

Development and validation of a thorax surrogate FE model for assessment of trauma due to high speed blunt impacts

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Abstract

Without being able to evaluate blunt thoracic trauma in terms of an acceptable injury criterion, it is not possible to develop or validate non-lethal projectiles, bullet proof vests and chest protectors for sports personnel etc. In order for the assessment of the blunt trauma caused by high speed projectiles, a novel design of a mechanical surrogate of the thorax (Mechanical THOrax for Trauma Assessment: MTHOTA) was conceptualized. An iterative impact analyses in the virtual testing environment were carried out by impacting the finite element model of the mechanical thorax with 37 mm diameter, 100 mm long wooden baton weighing 140 grams (20 m/s and 40 m/s impact speeds) and 37 mm diameter, 28.5 mm long wooden baton weighing 30 grams with 60 m/s impact speed. From the output of every simulation, force dynamic response (force-time), deflection dynamic response (deflection-time) and force-deflection response were elicited and compared with the corresponding human response corridors developed by Wayne State University's researchers. By suitably changing the design parameters of the mechanical surrogate, simulation iterations were continued till the responses were correlated with the human response corridors. Values of viscous criterion (VC_{max}), product of maximum chest deflection and the rate at which chest deforms, obtained from MTHOTA were in very good agreement with those obtained from the cadaveric test data. The methodology, concept and validation of the MTHOTA have been presented in this paper.

Key words : Blunt thoracic trauma, Surrogate, Viscous injury, Sports injury, Viscous criterion, Chest protective equipment, Less-lethal ammunition, MTHOTA, 3-RCS

1. Introduction

In order to develop and validate non-lethal weapons, bullet proof vests, chest protectors for sports personnel, it is essential to have the greater insight into the response of the human thorax subjected to high speed blunt impacts by projectiles of low mass. Blunt projectiles with mass of 20–200 g with impact speed 20–250 m/s represent the ballistic impacts pertinent to the contact & collision sports activities and non-lethal ammunition (Bir, 2000; Bir, et al., 2004). In past few decades, law enforcement agencies, military and defense forces have started using less-lethal weapons which were designed to temporarily incapacitate the subject in the situations where lethal force is not warranted. Very basic requirement of non-lethal weapons is that projectile impact should give short duration pain, sufficient to deter the subject and should not cause any serious injuries, which require hospitalization and medical treatment (Widder, et al., 1997; Widder, et al, 2003; Koene, et al., 2008). Depending upon the amount and the rate chest deformation, ribs get deflected and compress the internal organs and vessels in their way. Ribs get fractured, when the deflection exceeds the tolerance limit. Compression of the rib cage without any fractured ribs can cause minor injuries, such as bruises and cuts which requires only first aid. Depending upon the location and the number of ribs fractured, internal organs get penetrated with the broken ribs, which lead to serious thoracic injuries such as pneumo thorax, hemothorax, flail chest, lungs contusion, punctured liver, sternal fractures, heart contusion, fractured aorta etc. Though probability is very less,

aftermath of the blunt trauma could be ventricular septal defect (VSD), which is fatal if untreated. Design of the non-lethal weapons should be such that they should not cause any of these serious injuries mentioned above to the subject. Validation of the non-lethal projectiles is very challenging, as blunt thoracic trauma caused by impact ammunitions is greatly influenced by the location of the impact, projectile mass, speed and characteristics of the subject such as, age, gender, built, race, cloths worn etc. (technical report by Hubbs & Klinger, 2004). Due to that blunt projectiles such as, stiff plastic baton, wood baton projectiles, plastic and rubber bullets etc. reported to have caused serious injuries and fatalities (Hughes, et al., 2005; Krausz & Mahajna, 2002; Maguire, et al., 2007; Mahajna, et al., 2002; Rocke, 1983; Sheridan & Whitlock, 1983). Therefore, it is essential to validate (confirm that the effect is non-lethal) the non-lethal weapons by measuring the blunt thoracic trauma in terms of known engineering parameters, well before putting them into the use. In this paper authors have developed a novel concept of finite element (FE) model of a mechanical surrogate of the thorax, MTHOTA, to evaluate the blunt thoracic trauma in terms of a viscous criterion (VC_{max}).

Many research studies indicated that the blunt chest injuries involving motor vehicle accidents constituted more than 75% of overall such injuries and the blunt thoracic trauma alone was responsible for approximately 25% of overall accidental deaths (Hoyert & Hu, 2012; Mancini, 2012; Vlessis & Trunkey, 1997). In the past few decades, numerous experimental studies (such as pendulum impact tests, drop tests, simulated crash with volunteers, human cadavers and anesthetized animals as test subjects) had been carried out by various researchers and gained great insight into the various aspects of impact biomechanics of the thorax. Thoracic injury mechanisms, responses of the thorax (elastic, viscous and inertial responses) to the impact in terms of known engineering parameters and human tolerance limits (injury criteria such as acceleration, force, average spinal acceleration, thoracic trauma index, chest compression, viscous criterion etc.) were developed. Therefore, impact biomechanics became synonymous with the study of vehicular occupant in various crash situations. With the knowledge of the injury mechanisms and human tolerance limits, automotive occupant safety restraint systems (both active and passive) and various anthropomorphic test dummies (ATD) were developed. ATDs such as Hybrid III family of dummies for frontal impact tests, side impact dummies for lateral impact tests, were developed and validated with the outcome of the various simulated vehicle crash tests using cadavers and the animals as human surrogates. Due to the limitations such as, scarcity of human cadavers, lack of internal organs in ATDs, erroneous scaling from animal tests to human model etc., researchers have started developing numerical (Finite Element) models of human body to use as the surrogates in the vehicle crash tests in virtual test environment (Crandall et al., 2011; King, 1993; Yang & King, 2004). Chen (1978), Wang (1995), Chang (2001), Forbes (2005), Cihalová (2005, 2006 and 2009), Song et al., 2011, Zhao & Narwani (2005), Campbell & Tannous (2008) and Shigeta et al., 2009 developed finite element models of the full human body with the internal organs. These FE models were validated with the human response corridors established by Kroell et al., (1971, 1974); Nahum et al., (1973) and some other cadaver tests pertinent to the vehicular occupant in the crash scenarios. However, none of these ATDs (both physical and numerical models) and the full human body FE models were validated for the blunt ballistic impacts.

Wayne State University's scientist (Bir, 2000; Bir et al., 2004) carried out impact tests by subjecting the thoraces of 13 cadavers to 3 impact cases pertinent to the blunt ballistic impacts and developed the force-time, deflection-time, and force-deflection human response corridors and also evaluated thoracic injury in terms of VC_{max} . These human response corridors and viscous criterion values are very handy in development of thoracic surrogates for determination of trauma caused by blunt ballistic impacts. Bir et al (2000 and 2004) constructed a thorax surrogate, which is popularly known as 3 Rib Chest Structure (3-RCS), by combining the advantages of Hybrid III dummy's loading surface and BIOSID's continuous rib structure. She validated the surrogate with the human response corridors. To construct 3-RCS, 3 ribs of the BIOSID were mounted to a heavy spine box and the impact surface was created with a polyurethane bib. Urethane bib on the impact side of the surrogate provided the response of the thoracic wall's muscle and the damping material inside the 3-RCS provided the viscous response of the internal organs. However, 3-RCS is a physical surrogate and has got some limitations, such as impact on a small area on the bib (2 inch by 3 inch area at the centre of the bib) only provided useful biomechanical responses for the evaluation of the VC_{max} correctly (DuBay & Bir, 1998), lack of space for additional accelerometers, no provision to mount chest protectors or armors etc. Due to these limitations, cumbersome test methodology and expensive test set up, usage of 3-RCS might not be attractive especially during the development stage of new non-lethal weapons.

