Assessment of bullet effectiveness based on a human vulnerability model

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ABSTRACT

Introduction Penetrating wounds from explosively propelled fragments and bullets are the most common causes of combat injury. There is a requirement to assess the potential effectiveness of bullets penetrating human tissues in order to optimise preventive measures and wound trauma management.

Methods An advanced voxel model based on the Chinese Visible Human data was built. A digital human vulnerability model was established in combination with wound reconstruction and vulnerability assessment rules, in which wound penetration profiles were obtained by recreating the penetration of projectiles into ballistic gelatin. An effectiveness evaluation method of bullet penetration using the Abbreviated Injury Scale (AIS) was developed and solved using the Monte Carlo sampling method.

Results The effectiveness of rifle bullets was demonstrated to increase with increasing velocity in the range of 300–700 m/s. When imparting the same energy, the effectiveness of the 5.56 mm bullet was higher than the 7.62 mm bullet in this model.

Conclusions The superimposition of simulant penetration profiles produced from ballistic gelatin simulant has been used to predict wound tracts in damaged tissues. The authors recognise that determining clinical effectiveness based on the AIS scores alone without verification of outcome by review of clinical hospital records means that this technique should be seen more as a manner of comparing the effectiveness of bullets than an injury prediction model.

Key messages

- An advanced voxel model based on the Chinese Visible Human data was built.
- A digital vulnerability model was established to assess the effect of bullets on humans using the Abbreviated Injury Scale scores.
- An effectiveness evaluation method of bullets was developed and solved by the Monte Carlo sampling method.
- The effectiveness of rifle bullets was demonstrated to increase with increasing velocity in the range of 300–700 m/s.
- When imparting the same energy, the effectiveness of the 5.56 mm bullet was higher than the 7.62 mm bullet in this model.

INTRODUCTION

Penetrating wounds from explosively propelled fragments and bullets are the most common causes of combat injury experienced by UK service personnel on current operations.[1] The living tissues are damaged by the projectiles through three potential mechanisms. The first is the crushing and cutting effect of the presented surface of the projectile, which is responsible for the creation of a permanent wound cavity. In the second mechanism, the temporary cavity (TC) in the wound tract is created as the surrounding tissue flows away from the contact surface and undergoes deformation—elastic, plastic or both at the same time. Although the TC exists only briefly after the bullet passes through, its creation creates a wound. The size of the permanent cavity (PC), which is the most significant component of tissue damage, depends on the energy of the bullet, tumbling, expansion and fragmentation within the target. The TC produced by the bullet impact can be large, but causes only minor damage to most elastic tissues. The third mechanism is the pressure wave, which has been demonstrated experimentally in distant parts of the body.[2] A recent systematic review of the open literature was undertaken by Breeze *et al*[3] to determine how these mechanisms engender wounding in the living tissues. These authors also recommend that the development of models incorporate the underlying anatomical structures and relate them to these potential wounding mechanisms.[4] It is recognized that the effect of projectiles depends on their effectiveness,the point of impact and the path of the wound tract in the body.

When predicting injury and relating that to bullet penetration, the use of the Abbreviated Injury Scale (AIS) has been proposed.[5] The AIS uses a step function, and every time a threshold is crossed the AIS number increases. In general, more than one damaged organs are contained in the wound tract. For the whole body injury, the New Injury Severity Score (NISS)[6] has been shown to be an effective anatomical score based on the AIS. The NISS is defined as the sum of squares of the three highest scores among the AIS scores from each patient regardless of body regions. When NISS < 16, it is considered to be a minor injury, when $16 \le$ NISS ≤ 25 it is a serious injury, and when NISS > 25 it is a critical injury.

Ballistic gelatin can be used to reproduce the permanent and temporary cavities produced in animal muscles.[7–9] Numerical simulation can be used to reproduce this penetration of bullets into gelatin using different initial conditions. The method of the finite element parametric modelling has been studied based on APDL(ANSYS Parametric Design Language) and the general programming

