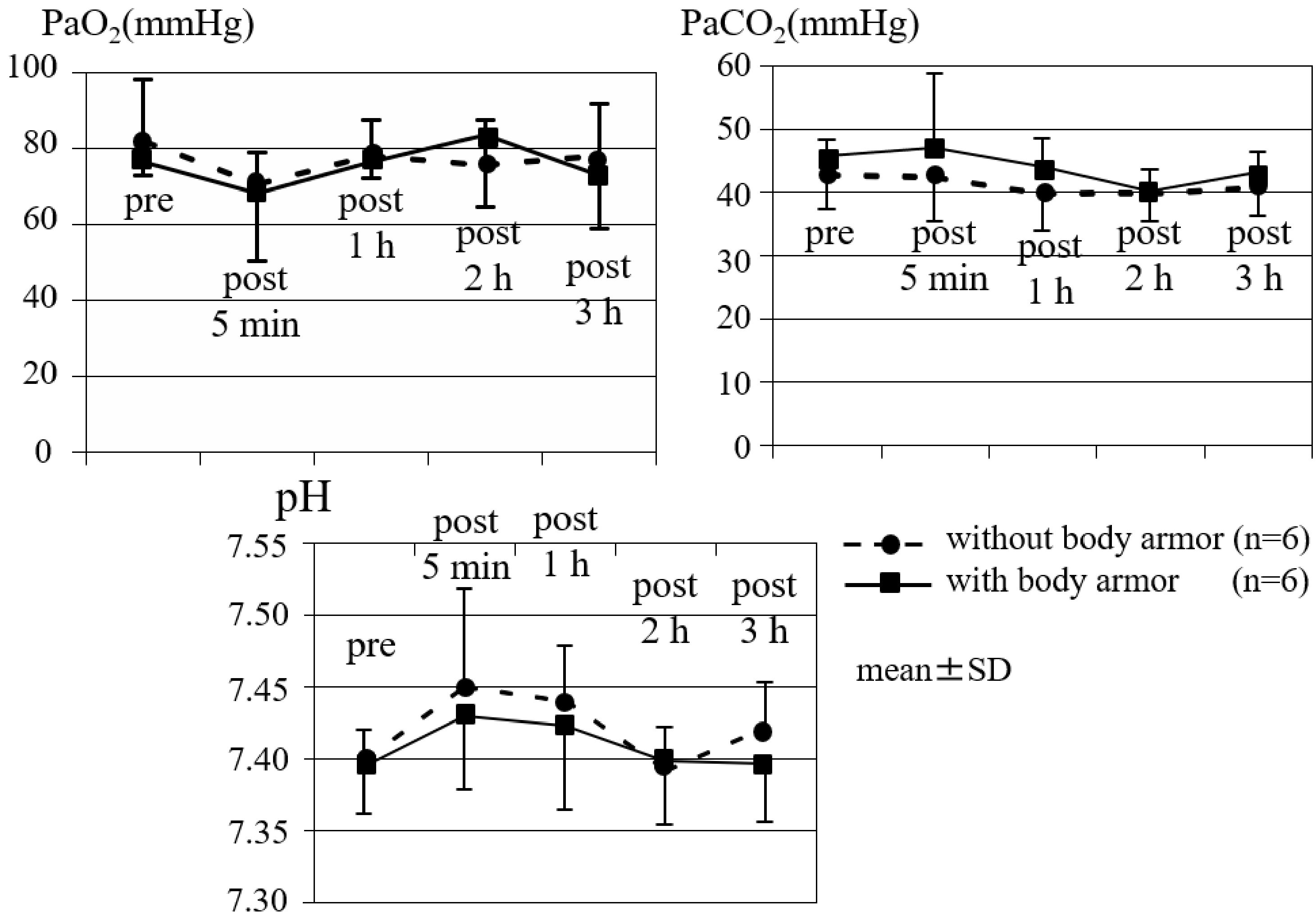


Figure 6

Results of blood gas analyses in the two groups with and without body armor among surviving pigs. The changes in the PaO2, PaCO2 and pH did not significantly differ between the two groups.

