Experimental study of the mechanical response of a physical human surrogate thoracic model impacted by a rubber ball

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Abstract. A physical human surrogate thoracic model was developed using biosimulant materials and the same anthropometry as a healthy adult male, and ballistic tests targeting the physical thoracic model were conducted using a rubber ball with a diameter of 16 mm at low (85-90 m/s), moderate (110-115 m/s), and high (130-135 m/s) velocities. The mechanical response to impact was recorded with sensors embedded into the organs. The internal organs pressure waves exhibited blast-like characteristics for the physical mode. Three parameters of initial pressure in organ were determined from the measured data: internal organs maximum pressure ($P_{\text{max}}$), internal organs maximum pressure impulse ($P_{\text{max}}I$), and the internal organs pressure gradient ($dP/dt$). The three parameters showed the same trend for the three different impact velocities, and these results represented a significant step in developing an understanding of the energy transfer characteristics of ballistic impacts to the human thorax. The results demonstrate the discriminating abilities of the model between threat levels, impact velocities and impact locations. It is found the first time to construct a physical human surrogate thoracic model dedicated to study the mechanism of the blunt injury impacted by the less-lethal ammunition, and the results of this research provided the function of a physical surrogate model of the human thorax which can transfer energy and propagate pressure waves during rubber bullet impacts. The model could be used to evaluate the efficiency of less-lethal ammunition before using it in the course of law enforcement, and the model provides a tool for forensic verification and validation.

1. Introduction
Rubber bullets are used in riot and crowd control, and are designed to incapacitate without causing serious injuries, but the literature reports numerous injuries and also some deaths related to shots by rubber or plastic ammunition, these injuries include penetrating and blunt thoracic trauma, and the victims all come from anti-terrorism operations and battlefields [1-6].

The blunt thoracic trauma caused by the rubber or plastic bullet included skin lesions, rib fractures, and heart, lung, liver or the other organs contusions [1, 3, 5-9], and these injuries were extensively studied through experimentations and simulations, however the mechanical response to blunt thoracic trauma are not well understood at present. For obvious reasons, effects of ballistic blunt thoracic trauma on human body cannot be experimentally studied and must be determined via surrogate.
Several models of ballistic blunt thoracic trauma are available, including human cadavers and large animals [7, 10-13]. In recent years, simulated body tissues such as ballistic gelatin and body simulator were introduced into the ballistic impact and penetrating experiments because of some human-body-like physical characteristics and mechanical response [13-18]. Peter Wahl et al. studied the injuries of the victims impacted by the rubber bullet [1-6, 8-9]. Cynthia A. Bir et al. investigated a surrogate that could be used to predict the risk of penetration of these ammunitions based on the data from biomechanical testing with post-mortem human specimens [13]. Nicolas Prat et al. compared the different responses of using the same rubber projectile to impact human cadavers and biological pig chests, measured the velocity and acceleration of the chest, the rib fracture and the other mechanical properties, got the differences between the human cadaver and pig [10]. Julien Pavier et al. measured the chest displacements, rib accelerations and strains, and rib fractures used different plastic projectiles impact the isolated thorax of porcine cadaver [11]. These studies proved that rubber or plastic bullets could cause serious penetrating or blunt impact trauma to the human body, and by measuring some mechanical parameters during the impact, some researchers established a physical model of human thorax used to study of behind armor blunt trauma.

However, these investigations were all due to victims injured by rubber bullets or conducted using animals as test subjects. These methods have limitations, such as the limited sample size, the difficulties in stalling mechanical sensors in viscoelastic material, and poor data reproducibility. In order to solve these problems J.C. Roberts et al. developed an experimental model of the human torso, constructed a computational finite element model at the same time, and also got the mechanical response of behind armor blunt trauma through the physical and computational model [15, 19]. But few researchers constructed a dedicated physical human surrogate thoracic model serviced for the investigation of mechanical response impacted by a rubber bullet. Besides, as revealed by Pavier’s and Prat’s reports, ballistic blunt thoracic trauma included skin lesions, rib fractures, and internal organs contusions which were associated with increased force and acceleration on the sternum and pressure in organs. These evidences suggested these mechanical responses are the likely mechanism behind such injuries. However, these mechanical responses of human thoracic impacted by the rubber bullets has been poorly documented to date.