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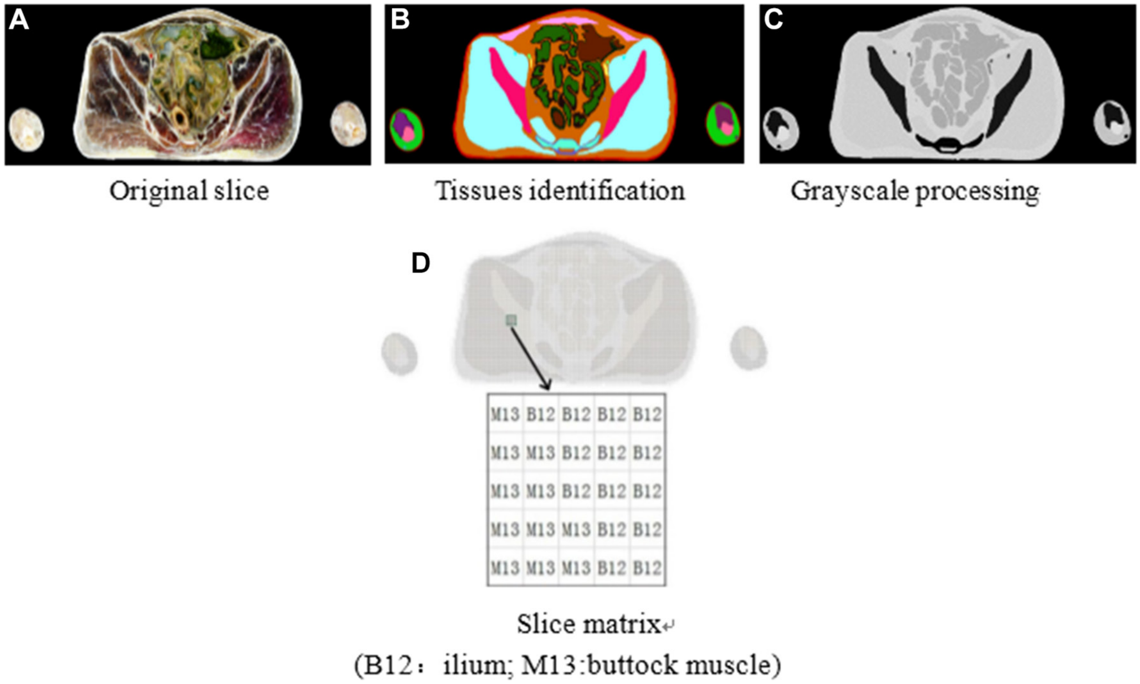

Figure 1 A pictorial view of slice processing.

tool VB(Visual Basic).[10 11] In addition, motion models of rifle bullet and cavity expansion in gelatin penetrations of rifle bullet have been established in a previous study by our group.[12] CT medical imaging techniques have allowed the construction of digital three-dimensional (3D) computational models based on the actual anatomy of individual humans. Recently, computer anatomical models have been introduced into the research of wound ballistics. Stanley and Brown[13] described a computer man anatomical model used as a target for personnel vulnerability analyses. The German Federal Office of Defence Technology and Procurement commissioned a 3D soldier model used in a VeMo-S software to assess the vulnerability of soldiers under the threat of penetrating projectiles with or without body protection.[14]