Researchers at the DSTO (Department of Science and Technology Organization) of Australia developed a reusable

thoracic surrogate AUSMAN, but not much published data were available on the surrogate. From the limited published research it was clear that AUSMAN was mainly developed for BABT studies (Bass et al., 2006). Similarly, both physical and FE human surrogate torso models (HSTM) developed by Roberts et al., (2005) had been in use for BABT studies.

As far as the numerical models of the thorax surrogates are concerned, only Nsiampa et al., (2011a, 2011b, 2012), validated their human thorax FE model with the human response corridors developed by Bir et al., (2004) and subsequently evaluated the performance of two non-lethal projectiles, namely, foam nosed projectile and 140g PVC baton. Though impact location greatly influences the outcome, as their thorax FE surrogate is modeled with lungs, ribs and chest wall, they have presented results for only one impact point and not validated for any subject specific responses.

In nutshell, from the published literature, it is evident that in spite of so many ATDs (both mathematical and physical models) and numerous detailed full human body FE models, only 4 (AUSMAN, 3-RCS, HSTM and FE model of the thorax by Nsiampa et al., (2011a and 2011b)) surrogates were validated for the impacts of interest. However, they are very cumbersome and expensive to use, necessitating the development of a FE model surrogate of the thorax which is simple yet effective and accurate in predicting the thoracic trauma caused by blunt ballistic impacts.

In this paper, the concept, development methodology, details of the FE model and impact simulations for the validation of MTHOTA are presented.

2. Methodology

A simple concept of MTHOTA was developed and details of the concept are shown in the “Fig.1”. A steel metal impact plate was added to one side of the corrugated collapsible structure and the other end is fixed. Low density, highly compressible, stiff TPE closed cell foam sheet is added to the impacting side of the metal plate. 4 metal plates were added to the collapsible corrugated structure.

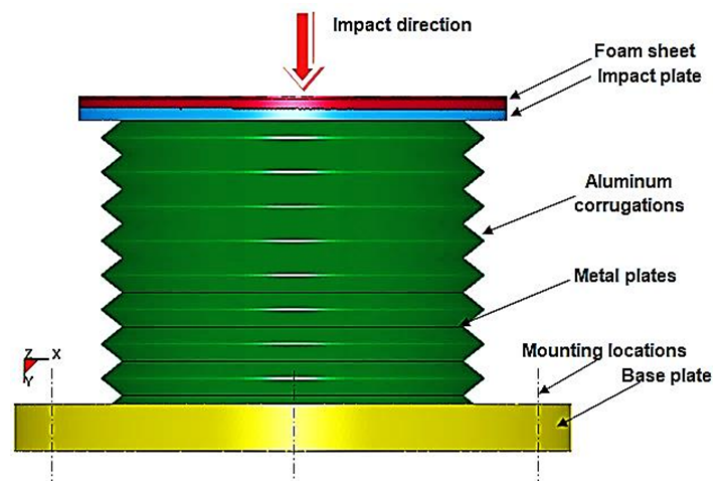


Fig. 1 Details of the concept of MTHOTA

Purpose of the foam sheet is to provide muscle response upon the impact. Metal impact plate, corrugations along with 4 metal plates together are to provide the inertial, elastic and viscous responses of the rib cage, internal organs etc.

The procedural steps involved in the validation method are shown in the “Fig.2”. Details of the wooden baton projectiles and impact velocities used in the present study are given in the Table 1.

Table 1 Impact conditions

Impact condition	Projectile details	Impact speed
LP_20	Wooden baton, 140 g, 100 mm length, 37 mm diameter	20 m/s
LP_40	Wooden baton, 140 g, 100 mm length, 37 mm diameter	40 m/s
SP_60	Wooden baton, 30 g, 28.5 mm length, 37 mm diameter	60 m/s

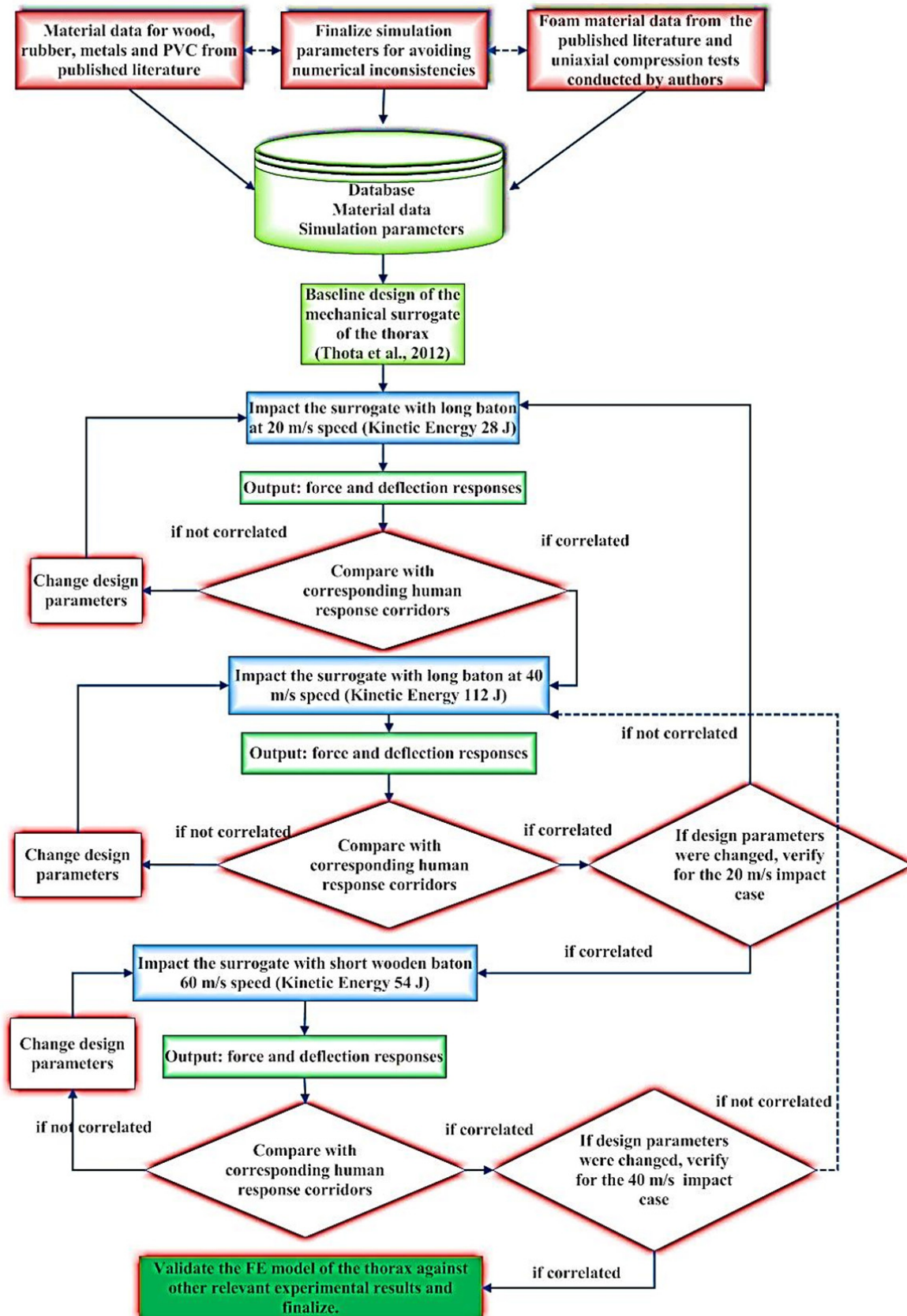


Fig. 2 Process flow chart for validating the thorax surrogate using human response

Aim of the study is to make the MTHOTA to emulate force-time, deflection-time responses and VCmax values of the human thorax for all of the impact conditions mentioned in the Table 1, by suitably changing the design parameters such as thickness of the foam (T_1), thickness of the impact plate (T_2), thickness of the corrugated sheet (T_3), thickness of the 4 metal plates (T_4), inner and outer diameter of the collapsible structure (D and d), height of the corrugation (h), height of the collapsible structure (H), locations of the 4 metal plates. Cross section of the MTHOTA along with the design variables is shown in the “Fig.3”.