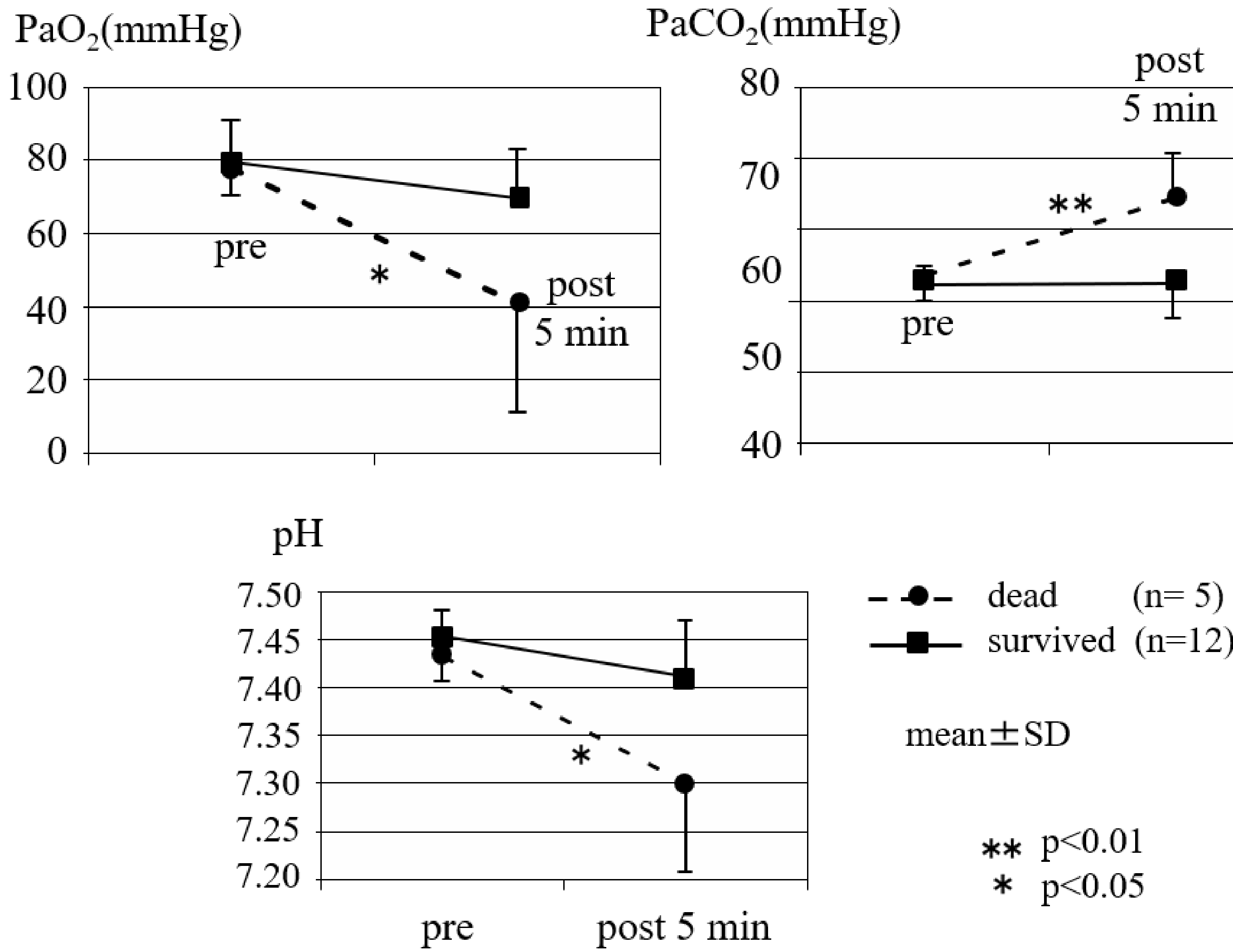


Figure 7

Results of blood gas analyses in surviving and dead pigs. Significant differences in the blood gas analysis results (PaO2, PaCO2 and pH) were noted between the surviving and dead pigs.