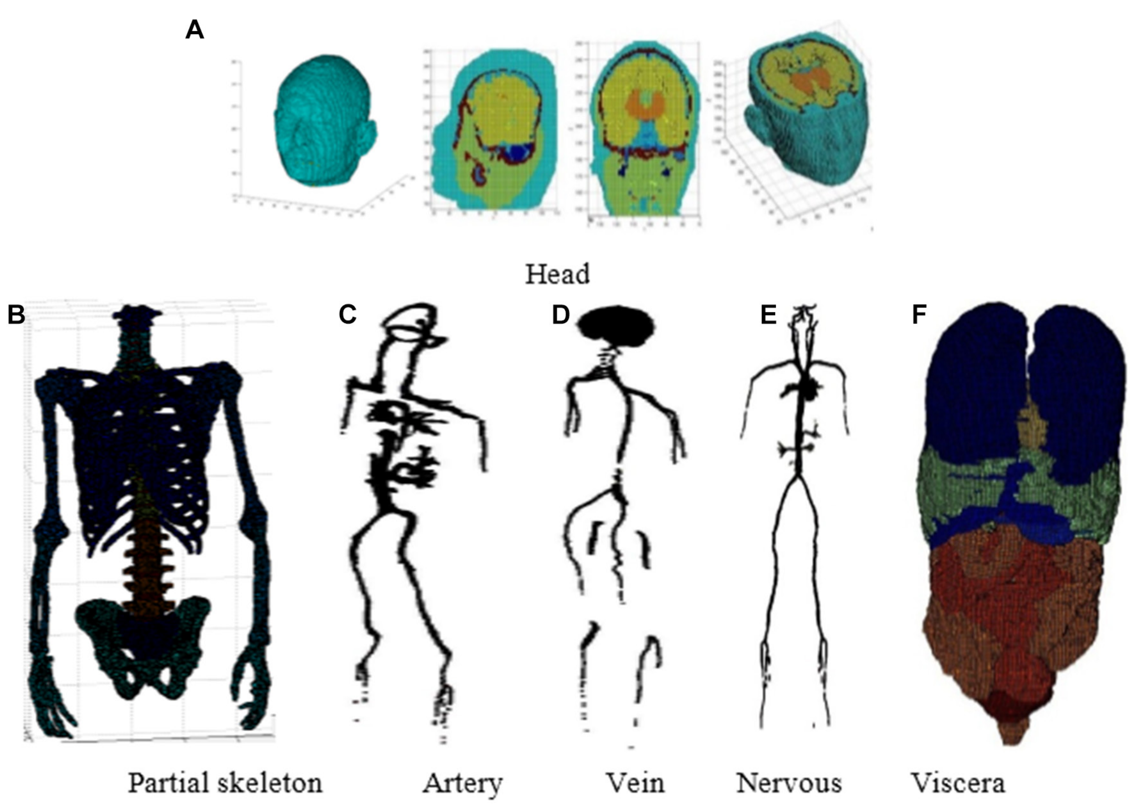

Figure 2 Partial organs and body parts in the voxel model.

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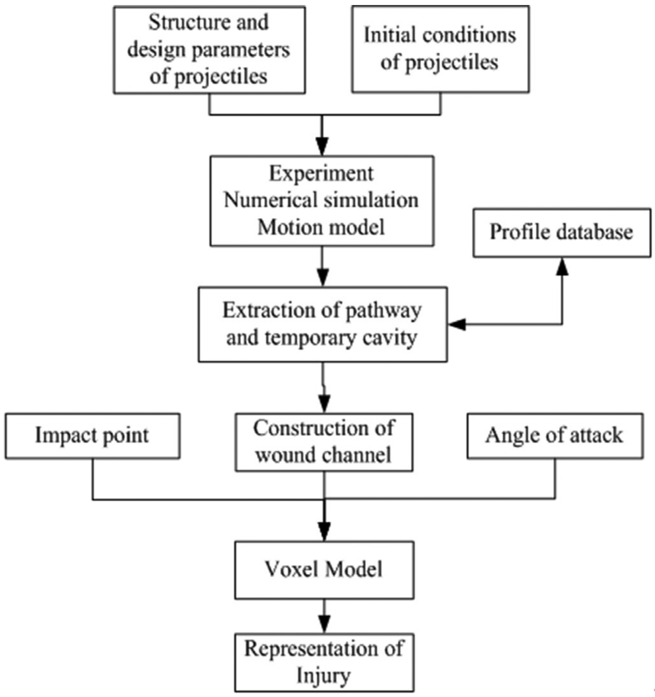

Figure 3 Implementation procedure of the reconstruction of the wound channel.

With further understanding of gunshot wound and development of targets, the methods used to assess bullet effectiveness are changing. In 1927, Hatcher defined the term '*Stopping Power*' (StP) with the assumption that a bullet requires a certain amount of energy E to penetrate the body to sufficient depth.[15] In 1935, Hatcher termed another measure of effectiveness, the '*relative stopping power*' (RSP), by replacing energy by momentum I.[15] In 1948, Taylor[16] proposed a momentum-based effectiveness formula '*Knockout Value*' (KO). Compared with *RSP*, rather than deformation of the bullet, the diameter is adopted in *KO*. In 1975, W Weigel (personal communication) assumed effectiveness to be proportional to the volume of the tract in a wood, and an empirical formula was derived by measuring the depth to which various bullets penetrated fir. In 1982, Sellier proposed the pain caused by the TC as a measure of effectiveness. He made this measure proportional to impact energy and inversely proportional to sectional density.[15] The above measures of effectiveness are determined purely from the bullet's physical/ballistic data (mass and velocity) and arbitrary constants. Introducing the tract in a body (or simulant), the relative incapacitation index (*RII*) was proposed to determine the effectiveness based on Computer Man,[17] while determination of the *RII* required extensive experiments and calculations. In 1984, Matunas[18] proposed an effectiveness formula, '*power index rating*' (PIR), based on the transferred energy and projectile diameter. In 1992, Marshall and Sanow[19] addressed the question of bullet effectiveness from the point of view of practical experience, that is '*street results*' (SR). For each calibre and type of bullet, they calculated the ratio of effective hits to the total number of real-life cases analysed. This percentage figure was then taken as the effectiveness of the bullet. However, the validity of the results is beset by a number of statistical and other pitfalls, just like RII.[15] In 1993, Caranta and Legrain[20] conducted an extensive set of experiments using clay as a simulant, and used the volume of the cavity created by the bullet to assess its effectiveness. In 1994, Macpherson[21] proposed an effectiveness method, '*wound trauma incapacitation*' (WTI), by introducing a criterion, which is the volume of gelatin damaged by the bullet. He determined the volume analytically using empirical constants obtained from experiments with gelatin. But it is difficult to repeat the process to produce comparable results. To sum up, the effectiveness criteria can be mainly divided into three categories, criteria based on the momentum of the bullet (RSP, KO), criteria based on the energy of the bullet (StP, PIR, $W_{H,}$ W_{TH}) and statistics-based criteria (RII, SR, WTI).[15]