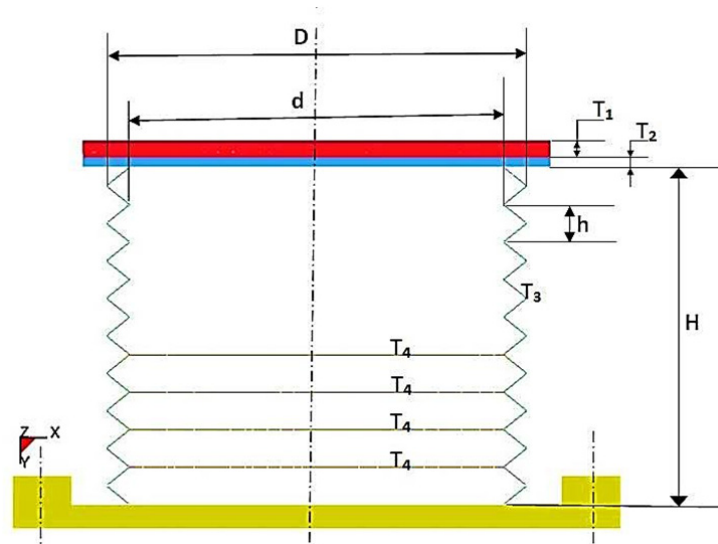


Fig. 3 Cross section of the MTHOTA concept and design variables

In order to gain greater insight into the behavior of MTHOTA to blunt ballistic impacts, the very first analysis was carried out with the dimensions of MTHOTA comparable with the human thorax and Anthropomorphic Test Dummies used in the automotive simulated crash tests (for instance, $D = 300$ mm, $H = 180$ mm, $T_1 = 10$ mm, $T_2 = 3$ mm, $T_3 = 2$ mm, $T_4 = 2$ mm. etc.). In this analysis, the surrogate was subjected to LP_20 impact condition and didn't yield any measurable deflection-time response. In some cases, MTHOTA responded to LP_40 and didn't give any response to SP_60, due to heavy impact plate and high stiffness of the corrugated structure. Because of this reason, profile of the corrugations was changed to less stiffer configuration and dimensions were reduced drastically to see the usefulness of the concept. With $D = 160$ mm, $H = 160$ mm, $T_1 = 8$ mm, $T_2 = 2$ mm, $T_3 = 4$ and $T_4 = 3$ mm, the thoracic surrogate gave measurable deflection-time responses to all 3 impact cases under consideration. By taking this configuration as the baseline design (ignoring all other configurations which didn't yield measurable deflection responses to all 3 impact cases), iterative analysis was carried out by varying the design parameters. For accomplishing the perfect correlation of MTHOTA with the cadaver test results (human response corridors), the methodology mentioned in the “Fig.2” was strictly followed.

Range of thicknesses (foam sheet, impact plate, Aluminum corrugations and 4 plates) chosen, material models, element types, element formulations used in the FE model of the MTHOTA are given in the Table 2. In all, nearly 850 simulation iterations were carried out by varying design parameters to achieve the correlation of the MTHOTA with the responses obtained from the cadaveric tests. Parameters of the final (validated) MTHOTA were given in the Table 2 and enclosed in the parenthesis. To finalize the appropriate element size, convergence study was performed. Suitable element sizes to achieve the solution convergence were given in the Table 2. Responses of the validated MTHOTA were given in the subsequent sections.

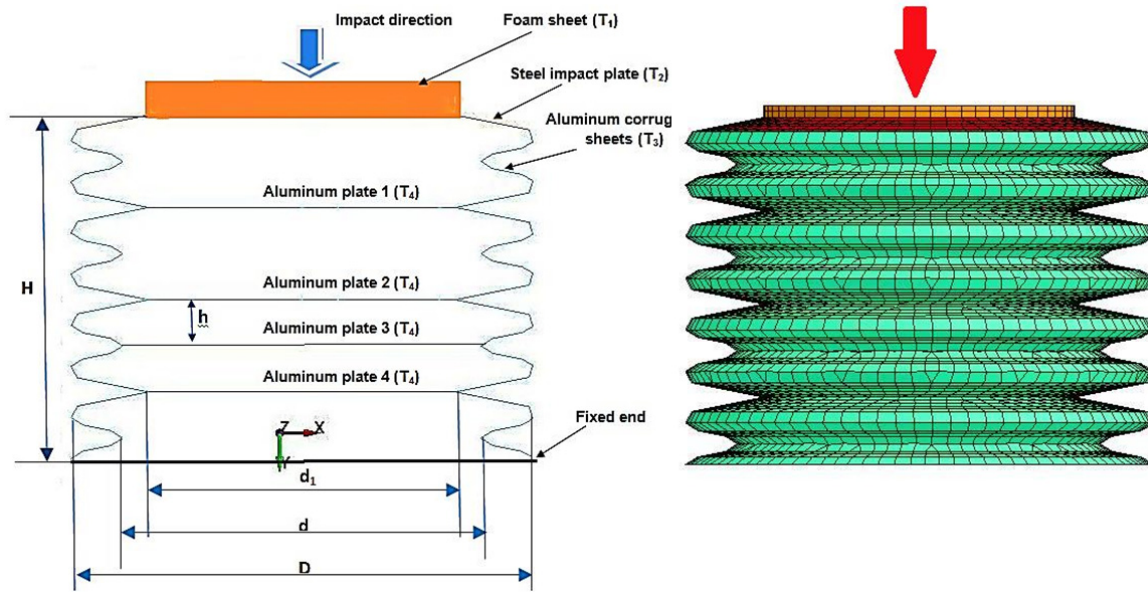


Fig. 4 Cross section of the base line configuration (shown on the left) and FE model (shown on the right) of MTHOTA

Table 2 Details of the MTHOTA finite element model

Component	Range of the parameter in mm (final values)	Element Type	Material model	Element size (final MTHOTA configuration)
Foam sheet	2.0 – 10.0 (4.0)	Brick (8 nodes)	MAT_LOW_DENSITY_FOAM or MAT_057 (Highly compressible closed cell foam)	Two layers in the thickness and 5 mm
Impact plate	0.5 – 4.0 (1.0)	Shell (3 and 4 noded)	MAT_ELASTIC or MAT_001 (Isotropic elastic material)	5 mm
Aluminum corrugations	0.5 – 3.0 (0.6)	Shell (3 and 4 noded)	MAT_PLASTIC_KINEMATIC or MAT_003 (Isotropic and kinematic hardening plasticity)	5 mm
Aluminum metal plates	0.5 – 4.0 (0.55)	Shell (3 and 4 noded)	Same as above	5 mm
Projectile	-	Brick (8 nodes)	MAT_WOOD or MAT_143 (transversely isotropic) /MAT_001 (isotropic elastic)	3 – 5 mm
D	140 – 160 (150)	-	-	-
d	110 – 130 (115)	-	-	-
d ₁	85 – 110 (100)	-	-	-
H	90 – 160 (110)	-	-	-
h	10 – 20 (16.5)	-	-	-

In all impact cases, the projectile was wooden baton and material properties for MAT_WOOD (MAT_143) were taken from the published literature (Green et al., 1999; Green, 2001; Murray et al., 2005; Kretschmann et al., 2010). PVC (with MAT_ELASTIC) as the projectile material yielded almost same output as wooden baton. Material data, experimentally obtained load curve data points of the TPE foam and details of the contact interfaces used in the present study are given Table 3, Table 4 and Table 5 respectively. Details of the contact interfaces and material models used in

the FE analysis can be found in the LS-DYNA keyword users' manual, Volume I and II.(Hallquist, 2007) respectively.