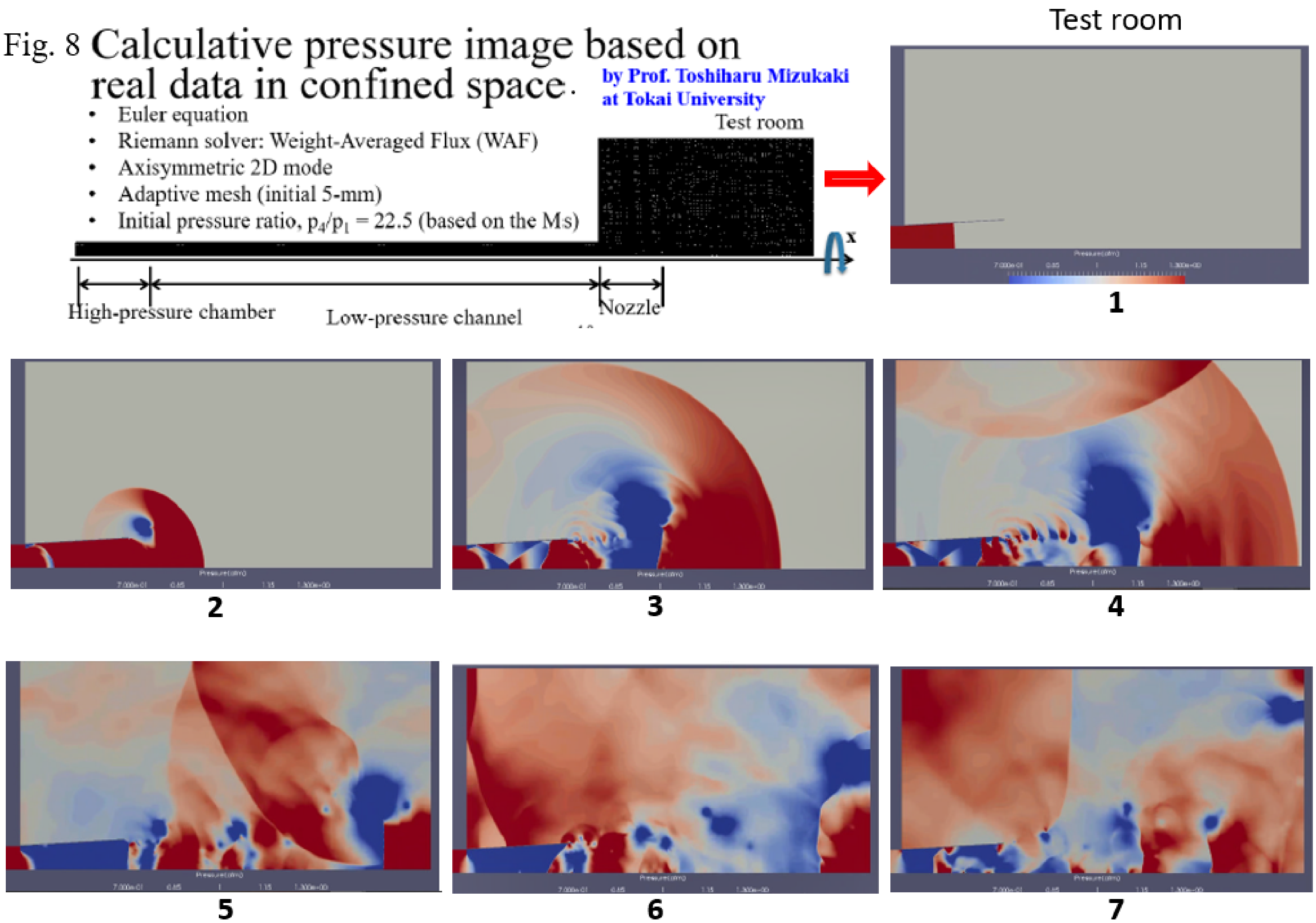