The aim of this study was to develop a physical human surrogate thoracic model, and get the mechanical responses of the organs in chest during the ballistic impact by rubber bullet, providing a better understanding about the mechanics of the less lethal blunt thoracic trauma. Several piezoelectric pressure sensors were embedded in the model, force and accelerometer sensor were attached on the sternum, and the mechanical response was measured by these sensors. Three characteristic parameters of the pressure wave were considered: initial maximum pressure ($P_{max}$), initial maximum pressure impulse ($PI_{max}$), and the initial pressure gradient ($dP/dt$), and the sensitivity of pressure parameters to impact velocity was examined. Moreover, the three pressure parameters in organs, the force and acceleration on the sternum impacted by the rubber bullets were further analyzed.

2. Material and methods

2.1. Preparation of the physical human surrogate thoracic model

A “skin-skeleton-organs” human physical thoracic model was developed to measure the mechanical responses to the rubber bullet impact (figure 1). The human physical thorax was molded from approximate geometry as the computed tomography (CT) data of a Chinese adult man. The model includes skin/muscle, internal organs (heart, lungs, liver, stomach), and thoracic skeleton (sternum, ribs, spine). The skin/muscle was made of polyurethane elastomer, while the internal organs and viscera were produced with different viscoelastic materials. Thermosetting resin mixed with calcium phosphate and fiberglass was used as the skeletal system material. Each part of the model was created from the exact geometry of the CT data. Figure 2 shows the finished surrogate organs, the skeleton (ribs, sternum, and vertebral column) along with the completed model with skin.
2.2. Mechanical response parameter recordings

The mechanical responses testing system consisted of a data acquisition system (HBM Gen7i, High speed, Germany, with a former has an eight-channel synchronous data acquisition card, its highest sampling rates can be up to 25 MHz in synchronous channel, we used the rate of 2 MHz, A/D resolution≥18 bit), four piezoelectric pressure sensors, a force and an accelerometer sensor.

The piezoelectric pressure sensors (PCB-113B24, with a measurement range of 0–6.9 MPa,) were embedded in the heart, liver, stomach and the left lung (figure 3) during molding of these organs, and provided the front surface of sensors parallel to and 50 mm away from the front surface of the model. Once the skeleton was completed, the force sensor (PCB-200B05, with a measurement range of 0–22.24 kN) was attached to the middle of the sternum, just behind the impact point; the acceleration sensor (PCB-M350D02, with a measurement range of 0–50 000 g) was attached to the middle back of the sternum, just behind the force sensor. Figure 4 shows the skeleton with sensors in the organs and the completed model with skin.
2.3. **Experimental set-up and procedures**

An integrated synchronization testing system was set up based on the velocity of bullet and the mechanical responses in the physical human surrogate thoracic model. The ballistic experiment synchronization testing system included a launch system, a velocity measuring system and a mechanical response measuring system (figure 5). A 16 mm air gun (figure 6) and 16 mm rubber balls were used in the experimental. The exit of the muzzle is 5 m distance from the targets along the ballistic direction. The impact locations on the model were same to the location of the mechanical sensor on the model. In the experiments, the impact velocities of rubber balls were measured by a high sensitivity laser screen target XGK-350.
During the experiments, used the air gun shot aimed at the location of each mechanical sensor on the model and launched the rubber ball at low, moderate, and high velocities of approximately 85 m/s, 115 m/s, 135 m/s, respectively. At least shot three rounds to each location for each velocity respectively. When the rubber ball went through the laser screen target, a voltage was produced and it could trigger the data acquisition system.

3. Results
The pressure in organs, force and acceleration on the sternum were collected and recorded by the data acquisition system for each ballistic impact test. And data were analyzed with FlexPro 6.0(Weisang GmbH, Germany).

3.1. Internal pressure of the physical thoracic model
The data acquisition system got the time histories of each pressure in the organs simultaneously. As shown in figure 7(a) - (d), the typical waveforms were captured by the pressure sensors in the internal organs of the human physical thoracic model when the rubber bullet impact at different locations with similar velocity (115 m/s). Due to the change in impact location, the value of pressure for the impacted organ has increased significantly while the other organs responses have decreased. And the sensor located in the organ which closest to the location of impact, responded with the largest peak value, and there was a delay in the times of these peak values in going the impact organ to the others, and the trend of the curves in different organs were similar.
Figure 7. Time histories of the pressures in organs, measured for a 16mm rubber ball impacted at the different locations with the velocity of 115 m/s.

