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## Effect of energy absorbing mechanisms on the blunt thoracic trauma caused by ballistic impacts

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**Abstract:** military and law enforcement officials have been using kinetic energy non-lethal weapons ranging from rubber bullets to projectiles with foam in situations which do not warrant the usage of lethal force. On many occasions, non-lethal projectiles have caused serious injuries. Therefore, a scholastic study was carried out to see the effect on the injury caused by the projectiles embedded with various energy absorbing mechanisms. Projectile – target interaction (kinetic energy transfer or energy gained by the target and Total energy of the projectile) plays a vital role in understanding the effect of the projectile on the target. Therefore, to evaluate the effect of the energy absorbing mechanisms on the blunt thoracic trauma, target considered should emulate the human thorax as far as the projectile-thorax interaction is concerned. A fully validated FE model of the thoracic surrogate (FE model of the MTHOTA surrogate of the thorax, which is validated with the human response corridors developed by Wayne State University's researchers) was impacted with a typical foam nosed projectile at a speed of 90 meters per second. A collapsible Aluminum foil attached to the hollow foam nose of the projectile and impact simulations were carried out for different thicknesses of the foil (0.3 mm and 0.5 – 4.0 mm with an increment of 0.5 mm). To nullify the effect of the variation in the mass and also for effective comparison, impact speed was adjusted so that kinetic energy of the projectile remain same for all analyses. For the design of the collapsible mechanisms considered for the study, foil thickness less than 2 mm, though foiled structure got collapsed it didn't absorb considerable amount of energy. More than 2 mm thickness, foil didn't collapse properly and whole projectile acted as stiff/solid round and produced more injury. Dynamic force response, dynamic displacement response, effect of the aluminum foil on the thoracic injury in terms of  $VC_{max}$  etc., were presented in this paper.

**Keywords:** blunt chest trauma, wood baton, TPE foam nose, MTHOTA surrogate, projectile-thorax interaction,  $VC_{max}$ .

### 1 Introduction

With the increase in peace-keeping missions, with an increase in situations where civil police called upon to subdue subjects of interest without application of the lethal force, military research organizations and law enforcement agencies have invested more time and resources to develop a wide variety of non-lethal weapons, ranging from chemical irritant sprays to impact munitions. This paper focuses on the impact munitions.

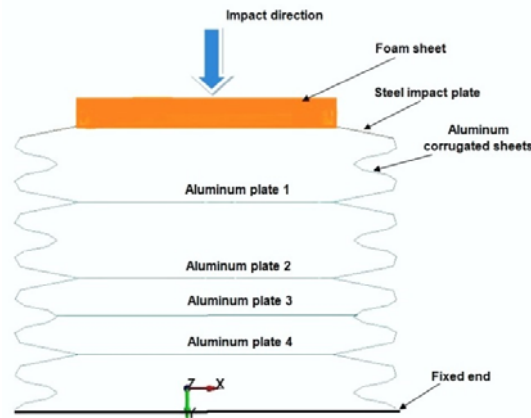
Though the application of non-lethal munitions intended incapacitate or deter the individual without causing injuries that require medical treatment more than a simple first aid, there have been many reported fatalities and serious injuries with the usage of these weapons. More than 55000 rubber bullets were fired to control the civilian riots in Northern Ireland during the six years period from 1970-75. After careful analysis of the medical professionals, it was estimated that rubber bullets caused five deaths, seriously injured more than 500 persons, while many sustained injuries that require hospitalization. During most recent confrontations of the Israeli-Police to subdue the Israeli-Arab rioters, usage of the rubber bullets have caused 13 deaths and many more serious injuries ( Krausz *et al* [1], Mahajna *et al* [2]). Similarly, during the year 1996, more than 8000 plastic baton rounds were fired to control the riots. More than 155 persons sustained serious injuries and of these 45 persons were hospitalized (Steele *et al* [3]). Even in North America five deaths and many injuries caused by the non-lethal weapons were reported (James [4]). Of these five deaths, four were dead due to the serious structural damage to the thorax and the other one died because of commotio-cordis. In order to reduce the fatalities due to

thoracic trauma caused by non-lethal projectile impacts, research organizations have developed direct impact munitions with the foam nose or breakable tip, which reduces the probability for severe injuries. Some of such munitions are eXact iImpact 1006, NS Spartan, NP and B&T and TASER-XREP projectiles. To investigate the effect of energy absorbing mechanisms on the blunt thoracic trauma, Thota *et al* [5] carried out scholastic study by impacting the thorax of the Hybrid III deformable dummy with a projectile, foam nose of which embedded with an Aluminum foil. However, the review carried out by the present authors revealed that thoraces of ATDs are not suitable as surrogates for blunt ballistic applications.