Projectile penetration profiles produced in simulants can be used as a criterion to measure the effectiveness of bullets, by relating the profiles to the characteristics of human tissue in the path of the projectile. Based on this presumption, an effectiveness assessment method of bullets was built using an advanced voxel model based on the Chinese Visible Human (CVH).[22] The aim of this study was to compare the effectiveness of different ammunition types on the penetration of tissues in the CVH model using the AIS scores.

METHODS

Establishment of vulnerability model

Contiguous slices from a single patient in the CVH data set were used to populate the anatomy of the model. The patient was a 35-year-old man with a height of 170 cm and weight of 65 kg. The patient was lying supine with the arms parallel and alongside the body. A set of 2110 horizontal cross sections were obtained. The pacing between slices is mainly 1 mm or 2 mm, and some with more details are as small as 0.1 mm. The image size is 3072×2048 pixels and the pixel size is 0.176 mm. Eight hundred and seventy-seven anatomical cross sections were selected and grouped according to body parts, 397 in the leg and foot, 143 in the abdomen, 224 in the thorax and arms, and 113 in the head and neck. The construction of voxel models requires the identification of the boundaries of different organs and tissues on a medical image. During identification, all the pixels belonging to an organ or tissue are assigned the same colour. This process is known as segmentation, as the image is literally divided into smaller segments in the manner. To complete the segmentation of various organs or tissues by different colours, preprocessing steps need to be adopted for slice images, including the increase of contrast, boundary detection and extraction. Then a set of tissue codes were obtained by greyscale processing, and each slice was stored as a 270×180 two-dimensional matrix. A pictorial view of slice processing is displayed in Figure 1.

The voxel model was constructed based on slice matrices with the origin at the corner of the bottom layer. The human model was assembled feet first, progressing in the +z direction until the total configuration was complete. Each layer was divided into cells measuring 2×2×2 mm. The human voxel model consists of 877 layers, containing over 6.5 million elements. One hundred and twenty-three types of tissue were distinguished. Each element was linked to an organ and coordinates. Partial organs and body parts in the voxel model are displayed in Figure 2, respectively.

To simplify the acquirement of wound tract, the PC in the wound tract only considers the path of the projectile in the gelatin, neglecting the influence of the tissue layers on the pathway, and contusion zone is derived by superimposing the TC in the gelatin over the human voxel man. For convenience of intersection calculation, the TC is split into same small volume elements with the human model. The reconstruction of wound tract can be divided into major three steps, as shown in Figure 3. First, the wound profiles are obtained. The initial conditions consist of incidence angle and impact velocity. Second,