Figure 8 shows the time histories of pressure in the organ which is closest to the impact location following the impact of a rubber bullet at low, moderate, and high velocities. It is found from different curves that the characteristics and trend of all pressure curves are well consistent for different velocities, and the higher of the impact velocity, the greater of the pressure, and the waveforms in different organs all exhibited blast-like features characterized by a steep shock front followed by a near-exponential decay.
3.2. Sensitivity of pressure parameters to impact velocity

In this paper, the peak values of pressure in the organ at the impact location were selected to analyze the sensitivity of pressure parameters to impact velocity. Data from the physical thoracic model were examined. The data of pressure were used to calculate the initial maximum pressure ($P_{\text{max}}$), initial maximum pressure impulse ($P_{I\text{max}}$), and the initial pressure gradient ($dP/dt$).

Table 1 lists the calculated $P_{\text{max}}$, $P_{I\text{max}}$, and $dP/dt$ values for each test. For all the three pressure parameters, the values for left lung and liver are significantly higher than those for heart and stomach under low, moderate, and high impact velocities respectively.

![Graph showing pressures in various organs](image)

**Figure 8.** Pressures in the left lung (a), heart (b), liver(c), and stomach (d) following the impact of 16 mm rubber bullet at low, moderate, and high velocities.

| Impact location  | Impact velocity(m/s) | $P_{\text{max}}$(MPa) | $P_{I\text{max}}$ (MPa s) | $dP/dt$(MPa/s) |
|------------------|----------------------|------------------------|-----------------------------|----------------|
| left lung/low velocity |
| 4-L-2            | 84                   | 4.26                   | 1.96                        | 38.57          |
| 4-L-3            | 88                   | 4.53                   | 1.99                        | 44.37          |
| 4-L-4            | 86                   | 4.48                   | 2.00                        | 41.44          |
| left lung/Moderate velocity |
| 4-M-2            | 113                  | 5.46                   | 2.35                        | 59.24          |
| 4-M-3            | 118                  | 5.87                   | 2.35                        | 67.58          |
| 4-M-4            | 111                  | 5.35                   | 2.27                        | 60.55          |
| left lung/High velocity |
| 4-H-1            | 135                  | 5.69                   | 2.68                        | 67.12          |
| 4-H-2            | 130                  | 5.65                   | 2.63                        | 62.59          |
| 4-H-3            | 139                  | 5.92                   | 2.66                        | 70.25          |
| Heart/Low velocity |
| 5-L-1            | 81                   | 1.24                   | 0.39                        | 8.93           |
| 5-L-2            | 90                   | 1.49                   | 0.49                        | 12.36          |
| 5-L-3            | 85                   | 1.31                   | 0.45                        | 10.29          |
| Heart/Moderate velocity |
| 5-M-1            | 115                  | 1.72                   | 0.55                        | 15.65          |
Linear regression analysis was performed to determine the sensitivity of internal organ pressure parameters to ballistic impact velocity. The $P_{\text{max}}$, $P_{I_{\text{max}}}$, and $dP/dt$ values obtained from the internal organs which at the impact location were plotted against impact velocity in figure 9(a) - (c). All of the three parameters were sensitive to impact velocity, corresponding to the analysis of variance finding that differences in $P_{\text{max}}$, $P_{I_{\text{max}}}$, and $dP/dt$ between different impact velocities were significant ($p < 0.01$) respectively.
Figure 9. The maximum pressure ($P_{\text{max}}$) (a), the maximum pressure impulse ($P_{\text{I, max}}$) (b), and the maximum derivative ($dP/dt$) (c) in the internal organs which at the impact location for different impact velocities.

Table 2 shows the correlation parameters ($R^2$, $p$) between the pressure parameters and impact velocity. For each correlation, data from the internal organs under low, moderate and high impact velocities were used. All of the three pressure parameters were correlated well to the impact velocity ($R^2 > 0.98$, $p < 0.0001$).
Table 2. Correlations between pressure parameters and impact velocity (N=9).

| Parameter | $R^2$   | p       |
|-----------|---------|---------|
| $P_{\text{max}}$ |         |         |
| Left lung  | 0.993   | <0.0001 |
| Heart      | 0.998   | <0.0001 |
| Liver      | 0.993   | <0.0001 |
| Stomach    | 0.992   | <0.0001 |
| $PI_{\text{max}}$ |         |         |
| Left lung  | 0.996   | <0.0001 |
| Heart      | 0.997   | <0.0001 |
| Liver      | 0.988   | <0.0001 |
| Stomach    | 0.988   | <0.0001 |
| $dP/dt$ |         |         |
| Left lung  | 0.996   | <0.0001 |
| Heart      | 0.993   | <0.0001 |
| Liver      | 0.994   | <0.0001 |
| Stomach    | 0.984   | <0.0001 |