Table 3 Mechanical properties of the materials used in the MTHOTA finite element model

Material name	Material properties used in the material data cards of LS-DYNA (v9.71 R7.0)				
	Density (kg/mm ³)	Young's modulus (GPa)	Poisson's ratio	Yield Stress (GPa)	Comments
Aluminum	2.17E-06	75.0	0.34	0.179	Aluminum alloy 3XXX series
Steel	7.87E-06	210.0	0.30	-	Structural steel
PVC	1.38E-06	2.30	0.33	-	Low density PVC
TPE foam	1.43E-07	10.0	Poisson's ratio input is not required. Load curve input (Engineering stress versus Engineering strain) is required. Experimentally obtained stress and strain data is given in Table 4.		

Table 4 Load curve data of the TPE foam used in the MTHOTA

Engineering Strain	Engineering Stress (GPa)
0.00	0.00
0.0266	5.00×10 ⁻⁵
0.03	1.19×10 ⁻⁴
0.04	1.60×10 ⁻⁴
0.0866	2.20×10 ⁻⁴
0.1	2.30×10 ⁻⁴
0.2	2.40×10 ⁻⁴
0.5	3.81×10 ⁻⁴
0.6	4.20×10 ⁻⁴
0.8	5.81×10 ⁻⁴
0.85	6.32×10 ⁻⁴
0.9	9.02×10 ⁻⁴
1.0	1.20×10 ⁻³

Table 5 Contact interfaces in the FE model of the MTHOTA

Contact interface	Type of the contact
Impact plate – Foam sheet	AUTOMATIC_SURFACE_TO_SURFACE
Projectile – foam sheet	CONTACT_NODES_TO_SURFACE
Impact plate - corrugations	CONTACT_NODES_TO_SURFACE
Corrugated sheet	SINGLE_SURFACE_CONTACT

Problems associated with the FE modeling of the low density foams and precautions to be taken to avoid the error termination were described below.

Premature termination due to negative volume of the element is most common error with FE analysis involving highly compressible foams (for instance TPE foam sheet in the present analysis). Due to the large deformations, elements may become so deformed that the volume of the element is evaluated as negative. When the deformations are so large, unless the severely deformed area is re-meshed or elements are smoothed, Lagrangian mesh can accommodate only limited amount of deformations. To avoid the error termination due to negative volume of the foam elements, the following precautions were taken.

- The variable “ERODE” in *CONTROL_TIMESTEP card was set to 1
- The variable DTMIN in *CONTROL_TERMINATION was set to non-zero value.
- The variable TSSFAC (Time step scale factor) in the *CONTROL_TIMESTEP was reduced to 0.5 from the default 0.9
- The variable DAMP in the MAT_LOW_DENSITY_FOAM data card was set to 0.5 (maximum recommended damping value) and the variables HU (hysteretic unloading factor) was set to 1.0 (no energy dissipation) and the variable SHAPE (shape factor for unloading) was set to 1.0
- Stiffened up the load curve (Engineering stress versus Engineering Strain) at large strains. This is very effective measure to avoid the error termination of the solution. The material data for the TPE foam used for the analysis is experimentally procured and after 90% of the strain, the data was manipulated to stiffen the material.

With the above mentioned precautions, premature termination of the simulation runs was completely avoided. Details of the contact interface definitions and definition and importance of the control cards (*CONTROL_TIMESTEP AND *CONTROL_TERMINATION) and all related variables (such as ERODE, DTMIN, DAMP, etc.) can be found in the theory manual (Hallquist, 2007) and keyword user’s manual, volume I and II (Hallquist, 2006) of LS-DYNA.

3. Results and discussion

3.1 Thorax surrogate (MTHOTA) impacted with long baton of 140 grams with 20 m/s impact velocity (LP_20)

Dynamic force response of the MTHOTA for LP_20 impact condition along with the force-time human response corridors for the respective impact case has been shown in the “Fig. 3”. Force response obtained for MTHOTA has been filtered using SAE class 300 filter.

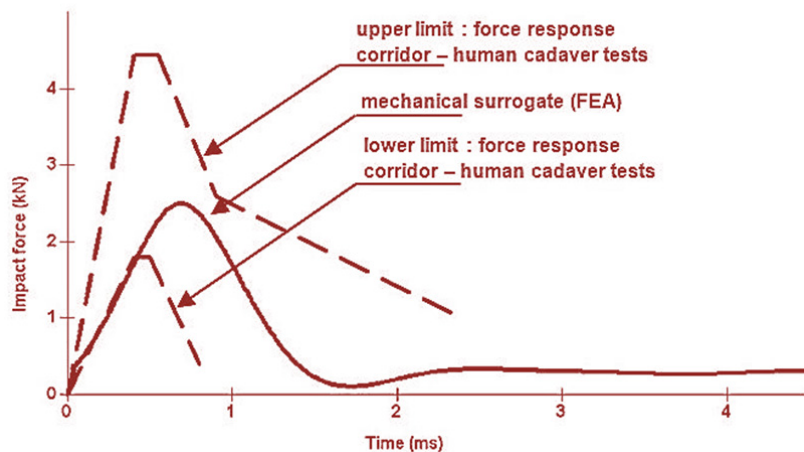


Fig. 5 Force response of the thorax surrogate MTHOTA when impacted with 140 g long baton at 20 m/s speed (measured using the accelerometer mounted on the back face of the projectile)

Peak impact force was measured as 2509 N which is within the range (3383 ± 761) of force-time response established for the condition A (Bir, 2000).

Deflection of the impact plate (any nodal displacement serves the purpose as impact plate has been modeled as rigid material) and deflection of the impact plate with respect to plate-3, both as function of time were measured and both deflection-time curves are shown in the “Fig. 6” and “Fig. 7” respectively. No filter was used for processing of dynamic deflection data.

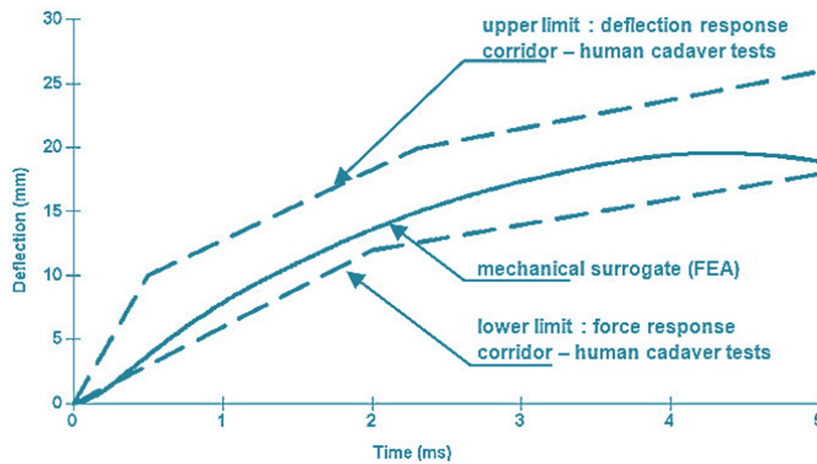


Fig. 6 Deflection response of the thorax surrogate MTHOTA when impacted with 140 g long baton at 20 m/s speed (measured using the node on the impact plate)

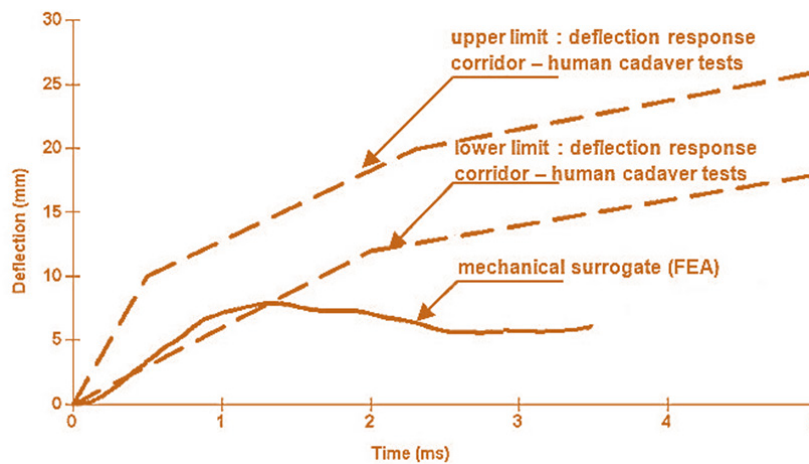


Fig. 7 Deflection response of the thorax surrogate MTHOTA when impacted with 140 g long baton at 20 m/s speed (measured using the node on the impact plate with respect to the node on the plate-3)