In order to study the effect of foam nose and also to investigate the effect of suitably integrated collapsible Aluminum with the projectile, on the blunt thoracic trauma, non-linear FEA simulations were carried out, in which a fully validated FE model thorax (MTHOTA) developed by Thota *et al* [6] was employed.  $VC_{max}$  values, biomechanical responses and projectile-thorax energy interactions pertinent to the present study were presented in this paper.

## 2 Mechanical THORax for Trauma Assessment (MTHOTA)

By measuring force-time, deflection-time and force-deflection responses of thoraces of nine human cadavers when subjected to three impact conditions (140 gram wooden baton at 20 m/s and 40 m/s impact speeds, 30 gram wooden baton at 60 m/s), Wayne state university researchers established human response corridors. A finite element model of the thorax surrogate made up of corrugations of the Aluminum was developed and correlated with these human response corridors (Bir *et al* [7], Bir *et al* [8], Thota *et al* [9], Thota *et al* [6]). Cross section of the FE model of the thorax surrogate is shown in the Figure 1.



**Figure 1:** Cross section of the MTHOTA FE model thorax surrogate

Impact conditions used for the development of the human response corridors and impacts of the solid sports balls fall under the category of blunt ballistic impacts (i.e., projectile of mass 20 – 200 gram with impact speeds of 20 – 250 m/s). Therefore, MTHOTA can be effectively used for the evaluation of the blunt thoracic trauma caused by the solid sport ball impacts. MTHOTA facilitates the calculation of the trauma in terms of  $VC_{max}$ .

Depending upon the convenience, one of the two methods to evaluate the  $VC_{max}$  using MTHOTA FE model surrogate, as described by Thota *et al* [6] was employed throughout the paper. MTHOTA surrogate is correlated with the cadaver test results (Bir *et al* [7]) such a way that equation (1) provides the  $VC_{max}$  value in m/s for all blunt ballistic impacts.

$$VC_{max} = S. (Y_{max}/D). (Y_{max}/T) \quad (1)$$

Where,

$VC_{max}$  = Viscous Criterion in m/s

S = Scaling factor = 0.366 and 1.3 for method-1 and method-2 respectively

$Y_{max}$  = Max deflection of the impact plate (method-1) in mm

= Max deflection of the impact plate with respect to the plate-3 (method-2) in mm

D = Dummy constant = 110 mm and 180 mm for the method-1 and method-2 respectively.

T = Time at which deflection is maximum

### 3. Methodology

At first, to highlight the efficacy of the foam nose as an energy absorbing mechanism, non-linear CAE simulations were carried out to evaluate the thoracic trauma caused by three projectiles, two with foam noses and the third is a wooden baton, with equal kinetic energy. Further study was carried out to investigate the effect of collapsible Aluminum foil when integrated with the projectile.

In all, the following non-linear FEA simulations were carried out and in all impact cases, MTHOTA has been employed as the thorax surrogate.

- a) Projectile with foam nose with the design similar to XM1006 (here onwards referred to as P1). FE model of the projectile was prepared using the design details of XM 1006 from the technical report published by Lyon [10]. As foam nose properties were not given in the report, an experimentally obtained TPE foam material data published by Thota *et al* [6] was utilized for the foam nose.
- b) Projectile with foam nose that is equivalent to NS Spartan projectile (here onwards referred to as P2). FE model of the projectile was prepared with PVC base and foam nose material properties published by Nsiampa *et al* [11].
- c) Wooden baton projectile with mass 140 g, length 100 mm and diameter 37 mm (here onwards referred to as P3). FE model of the projectile was prepared with the wood material properties published by Green *et al* [12], Green [13] and Murray *et al* [14].
- d) P1 with hollow foam nose, embedded with a collapsible Aluminum foil of thicknesses 0.5 – 4.0 mm with an increment of 0.5 mm.
- e) P1 with hollow foam nose embedded with a 0.3 mm thick Aluminum foil