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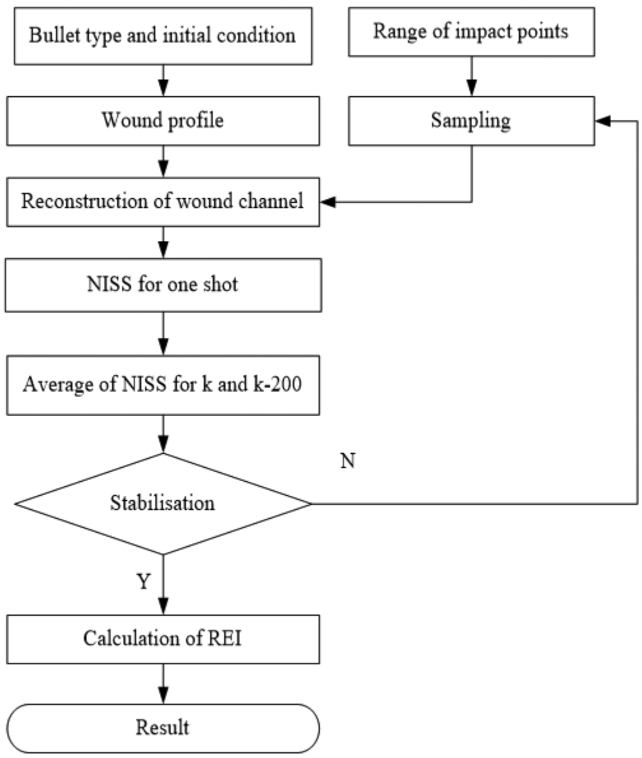

Figure 4 The assessment procedure of bullet effectiveness. NISS, New Injury Severity Score; REI, Relative Effectiveness Index.

the obtained wound profile is constructed and mapped to the voxel model by coordinate transformation in combination with the impact point and angle of attack, and then the intersection of the wound profile with the different body parts is obtained. Finally, the physical damage of the human body is represented along the missile path, and statistical analysis of the injury can be performed.

The degree of damaged tissue in the organs can be quantified by the intersection of the wound profile with body parts. To assess the trauma quantitatively, an index '*New Single Damage Index*' (NSDI) was proposed to assess damaged tissue based on the AIS. The NSDI consists of injury index $NSDI_{PC}$ caused by PC and injury index $NSDI_{TC}$ caused by TC for an organ to distinguish the damage effect of TC and PC on the human body. Ten surgeons with experience in treating gunshot wounds from the Third Military Medical University were asked to evaluate the range of the PC and TC injury levels of each tissue in 3D human geometrical model, including the related blood loss per unit time in each injury level. The minimum and maximum injury levels of each organ were indicated by a range of units between 0 and 6. The threshold volume or the area of the maximum physical damage is set for each organ to fail. It is assumed that TC has no influence on the hard tissues, such as bone. The NSDI is linearly proportional to the volume or area of tissue damaged between its minimum and maximum injury levels. For an organ or tissue, the NSDI is the maximum value of between $NSDI_{PC}$ and $NSDI_{TC}$ as follows:

$$NSDI = max\left(NSDI_{PC}, NSDI_{TC}\right) \quad (1)$$

in which $NSDI_{TC}$ can be calculated by

$$NSDI_{TC} = D\left(i\right)_{min} + F\left(i\right)\left(D\left(i\right)_{max} - D\left(i\right)_{min}\right) \quad (2)$$

where

$$F\left(i\right) = \begin{cases} \frac{\Delta V(i)}{a \cdot V(i)} \Delta V < a \cdot V \\ 1 \Delta V \geq a \cdot V \end{cases}$$

i: injury organ.
$D\left(i\right)_{min}$: the minimum injury level of damaged organ i.
$D\left(i\right)_{max}$: the maximum injury level of damaged organ i.
ΔV: damaged volume or area of organ i.
V: total volume or area of organ i.
a: threshold per cent of maximum damaged volume or area of organ i to fail.

The formula for $NSDI_{PC}$ is similar to equation (2). In calculating $NSDI_{PC}$, the minimum and maximum injury levels are equal for some organs, such as blood vessels and bone for crushes of high-velocity bullet. Blood loss is considered another organ in the model. It is a time-dependent variable, and the injury level due to bleeding can be calculated by

$$NSDI_B = \frac{\sum_{i=1}^{max} \cdot v\left(i\right) \cdot t}{a_2 \cdot V_{blood}} \cdot D_{blood} \quad (3)$$

$NSDI_B$: injury level of blood loss.
V_{blood}: amount of blood in the human body.
a_2: threshold per cent of maximum blood loss to fail.
D_{blood}: maximum injury level of blood.
$v\left(i\right)$: blood loss per unit time, which depends on the degree and type of the damaged organ. For blood vessel, v is related to the damaged cross-sectional area. For liver, spleen and other solid organs, v is related to the damaged volume. Theoretically, if the gunshot wound is not treated, injury by blood loss will be more and more serious.