3.1.1 Evaluation of blunt thoracic trauma in terms of Viscous Criterion (VC_{max})

Lau & Viano (1981, 1986) proposed Viscous Criterion (VC), which is a function in the time formed by the product of the velocity of chest deflection and the chest compression at that instance. Viano & Lau, (1988); Viano et al., (1989) conducted numerous experiments, in which thoraces of the cadavers were subjected to the lateral impact loads in simulated vehicle crashes. He found that VC value based on maximum chest deflection and rate of chest compression (VC_{max}) is better injury predictor than all other injury criteria. Values of VC_{max} can be expressed in terms of abbreviated injury scale (details of AIS can be found in the references (Civil and Shwab 1988; Gennarelli et al. 1985; States et al. 1971; States 1969). For instance,

For frontal loading on the thorax (Viano, et al., 1989, Viano, et al., 2000),
 $VC_{max} = 1.0$ m/s; 25% probability of AIS3+
 $VC_{max} = 1.3$ m/s; 50% probability of AIS3+

Similarly, for lateral/side impact of the thorax (Viano, et al., 1989, Viano, et al., 2000),

$VC_{max} < 1.0$ m/s;	AIS 0-2
>1.0 m/s;	AIS 4, 5
$= 1.47$ m/s;	25% probability of AIS4

In case of occupant of the vehicle frontal and side impact scenarios, $VC_{max} \leq 1.0$ m/s was taken as specification in vehicle standards such as ECE-R94, ECE-R95, EuroNCAP (front and side impact) and FMVSS 214. Defense and military research organizations have also considered $VC_{max} \leq 1.0$ m/s as the specification for the non-lethal weapons.

In case of the front and side impact dummies, viscous criterion can be calculated by using the formula given below.

$$VC = S \cdot (Y/D) \cdot (dY/dt) \quad (1)$$

Where,

VC = Viscous Criterion

S = Scaling factor

Y = Chest deflection

D = Dummy constant, and

dY/dt = Rate of chest deflection

Values of the S and D vary with the ATD used in the simulated vehicle crash tests. In case of human cadavers, Lau and Viano (1986) suggested 1.3 for S and 180 mm for D.

VC_{max} can be calculated by using maximum thoracic deformation and the time at which maximum deformation occurred using the above equation.

The following two methods have been developed for the calculation of VC_{max} using MTHOTA. VC_{max} values are good enough for validation of the non-lethal ammunition, chest protectors etc.

3.1.1.1 Method-1

- (i) Perform the FE simulation by impacting MTHOTA with the blunt projectile
- (ii) Measure the dynamic deflection (deflection-time) response of the metal impact plate.
- (iii) Measure the maximum deflection and time taken for attaining the maximum deflection
- (iv) Calculate maximum deformation velocity
- (v) Evaluate VC_{max} using the "Eq. (1)". Use scaling factor as 0.366 and 110 mm as deformation constant. It is important to note that Bir (Bir, 2000) has used 1.3 as scaling factor and 180 mm as the deformation constant for the calculation of VC for all her experiments involving cadavers and 3-RCS surrogate.

For the LP₂₀ impact condition of MTHOTA, from the "Fig. 6", it is evident that impact plate's maximum displacement was 19.6 mm and it took 4.16 ms to reach the maximum displacement. Maximum compression can be calculated by normalizing the maximum displacement with 110 mm which is depth of the MTHOTA. Therefore,

$$VC_{max} = 0.366 (19.6/4.16) (19.6/110) = 0.31$$

3.1.1.2 Method-2

- (i) Perform the FE simulations by impacting MTHOTA with the blunt projectile.
- (ii) Measure the dynamic deflection (deflection-time) response of the rigid impact plate with respect to the plate-3
- (iii) Measure the maximum deflection and the time at which deflection attained maximum.
- (iv) Evaluate maximum deformation velocity
- (v) Evaluate VC_{max} using the "Eq. (1)". Use 1.3 for scale factor and 180 mm as deformation constant.

Thorax surrogate MTHOTA subjected to the same LP₂₀ impact condition, from Fig. 7, 85 mm of maximum displacement of the impact plate with respect to plate-4 occurred at 1.3 ms. Therefore, VC_{max} was calculated as follows.

$$VC_{\max} = 1.3 (7.85/1.3) (7.85/180) = 0.34$$

Though VC_{\max} calculated using both methods mentioned above was very well correlated with the VC_{\max} measured from the cadaver tests, only method-2 has been used for the calculation of VC_{\max} for remaining cases of impact simulations.

3.2 Thorax surrogate (MTHOTA) impacted with the long baton of 140 grams with 40 m/s impact velocity (LP_40)

Force response of the thorax surrogate MTHOTA, dynamic deflection of the impact plate and the dynamic deflection of the impact plate with respect to the plate-3 were calculated from the output of FE simulations in which thorax surrogate MTHOTA was subjected to the LP_40 impact condition and are shown in “Fig. 8”, “Fig. 9” and “Fig. 10” respectively.

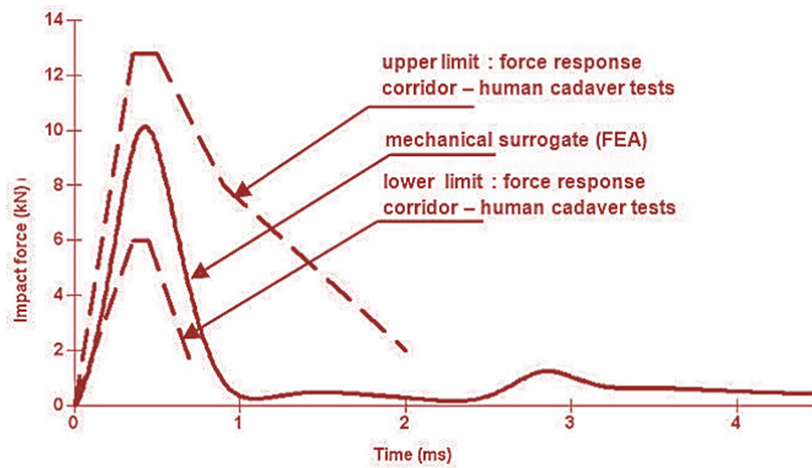


Fig. 8 Force response of the thorax surrogate MTHOTA when impacted with 140 g long baton at 40 m/s speed (measured using the accelerometer mounted on the back face of the projectile)

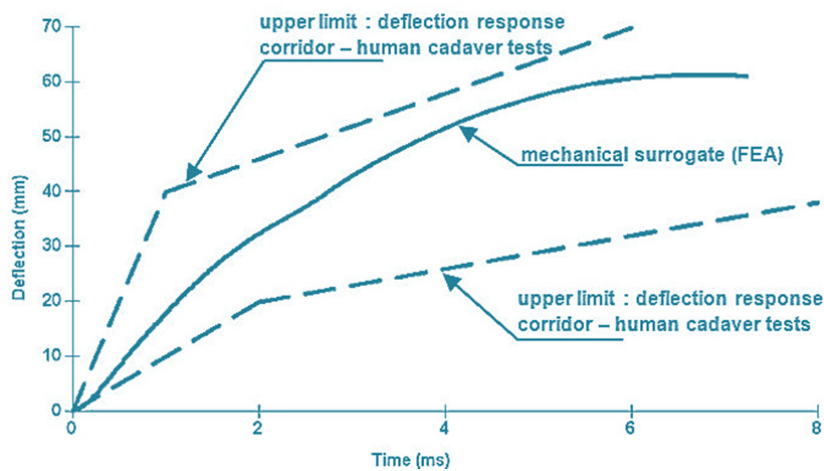


Fig. 9 Deflection response of the thorax surrogate MTHOTA when impacted with 140 g long baton at 40 m/s speed (measured using the node on the impact plate)