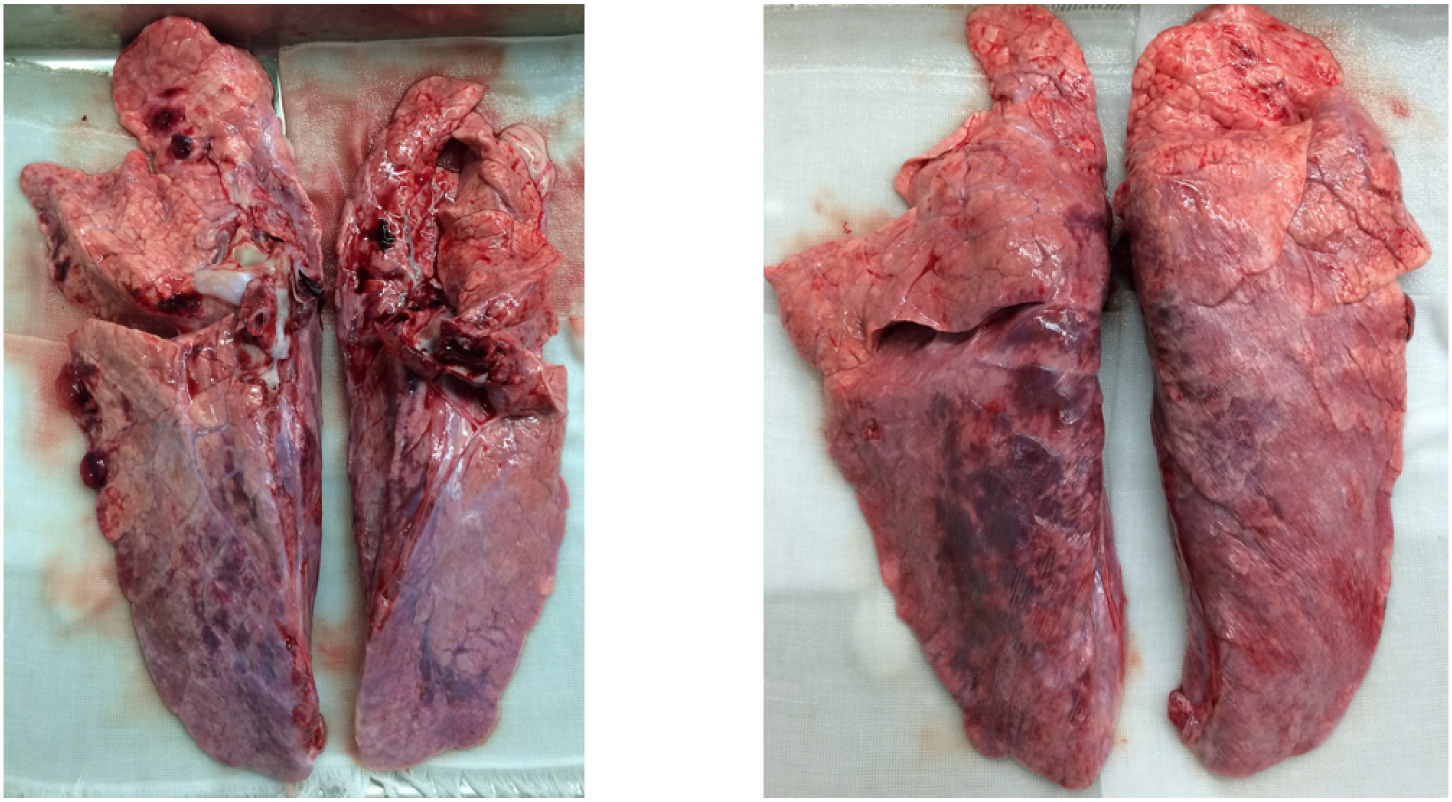