3.3. Force and acceleration on sternum

In order to provide an experimental method to evaluate the sternum injury, the maximum force ($F$) and acceleration ($a$) on the sternum were collected and analyzed. The skeleton was considered as rigid compared to the rubber bullet. Table 3 lists the forces and accelerations on the sternum impact for different velocities. The average means of force were 3559.0 N, 4214.2 N, and 4394.4 N, and the average means of accelerations were 2217.9 g, 2773.9 g, and 3495.3 g for the physical thoracic model under low, moderate and high impact velocities respectively, and the maximum forces and accelerations show slightly error for the similar impact velocity, the error is caused by the experimental errors, including bullet's raw and possible inconsistency between the impacting point and the two sensors location.

Table 3. Force and acceleration on the sternum.

| Impact velocity | $F$ (N) | $a$ (g) |
|-----------------|---------|---------|
| Low             | 3653.0  | 2237.8  |
| Low             | 3456.7  | 2271.1  |
| Low             | 3567.4  | 2144.8  |
| Moderate        | 4508.6  | 2607.9  |
| Moderate        | 4261.2  | 2717.2  |
| Moderate        | 3872.8  | 2996.7  |
| High            | 4235.8  | 3170.0  |
| High            | 4578.3  | 3746.9  |
| High            | 4369.2  | 3568.9  |

Figure 10 shows the typical time histories of the force and acceleration sensor on sternum for different velocities. The trend of all force curves are well consistent for different velocities, and the same to acceleration, in addition the force and acceleration increased as the impact velocity increased.
4. Discussion
Blunt thoracic trauma including thoracic impact from a less-lethal kinetic ammunition or behind armor blunt trauma may cause many physiologic dysfunctions and physical damages, and these injuries have been extensively described [12, 20-21], and include respiratory dysfunctions, cardiac output alterations, and haemorrhages, which could cause short-term death. Blunt trauma injuries to the thorax resulting from less-lethal kinetic projectile impact have been studied through the victims who came from the anti-terrorism operations and battlefields [5, 8], human cadavers [10, 22], large animals [11]. These types of models have accurate anatomy or physiology response to humans, but these subjects have limits yet, such as they are all difficult to get the mechanical response parameters, the sample size is limited and poor data reproducibility to calculate the injury. In our study, a physical human thoracic model was constructed because of its reusability which may contribute to providing comparatively repeatable mechanical response data. As previously studies, skin lesions, rib fractures, and contusions of internal organs such as heart, lung, liver and stomach have been reported as blunt trauma injuries to thorax. Many authors indicate that the skin and skeleton absorb 13% to 20%of incident energy. A study of transthoracic transmission of blast waves revealed that blast waves pass through the thicker chest of human while maintaining similar to their original magnitude [23]. Therefore, the structure configuration of the “skin- skeleton-internal organs” for human physical thoracic model constructed in this study is suitable for investigating the biomechanical response of rubber bullet impact to the thorax.

Figure 10. The typical time histories of the force and acceleration on the sternum for different velocities.
Internal organs pressure was observed in the internal organs as the result of exposure to ballistic impact by a rubber bullet. However, the pressure waves propagating through the tissue have some of the characteristics of blast waves. Due to these pressure waves, the peak pressure, impulse and derivative of the pressure can be regarded as contributors to injury [23-24]. Thus, three parameters, $P_{\text{max}}$, $PI_{\text{max}}$, and $\frac{dP}{dt}$ were extracted from the recorded pressure curve to describe the characteristics of the internal organs pressure response. $P_{\text{max}}$ corresponds to the maximum value of the first positive phase of the internal organs pressure versus time curve recorded after the impact, and corresponding to local compression of the surrounding tissue under skeleton deflection. $PI_{\text{max}}$ corresponds to the positive area under the internal organs pressure curve, and refers to the amount of energy transferred to the thorax; it depends not only on $P_{\text{max}}$, but also on the duration of the positive phase. $\frac{dP}{dt}$ was the derivative value of the internal organs pressure, at instant $t$. In a previous study on the chest response assessment of post-mortem swine under blast loadings indicated that the internal organs pressure is an appropriate predictor for studying the effects of blunt trauma injuries [23]. Injury criteria based on internal organs pressure have not yet been determined for blunt trauma injury to the thorax. The intrathoracic pressure impulse was also found to be a useful predictor for pulmonary contusion volume after ballistic blunt impact thoracic trauma [24]. Further investigations are needed to clarify the function of intrathoracic pressure as an injury criterion for blunt trauma injuries to the thorax.