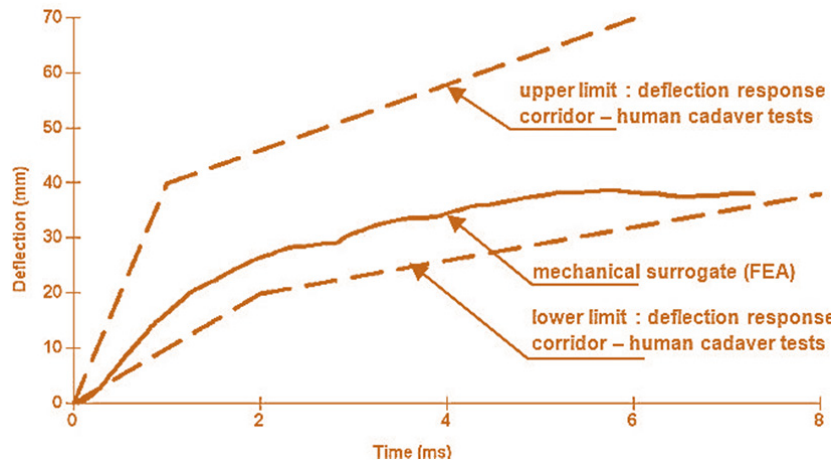


Fig. 10 Deflection response of the thorax surrogate MTHOTA when impacted with 140 g long baton at 40 m/s speed (measured using the node on the impact plate with respect to the node on the plate-3)

Peak impact force measured for this case was 10200 N at the impact duration 0.41 ms, which is very well correlated with human response corridor for the respective impact case as the peak force is within the range of 7400 – 12600 N.

From “Fig. 10”, maximum deflection was measured as 38.5 mm and the time taken for the maximum deflection was approximately 5.7 ms. Using method-2, VC_{max} was calculated as 1.87.

3.3 Thorax surrogate (MTHOTA) impacted with the short baton of 30 grams with 60 m/s impact velocity (SP_60)

Force-time, deflection-time responses of the impact plate and the same with respect to the plate-4 were elicited from the output of the FE impact analysis of MTHOTA for SP_60 impact condition. These responses are shown in “Fig. 11”, “Fig. 12” and “Fig. 13” respectively.

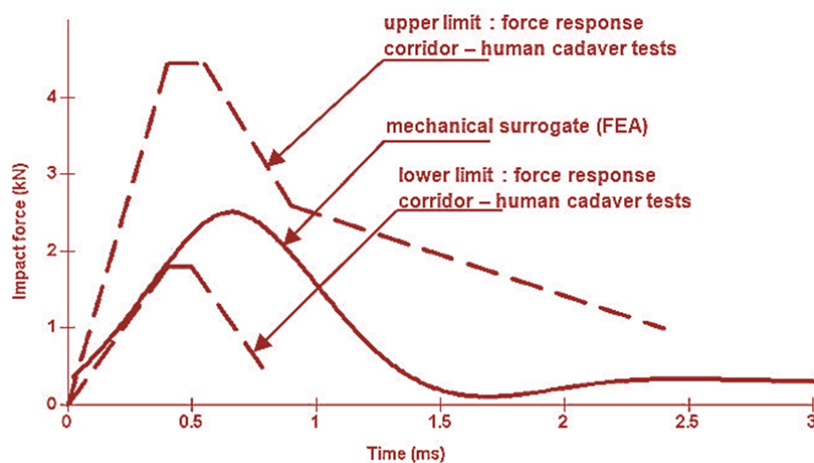


Fig. 11 Force response of the thorax surrogate MTHOTA when impacted with 30 g short baton at 60 m/s speed (measured using the accelerometer mounted on the back face of the projectile)

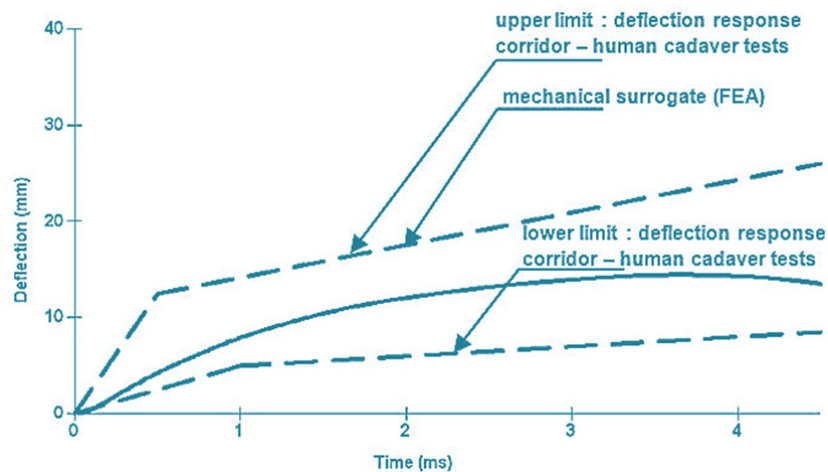


Fig. 12 Deflection response of the thorax surrogate MTHOTA when impacted with 30 g short baton at 60 m/s speed (measured using the node on the impact plate)

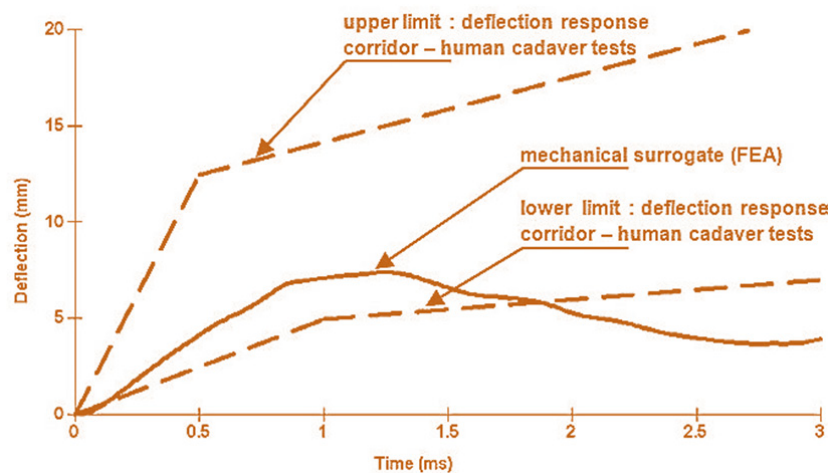


Fig. 13 Deflection response of the thorax surrogate MTHOTA when impacted with 30 g short baton at 60 m/s speed (measured using the node on the impact plate with respect to the node on the plate-3)

30 gram wooden baton with 60 m/s impact velocity is very much relevant to latest impact munitions (non-lethal projectiles such as XM1006, Direct Impact-OC, Direct Impact-Inert and extended range versions of all these ammunitions), except impact velocity (muzzle velocity) is in the order of 100 m/s in case of kinetic less lethal ammunition. For the case of MTHOTA subjected to LP_40 impact, variation in the total energy of the projectile and the surrogate as a function of time are shown in the “Fig. 14” and stress wave propagation in the surrogate is delineated in the “Fig. 15”.

From the “Fig. 14”, it is evident that the total energy of the MTHOTA (foam sheet, impact plate, corrugated sheets and 4 plates together), at any instance during the impact is equivalent to the difference between the projectile’s initial kinetic energy and the total energy at that instance.