Figure 8

Numerical results concerning the propagation of blast waves inside the test room. This figure shows a computer-generated pressure image created based on the real sizes of the shock tube and test room and the measured pressures in a confined space. (1) – (7) show the time-resolved development of the blast waves discharged from the nozzle into the test room. The color indicates the overpressure: red indicates ≥30.4 kPa, and blue indicates ≤-30.4 kPa, generated by the blast waves. Finally, the overpressure inside the test room increased (in the entire region) due to the multiple reflected blast waves.



front view back view

Figure 9

Macroscopic views of blast lung in the non-body armor group. Hemorrhaging was seen on the surface of the bilateral lungs in the non-body armor pig. Lung hemorrhaging was noted in all lungs of animals injured by the blast wave and wind as well as in all animals in the body armor group.

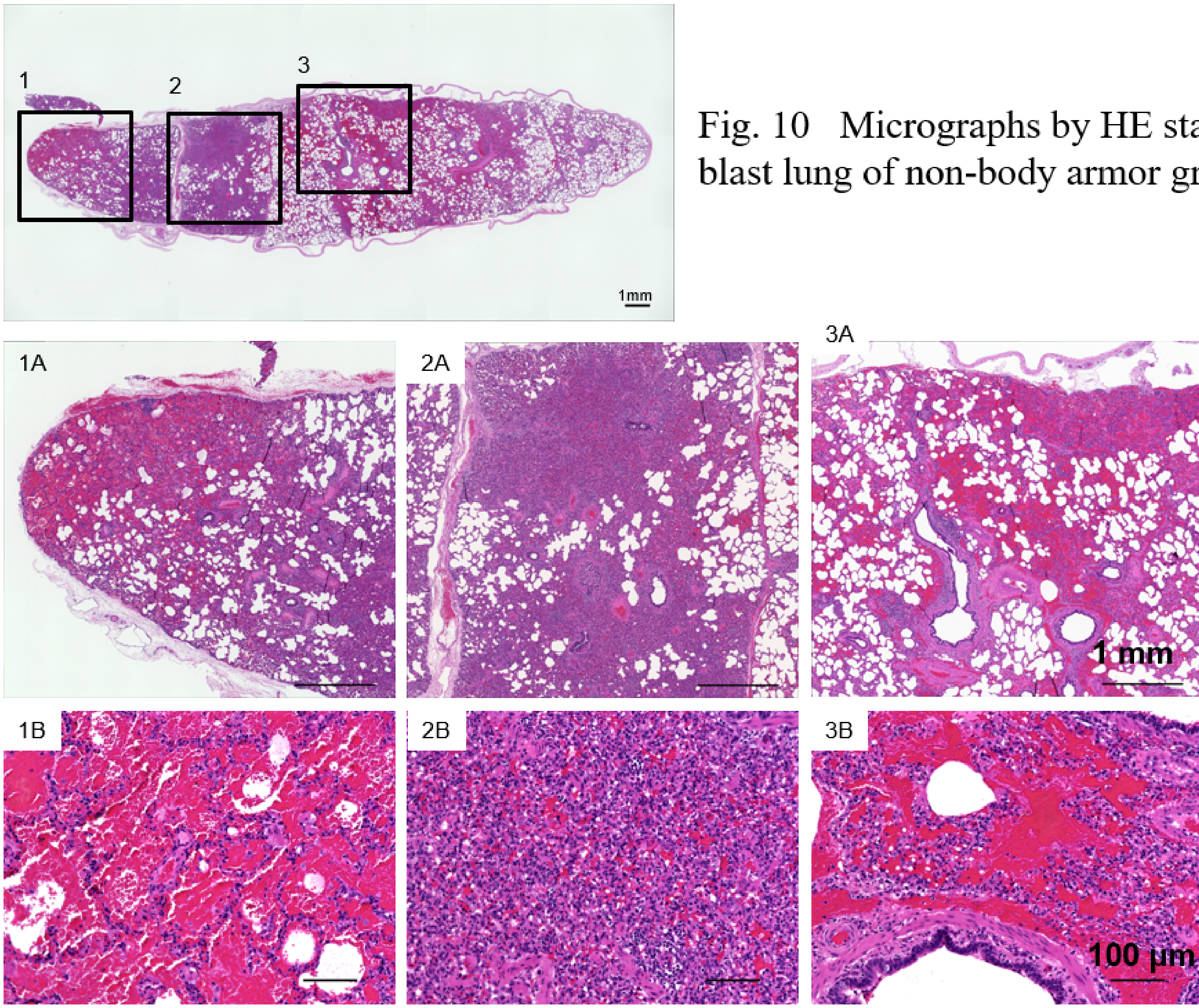


Figure 10

Micrographs after Hematoxylin-Eosin staining of the blast-exposed lung of the non-body armor group.