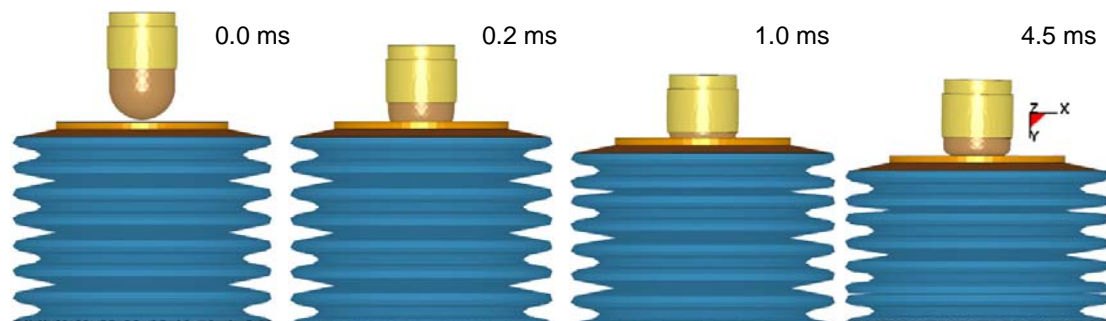
Former three simulations, impact velocity used such a way that all projectiles initial kinetic energy was equivalent to 112 J, so that effect of foam nose could be highlighted. Later two cases of simulations were carried out to investigate the effect of the collapsible Aluminum foil.

### 4. Results and discussion

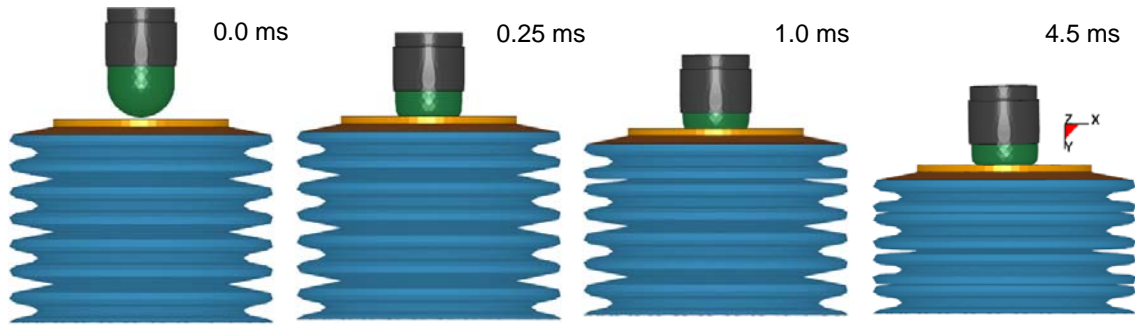
#### 4.1 Effect of the foam nose on the blunt thoracic trauma

Non-linear FEA simulations were carried out by impacting the MTHOTA surrogate with projectiles P1, P2 and P3 with 90.6 m/s, 73 m/s and 40 m/s impact speeds respectively, such a way that kinetic energy of the projectile at the time of impact would be 112 J in all three cases.

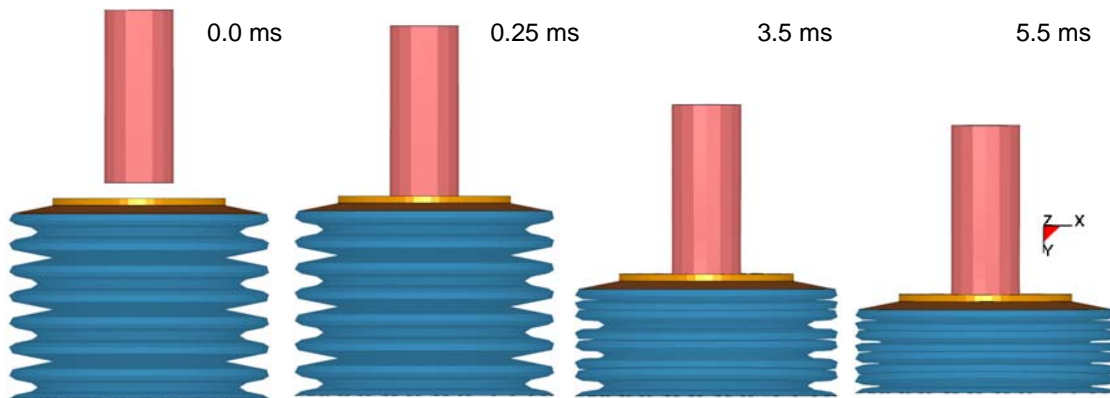
Using the time histories of the nodes of the impact plate and plate-3, deflection – time responses were elicited for all three cases. Stages of the MTHOTA and P1, P2 and P3 projectiles during the impact and dynamic deflection responses for all three cases were as shown in the Figure 2, Figure 3, Figure 4 and Figure 5, respectively.