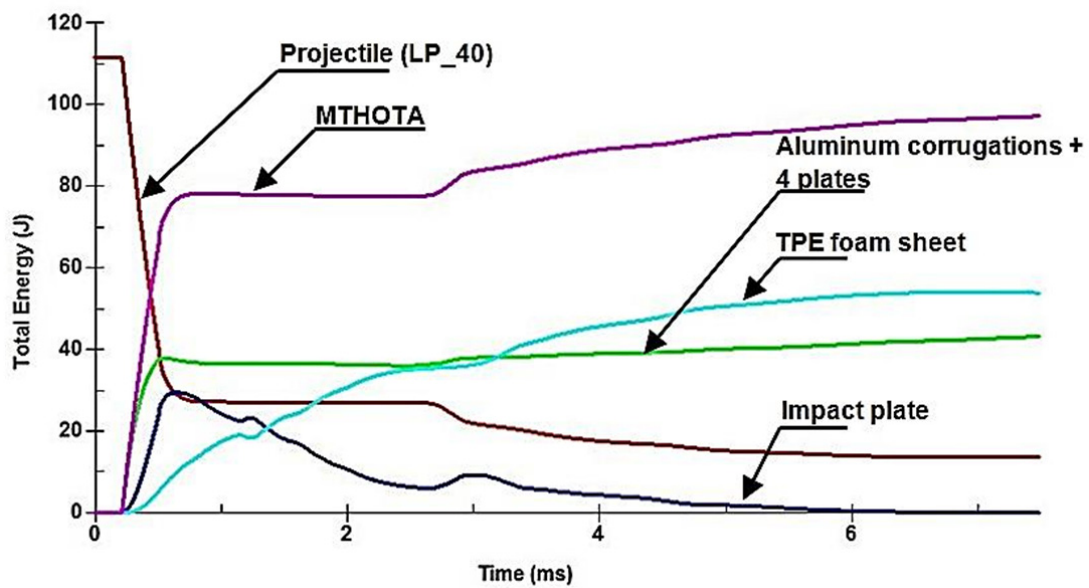


Fig. 14 Variation in the total energy of the projectile and the surrogate during the impact

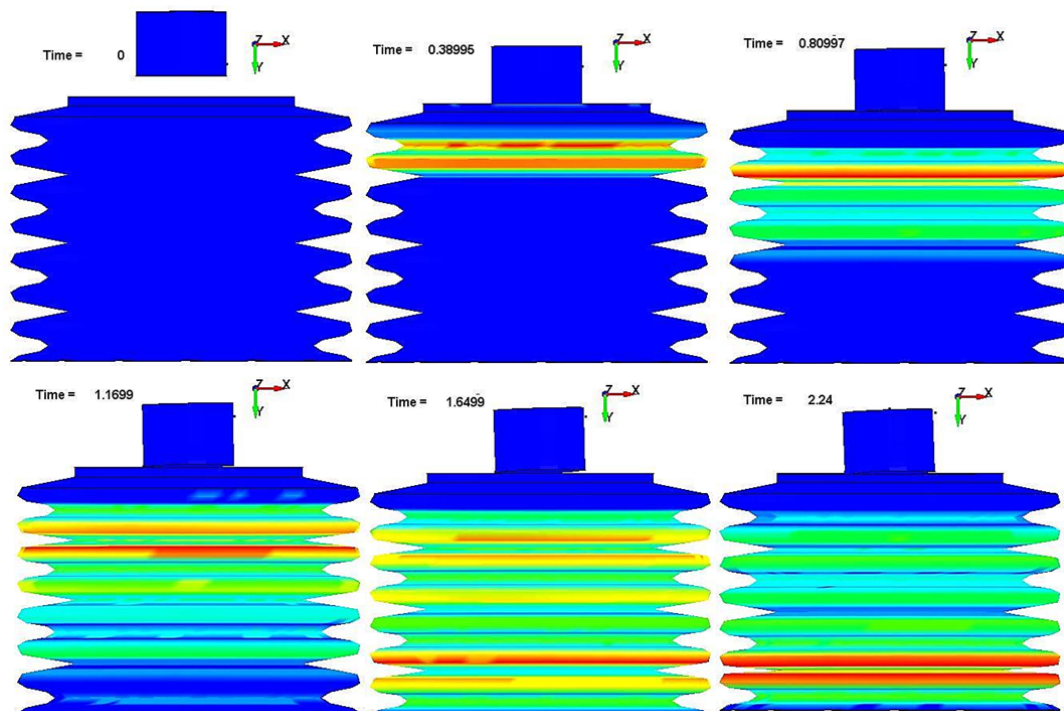


Fig. 15 Stress wave propagation in the thorax surrogate (MTHOTA) during the impact (short baton of 30 g at 60 m/s)

From the dynamic force response as a function of time for this impact case, it is clear that peak impact force of 2510 N occurred at approximately 0.7 ms of impact time. Force response of MTHOTA for SP_60 impact case too was very well correlated with the human response corridors for the respective impact case.

VC_{max} for this impact case was evaluated as 0.33, using the 7.55 mm of maximum deflection of the impact plate with respect to plate-3, which occurred at 1.22 ms time.

VC_{max} values obtained for all 3 impact cases of MTHOTA and those obtained from respective impact cases of cadavers and 3-RCS surrogate are compared and are as shown in the “Fig. 16”.

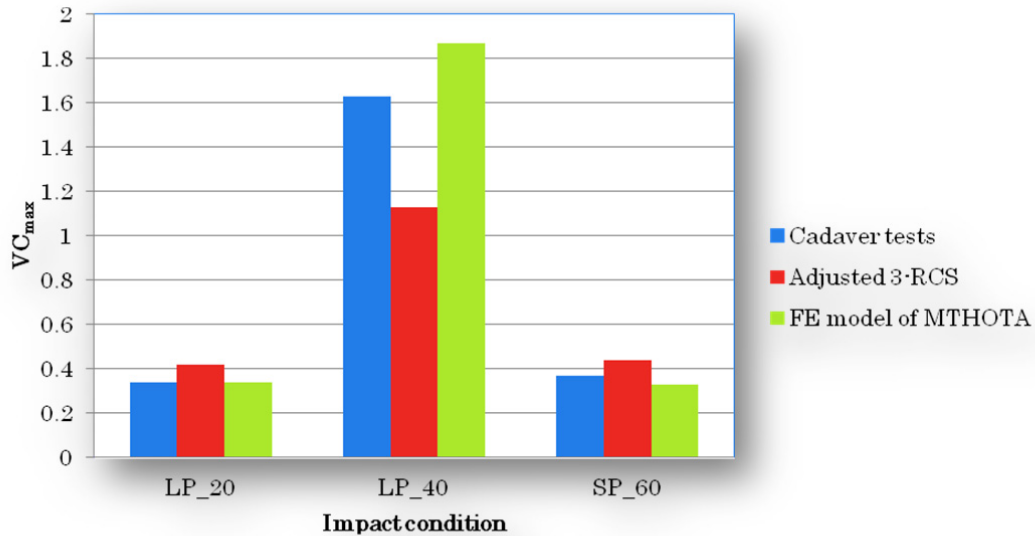


Fig. 16 Comparison of VC_{max} values obtained from MTHOTA with human cadaver tests and adjusted 3-RCS surrogate (Bir, 2000 and Bir, et al., (2004)

From 3 impact cases, it has been evident that the dynamic force response, dynamic deflection response and VC_{max} values of MTHOTA for all impact cases were very well correlated with the test data obtained from cadaveric experiments for the same impact cases. Being able to accurately measure the blunt thoracic trauma in terms of Viscous Criterion, the FE model of the thorax surrogate MTHOTA can be confidently used for validation of less-lethal ammunition and sports personal protective equipment.