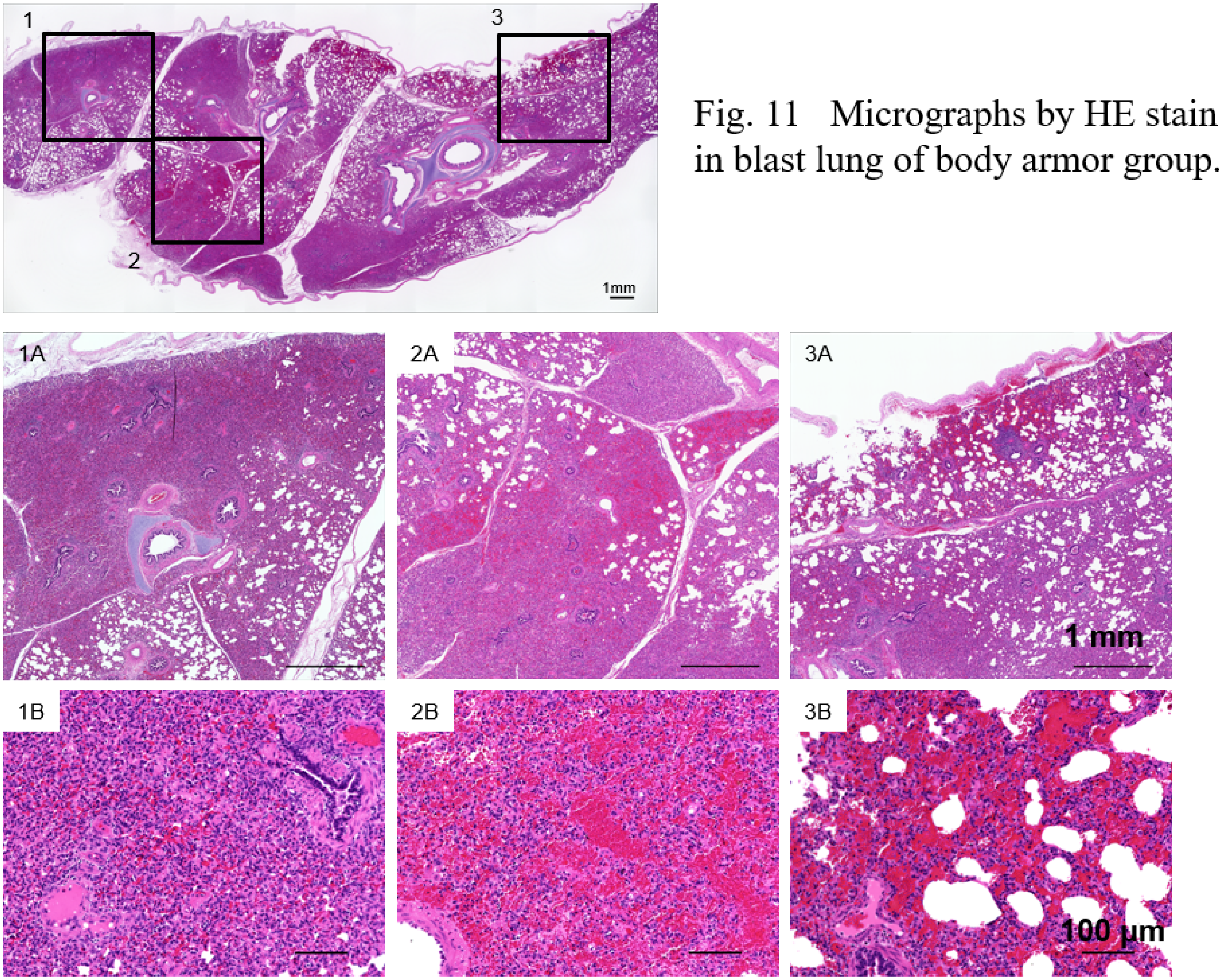


Figure 11

Micrographs after Hematoxylin-Eosin staining of the blast-exposed lung of the body armor group. The severity of lung hemorrhaging was similar between the non-body armor and body armor groups.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- ICME2020Table.pptx