In order to obtain a large range of internal organs pressure responses, the physical thoracic model was exposed to ballistic impacts of a 16mm rubber ball bullets at low (85-90 m/s), moderate (110-115 m/s), and high (130-135 m/s) velocities.

Ballistic blunt impacts produced the time histories of internal organs pressures at the same time when the ballistic impact occurred to the surrogate model. And the $PI_{\text{max}}$ and $\frac{dP}{dt}$ were calculated. As shown in figure 7, the sensor located in the organ which closest to the location of impact, responded with the largest peak pressure, and there is a delay in the times of these peak values in going the impact organ to the others, and the trend of the curves in different organs are similar. Due to the change in impact location, the value of pressure for the impacted organ has increased significantly while the other organs responses have decreased. Form table 1 we can find that as the same impact location and similar velocity, the peak values of pressure through different rounds at each of the four sensors were relatively stable, and the difference may be caused by the performance of each organ material. As shown in figure 9 and table 1, $P_{\text{max}}$, and $PI_{\text{max}}$, has the similar regular, and they were all stable and quite sensitive to impact velocity, Prat et al. confirmed that use $PI_{\text{max}}$ to predict the extent of pulmonary lesions and rib fractures in ballistic blunt thoracic trauma was feasible [24].

As shown in figure 10 and table 3, the force and acceleration on the skeleton could be obtained stably by using the model. In a previous study on the thoracic wall behavior in large animals and human cadavers impacted by a less-lethal projectile, the types of 40 mm projectiles (rubber nose with a hard plastic back) was used to impact the post-mortem human subject model with an impact kinetic energy between 70 J and 200 J, and the accelerations were got approximately from 2 400 g to 7 500 g, indicating that the risk of rib fractures correlated well with skeleton accelerations[10]. In addition J.C. Roberts et al constructed a computational finite element and experimental models of the human torso for non-penetrating ballistic impact testing, compared the acceleration of sternum for the two models, the peak accelerations has a good agreement and the sternum accelerations varied by the test conditions [15]. Julien Pavier et al investigated the response in the vicinity of the impact used isolated thoraxes of porcine cadavers, and got the rib accelerations, calculated the deformation of the rib. In this study, it’s found that the force and acceleration are proportional to impact velocity. All the experimental data indicating that the physical thoracic human model is suitable for collecting the mechanical response parameters in less-lethal kinetic ballistic impact, and $P_{\text{max}}$ and $PI_{\text{max}}$ are two promising parameters for predicting blunt injury severity resulting from a less-lethal projectile impact the human thorax. But it’s necessary to point out that although the model have similar anatomy and anthropometry to humans, but lack of living physiology response to less-lethal kinetic ballistic impact, and the mechanical response parameters comparison between the physical model and large animals are not provided.
5. Conclusions
The study investigated the use of a realistic dummy as a research tool for mechanical response parameters testing of a rubber ball to impact the human thorax. A demonstration of the model’s ability to discriminate threats of rubber bullet as different velocities and impact locations has been provided. All of these results provide insight into energy transfer from the rubber bullet to the human surrogate thoracic model by recording the pressure, force and acceleration profiles within biosimulant organs during ballistic impacts. The model is capable of realizing response differences caused by the velocity of rubber bullet, internal structural surroundings, and distance from the point of impact. This device could provide further insight into less-lethal ammunition performance. We hope our work may help predict the mechanical responses of living human to rubber bullet ballistic impact based on surrogate tests. Despite the model can collect the mechanical response parameters of the less-lethal projectile to impact the human thorax, there’s the limitation that the physical model was in lack of living physiology response and the mechanical response parameters comparison between the physical models with live animals.

Future studies will be performed to improve the physical surrogate thoracic model biofidelity including increased anatomic detail and additional material characterization. The mechanical response parameters in the physical thoracic model with that in the live animals or postmortem human subjects will be further compared. Of course, an effort should be made to adjust the material properties of the physical model to correct its response and provide better correlation with the live animals.

Acknowledgments
Authors thank Jing Chen, Jianyi Kang and Zhuangqing Fan of Research Institute of Surgery, Daping Hospital, Army Medical University for their help in conducting the experiments.

This work was supported by the Science and Technology on Transient Impact Laboratory (No.:STTIL61426060103162606007).

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