Without changing the relationship of the NISS and AIS, replacing AIS by NSDI, the gunshot wound can be evaluated by

$$NISS = NSDI_{MAX1}^2 + NSDI_{MAX2}^2 + NSDI_{MAX3}^2 \quad (4)$$

in which $NSDI_{MAX1}$, $NSDI_{MAX2}$ and $NSDI_{MAX3}$ are the three biggest $NSDI$ values of all the damaged organs or tissues.

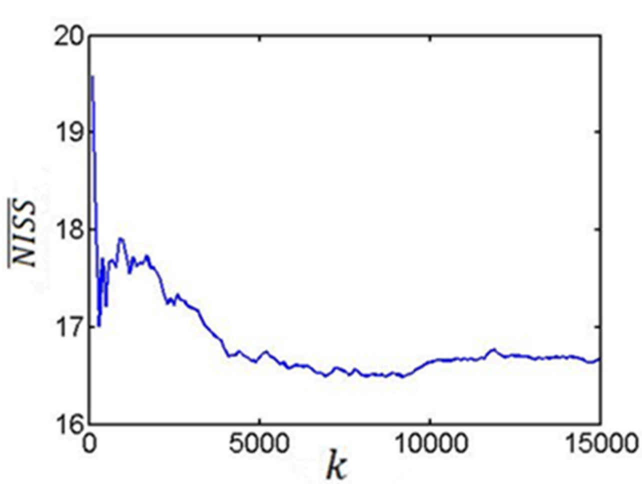

Figure 5 The average of New Injury Severity Score (NISS) varies with *k* for 7.62 mm rifle bullet.

Effectiveness assessment method

Compared with the traditional effectiveness methods, the proposed method considers the characteristics of tissues and impact point. The effectiveness assessment procedure of the bullet is illustrated in Figure 4. The human vulnerability model was treated as a target for the penetration of a specific

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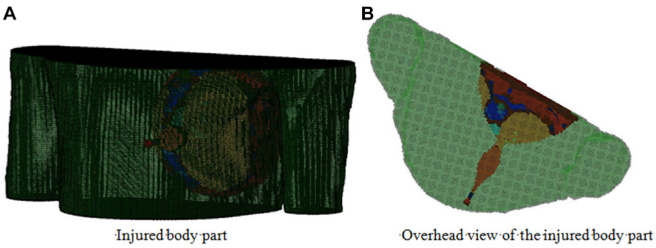

Figure 6 Position of gunshot wound in the voxel model.

type of bullet with an initial condition. The amount of the points is 326, evenly distributed across the front of the human body. A Monte Carlo method is introduced to sample impact points. For each sampled point, the severity of the human body is evaluated and a value of NISS can be obtained for one shot. Sampling quantity k will increase until the NISS average of the samples stabilises. The ratio of the average to benchmark is assumed as the Relative Effectiveness Index (REI) to indicate the effectiveness of the bullet. Here the benchmark is the average value of the NISS of the 7.62 mm rifle bullet with an incidence angle of 3° and impact velocity of 700 m/s for a certain number of samples.

It is because the injury caused by PC is much greater than TC, and high-velocity bullet can easily penetrate through the body. To assess the effectiveness of bullets as distinguished as possible, only $NSDI_{TC}$ is used to calculate the NISS, that is

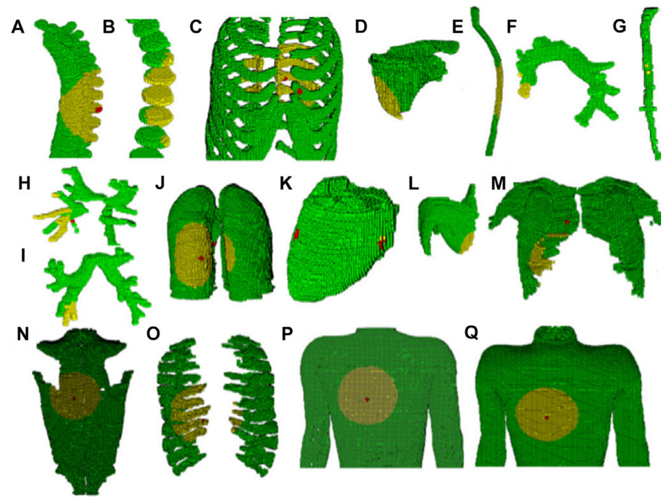

Figure 7 Damaged tissues: red, permanent cavity; yellow, temporary cavity. (A) Thoracic vertebra, (B) intervertebral disc, (C) ribs, (D) shoulder blade, (E) spinal cord, (F) pulmonary artery, (G) azygos vein, (H) pulmonary vein, (I) bronchia, (J) lung, (K) heart, (L) shoulder muscle, (M) pectoralis, (N) dorsal muscles, (O) intercostal muscles, (P) skin, and (Q) soft tissue in chest and abdomen.

$$NISS = NSDI_{TC1}^{2} + NSDI_{TC2}^{2} + NSDI_{TC3}^{2} \quad (5)$$

in which $NSDI_{TC1}, NSDI_{TC2}, NSDI_{TC3}$ are the three biggest $NSDI_{TC}$ values of all the damaged organs or tissues.