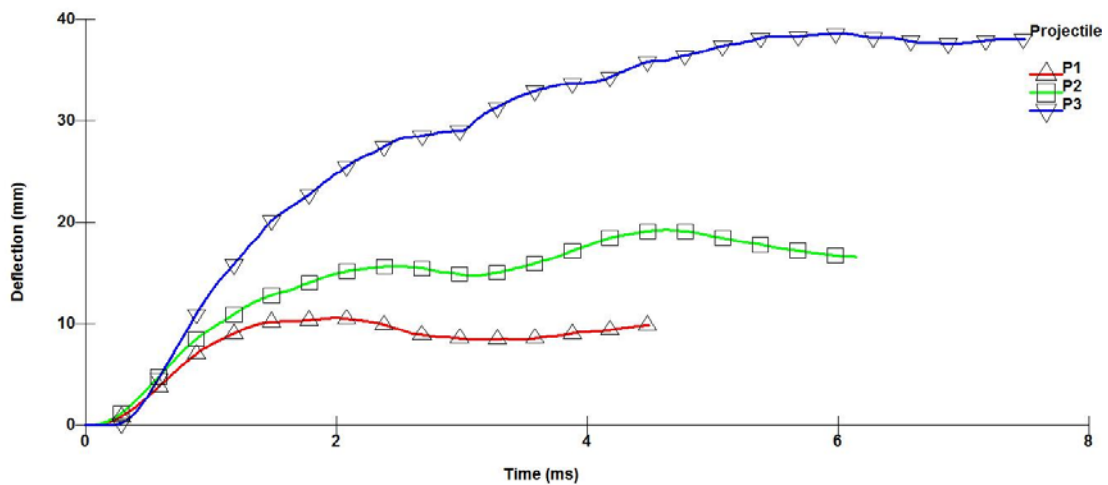
**Figure 2:** Stages of the projectile P1 and the surrogate MTHOTA during the impact



**Figure 3:** Stages of the projectile P2 and the surrogate MTHOTA during the impact



**Figure 4:** Stages of the projectile P3 and the surrogate MTHOTA during the impact



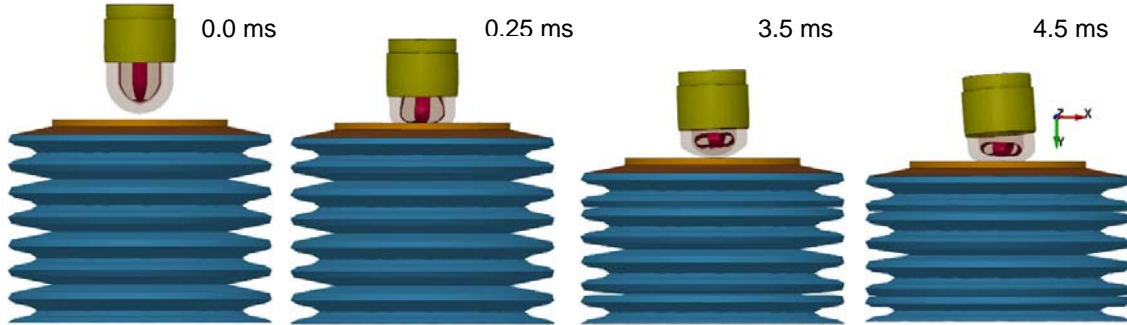
**Figure 5:** Relative deflection of the impact plate with respect to the plate-3

Maximum deflections of the impact plate with respect to the plate-3, obtained from the Figure 5, the equation (1), P1, P2 and P3 projectile impacts yielded  $VC_{max}$  values 0.388, 0.6 and 1.87 m/s respectively.  $VC_{max}$  values clearly shows the influence of the foam on the blunt thoracic trauma.

In order to elicit the effect of the collapsible Aluminium foil, only P1 projectile was considered.