Table 1 Statistical analysis of damaged tissues

Tissue type	Total volume (voxel)	Damaged type	Damaged volume (voxel)	Damage percentage	Graphic number in Figure 7
Thoracic vertebra	42 444	PC	23	0.0542	A
		TC	14 428	33.993	
Intervertebral disc	20 101	TC	1661	8.263	B
Ribs	68 233	PC	169	0.248	C
		TC	6800	9.966	
Shoulder blade	18 630	TC	737	3.956	D
Spinal cord	3356	TC	522	15.554	E
Pulmonary artery	3599	TC	59	1.639	F
Azygos vein	899	TC	2	0.222	G
Pulmonary vein	3170	PC	1	0.0603	H
		TC	224	7.066	
Bronchia	4707	TC	141	0.299	I
Lung	433 982	PC	946	0.218	J
		TC	43 571	10.003	
Heart	52 068	PC	933	1.792	K
		TC	2473	4.750	
Shoulder muscle	168 835	TC	1149	0.681	L
Pectoralis	118 233	PC	85	0.0719	M
		TC	1988	1.681	
Dorsal muscles	320 601	PC	102	0.0318	N
		TC	25 279	7.885	
Intercostal muscles	45 906	PC	8	0.0174	O
		TC	3187	6.942	
Skin	220 531	PC	48	0.0218	P
		TC	10 230	4.639	
Soft tissue in chest and abdomen	1 148 318	PC	173	0.0151	Q
		TC	27 221	2.371	

PC, permanent cavity; TC, temporary cavity.

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Table 2 Damage index of organs in the trauma caused by 7.62 mm rifle bullet

Tissue type	NSDI	Tissue type	NSDI
Thoracic vertebra	3	Lung	4
Intervertebral disc	0	Heart	6
Ribs	1	Shoulder muscle	0.2
Shoulder blade	0	Pectoralis	0.5
Spinal cord	2.93	Dorsal muscles	2.36
Pulmonary artery	1.16	Intercostal muscles	2
Azygos vein	1.016	Skin	0.18
Pulmonary vein	4	Soft tissue in chest and abdomen	0.28
Bronchia	1.2		

NSDI, New Single Damage Index.

Equation (6) is used to judge whether the average of the NISS meets the requirement. REI was obtained by equation (7).

$$\left|\frac{\bar{NISS}_k - \bar{NISS}_{k-200}}{\bar{NISS}_{k-200}}\right| < 0.001 \quad (6)$$

in which $\bar{NISS}_k$ is the mean value of NISS for k samples.

$$REI = \frac{\bar{NISS}_k}{\bar{NISS}_{7.62}} \quad (7)$$

where $\bar{NISS}_{7.62}$ is the benchmark.

The wound profiles of the 7.62 mm rifle bullet penetrating gelatin with an incidence angle of 3° and impact velocity of 700 m/s were extracted from simulated results. $\bar{NISS}_k$ was calculated for the different amounts of samples. The relation between $\bar{NISS}$ and k was obtained, as shown in Figure 5. It can be concluded that when $k > 7000$, $\bar{NISS}_k$ tends to be stable and meets the requirement of equation (7). Then $k = 9000$ and $\bar{NISS}_{7.62} = 16.5$ are assumed as the basis for the effectiveness assessment of bullets.

RESULTS

Gunshot in the chest by 7.62 mm rifle bullet

The wound tract of the human body shot in the chest with a 7.62 mm rifle bullet at an impact velocity of 668 m/s and attack angle of 0° is given in Figure 6. In the figure, tissues are distinguished by colour. Statistical analysis of damaged tissues is presented in Table 1, in which TC indicates injury due to temporary cavity and PC due to permanent cavity. Each damaged tissue is represented in Figure 7 independently, in which green indicates undamaged tissue, yellow the TC injury and red the PC

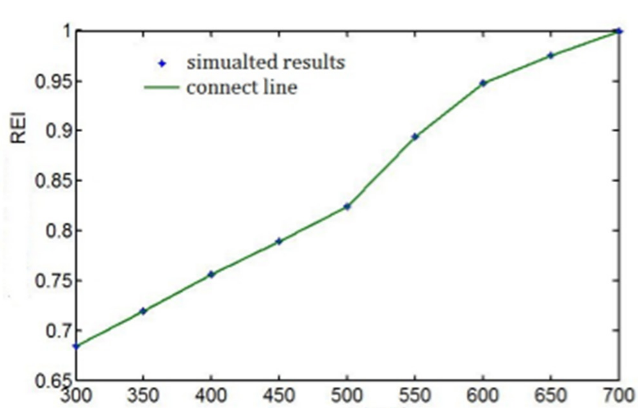

Figure 8 Change of Relative Effectiveness Index (REI) with impact velocity for 7.62 mm rifle bullet.

Table 3 Comparison of the effectiveness of 7.62mm and 5.56mm rifle bullets

Calibre of the rifle bullet (mm)	Impact energy (J)	Impact velocity (m/s)	Incidence angle (°)	Relative Effectiveness Index
7.62	987.5	500	3	0.825
5.56	987.5	702.7	3	1.002

injury. The injury in the chest was evaluated based on the injury assessment measure. The damage index of the organs is listed in Table 2. It can be seen that the three biggest NSDIs are 6 in the heart, 4 in the lung and 4 in the pulmonary vein. Because of the existence of NSDI=6, the severity of the human body is NISS=75, which means the human dies immediately after the trauma.

Effect of impact velocity on effectiveness

To research on the effect of impact velocity on the effectiveness, the gelatin penetration of the 7.62 mm rifle bullets with different impact velocities (300 m/s~700 m/s) and an incidence angle of 3° was simulated based on the motion model of rifle bullet[12] and cavity expansion in gelatin penetrations of rifle bullet. The pathway of the bullets and TC in gelatin were extracted from the calculated results. The effectiveness of the 7.62 mm rifle bullet was evaluated in the proposed method based on the vulnerability model with k=9000. Change of REI with the impact velocity is shown in Figure 8. It can be found that the effectiveness of the bullet is almost increased linearly with increasing velocity in the range of 300–500 m/s. In the range of 500–700 m/s, the effectiveness increases rapidly and then continues with growth dropping.

Effectiveness comparison of rifle bullets

The effectiveness of a 7.62 mm rifle bullet and a 5.56 mm rifle bullet with the same impact energy were compared. $k = 9000$ and $\bar{NISS}_{7.62} = 16.5$were used in the model. The initial parameters and the results are listed in Table 3. It can be found that the 5.56 mm rifle bullet is better than the 7.62 mm with the same energy and incidence angle in terms of the effectiveness on human body.

DISCUSSION

To assess the effect of bullets on livings, an effectiveness assessment method of bullets was proposed based on the human vulnerability model. Wound profiles in simulant were used as criteria, and the characteristics of damaged tissues in the wound tracts were considered. In the proposed method, an advanced voxel model based on the CVH data was built, consisting of 123 kinds of tissues. Distinguishing the damage effect of TC and PC, vulnerability model was established based on the voxel model, reconstruction of wound tract and injury assessment measures, in which wound profiles are obtained by simulating the gelatin penetration of bullets. Further, an effectiveness evaluation method of bullets was developed and solved by the Monte Carlo sampling method. The feasibility and effectiveness of the proposed method are verified by example analysis.

The authors do recognise that this approach to effectiveness assessment of bullets has a number of limitations. Predicting effectiveness based on the AIS scores alone without verification of outcome by review of clinical hospital records means that this technique should be seen more as a manner of comparing effectiveness of bullets than an injury prediction model.[4] The

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PC and TC are obtained based on gelatin penetration, not accounting for the possibility of ricochet, the influence of different tissues on the bullet path and the fragmentation of projectile in the penetration process. In addition, the model originates from only one human scan, which is potentially not reflective of the wider population. Finally, the wound tract within the model does not consider the effect of the TC on bone and hollow viscuses, and we would recommend further research in this area.

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Competing interests None declared.

Patient consent Obtained.

Ethics approval This study was approved by Laboratory Animal Welfare and Ethics Committee of the Third Military Medical University.

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