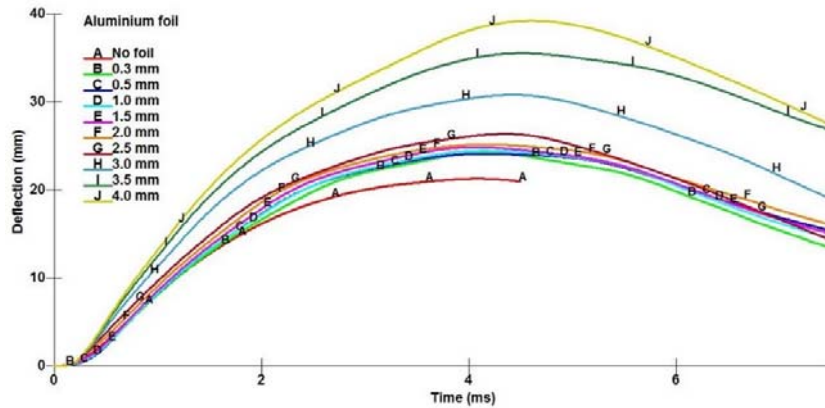
## 4.2 Projectile P1 with 2/3<sup>rd</sup> hollow nose, integrated with Aluminium foil

Collapsible Aluminium foil of nine thickness cases (0.3 mm and 0.5 – 4.0 mm with an increment of 0.5 mm) were considered for the study. Stages of the 'P1 with 2.0 mm thick foil' and the surrogate during the impact were as shown in the Figure 6.



**Figure 6:** Stages of P1 projectile with 2.0 mm thick foil and the surrogate during the impact

Deflection-time responses for all impact cases were as shown in the Figure 7.



**Figure 7:** Deflection-time response (from the nodal histories of the impact plate)

From the output of every case,  $VC_{max}$  values were elicited by substituting the maximum deformation of the impact plate and S & D values for the method-1 in the Equation (1).  $VC_{max}$  values were given in the Table 1.

**Table 1:**  $VC_{max}$  values due to impacts with P1 and foil

Foil thickness (mm)	Projectile mass (g)	Velocity (m/s)	Energy (J)	$VC_{max}$ (m/s)
No foil	27.31	90	110.61	0.378
0.3	27.31	90	110.61	0.46
0.5	27.66	89.43	110.61	0.38
1	28.51	88.09	110.61	0.4
1.5	29.35	86.82	110.61	0.421
2	30.2	85.59	110.61	0.426
2.5	31.04	84.42	110.61	0.425
3	31.9	83.28	110.61	0.59
3.5	32.73	82.21	110.61	0.78
4	33.58	81.17	110.61	0.92

Variation of the kinetic energy, internal energy and total energy of the surrogate during the impact time were as shown in the Figure 8, Figure 9 and the Figure 10 respectively.

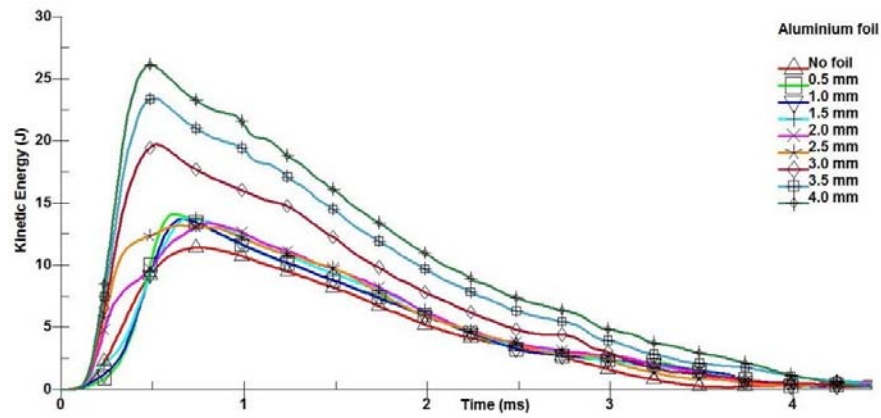


Figure 8: Kinetic energy of the MTHOTA surrogate during the time of impact

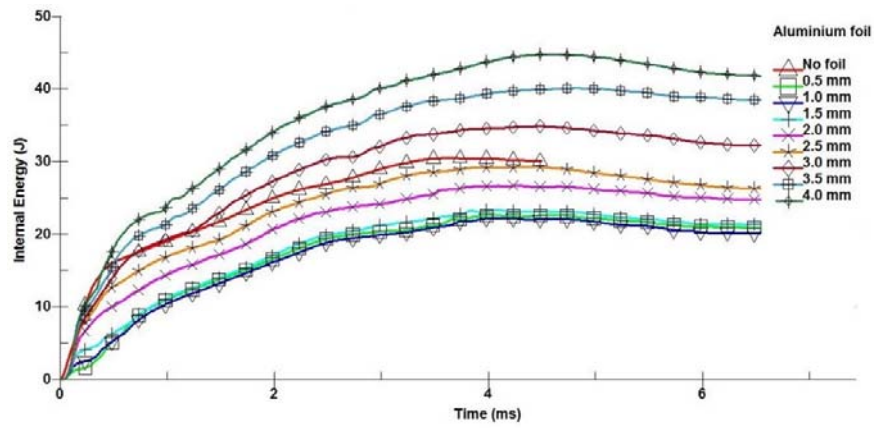


Figure 9: Internal energy of the MTHOTA surrogate during the time of impact

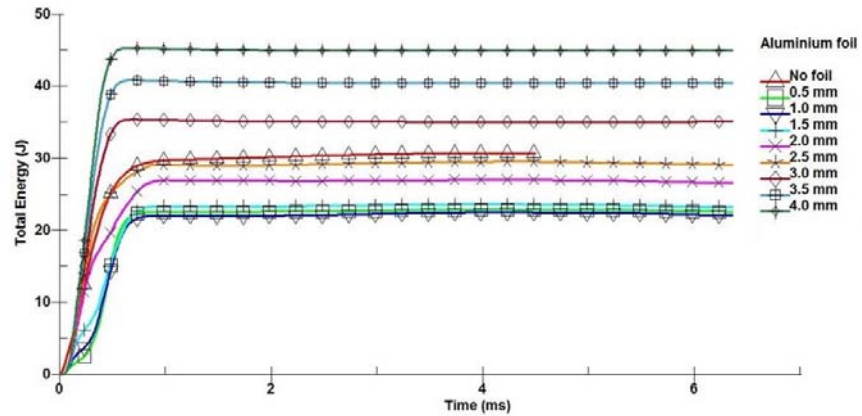


Figure 10: Total energy of the MTHOTA surrogate during the time of impact

$VC_{max}$  values obtained for P1 and P1 with 0.3 thick Aluminium foil have got very significance in the study. Because, weight of the 0.3 thick foil was equivalent to the weight of the foam removed from the nose. Therefore, these two cases can reveal the effect of the Aluminium foil, as all other parameters kept same. Aluminium foil of 0.3 mm thick has increased the blunt thoracic trauma as the  $VC_{max}$  value was more than that of the P1 with full foam nose. 0.3 thick foil is too flimsy and could not absorb much energy and exposed the thorax to the stiff PVC base of the projectile, which increased the  $VC_{max}$  or thoracic injury. With the increase in the thickness of the foil, up to 2.5 mm, foil absorbed enough amount of energy but could not reduce the blunt trauma. Further increase in the thickness, due to small size, the foil became too stiff and could not get crumpled and increased the impact on the surrogate. The effect of foil is apparent from the  $VC_{max}$  values presented in the Table 1.

From the Figures 8 – 10, it is clear that total energy (kinetic energy and internal energy) of the MTHOTA surrogate is less with the P1 with foil up to 2.5 mm than that of the P1 with full foam nose. Though imparting lesser energy causes lesser trauma to the thorax, in this paper only  $VC_{max}$  values were considered for the discussion.

## 5. Conclusions and recommendations

From the outcome of the study (from the  $VC_{max}$  values) obtained for the P1 with Aluminum foil, it was clear that Aluminum foil was not effective as an energy absorbing mechanism. Small size causes an adverse effect in a complete range of thicknesses. Thin foil exposes the thorax to the hard/stiff PVC base and also absorb very little energy. P1 projectile with thinner foil cause more blunt thoracic trauma. With the increase in thickness, due to small size, the foil becomes stiffer and do not collapse or crumple. Therefore, the projectile will not get decelerated and impacts the thorax like a stiff object and causes more trauma. In a nutshell, collapsible foils are not suitable for reducing the risk of higher thoracic injuries due to non-lethal ammunition.

Further study may be required with different configurations of the collapsible foil to find out the suitability of such foils in the non-lethal munitions.

Though P1 and P2, both considered for the study were with foam nose, injury caused by the P1 would be very less than P2. Therefore, to alter the severity of the injury caused by a projectile, the better option would be suitably changing the foam nose design and material.

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