3.4 Further validation of the MTHOTA

Though the FE model of the mechanical thorax surrogate MTHOTA has been validated, to verify its robustness and reliability, it was subjected to further corroborative tests using the data published by well-known researchers working on the design, development and validation of non-lethal projectiles.

3.4.1 Sponge nose PVC grenade of mass 41.9 gram and size of 40 mm diameter

Two cases of finite element simulations have been carried out with MTHOTA subjected to the impact with a sponge nosed projectile with 37 m/s and 73 m/s speeds of impact. Approximate dimensions and material properties of sponge nose were collected from the literature (Nsiampa et al., 2012).

Initial and final stages of MTHOTA subjected to the impact by sponge nose projectile with 73 m/s are shown in the “Fig. 17” and cross sections of the same are shown in the “Fig. 18”.

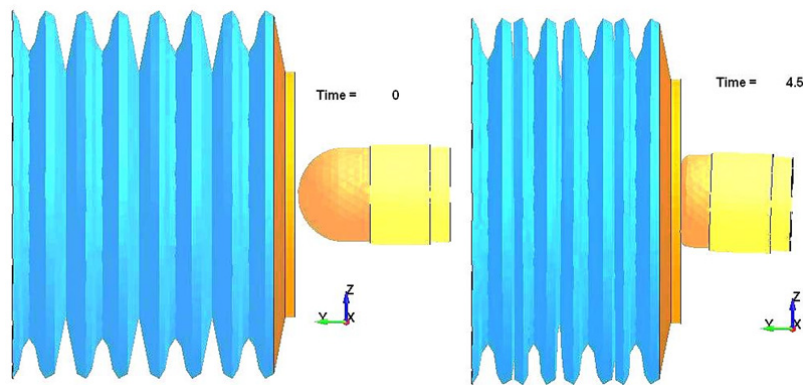


Fig. 17 Sponge nosed projectile (mass of 41.9 g, 40 mm diameter) impacting the thorax surrogate (MTHOTA) at 73 m/s impact speed. Initial and final stages of the MTHOTA and projectile

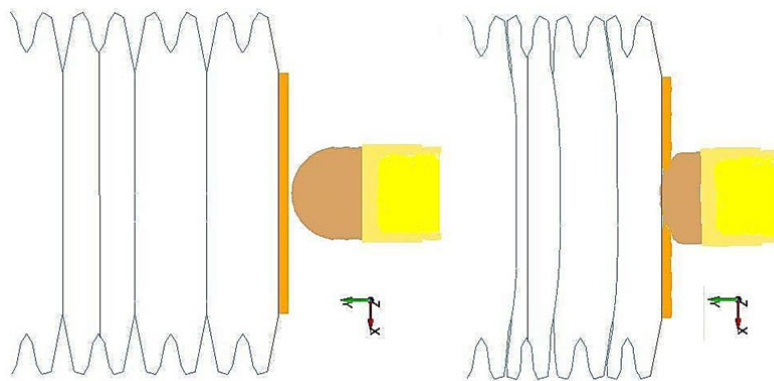


Fig. 18 Sponge nosed projectile (mass of 41.9 g, 40 mm diameter) impacting the thorax surrogate (MTHOTA) at 73 m/s impact speed. Cross sections of the MTHOTA and projectile at start and end of the impact duration.

Dynamic deflection (as the function of time) of the impact plate with respect to plate-3, are shown the “Fig. 19”.

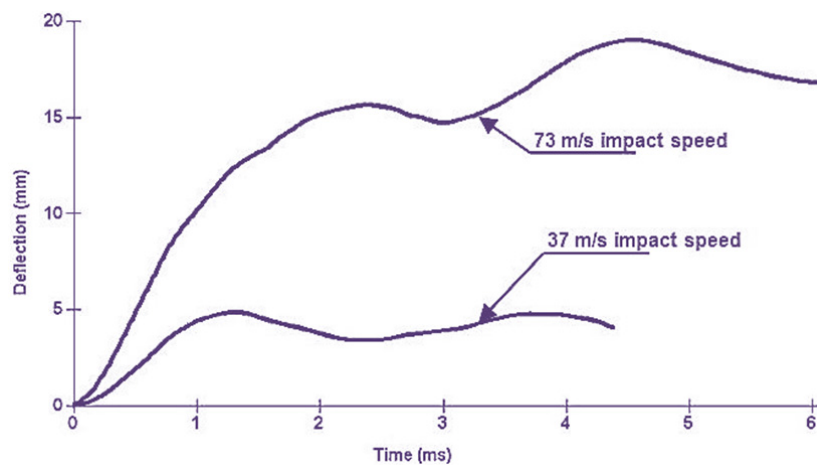


Fig. 19 Dynamic deflection of the impact plate, with respect to plate-3 when MTHOTA impacted with sponge nose projectile at 37 m/s and 73 m/s

VC_{max} for both impact cases have been evaluated using the method-2 described in previous sections and were compared with the results presented by Nsiampa, et al., (2012), Bir (2000) and Bir, et al., (2004) and are as shown in the “Fig. 20”.

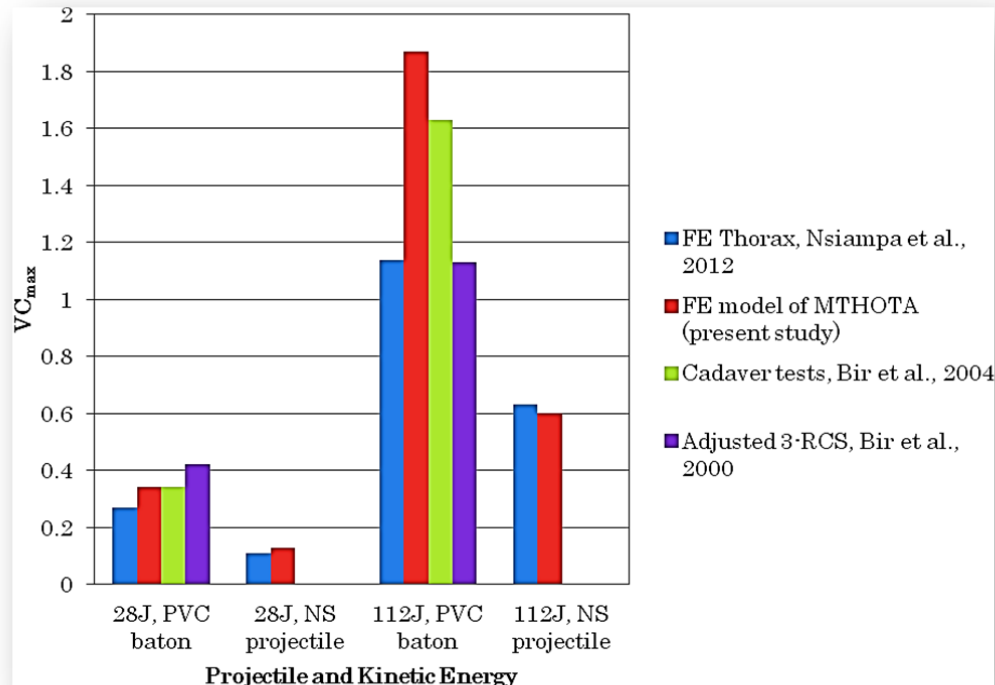


Fig. 20 Comparison of the VC_{max} values obtained by using MTHOTA with those obtained from cadaveric tests and adjusted 3-RCS (Bir 2000; Bir, et al., 2004) and FE Thorax model (Nsiampa, et al., 2012)

3.4.2 Rubber ball of 60-cal, 15 mm diameter, 3.7 gram

As mentioned in the specification manual (titled ".60-CAL STINGER, 37 mm black powder, Rubber ball round," published by Defense Tech, USA in 2006), .60-cal stinger rubber ball round has been developed by modifying the designs of 28A and 28B and designs of Federal Laboratory's manufactured RB25 and RB40 rounds. DuBay and Bir (1998) evaluated VC_{max} for the 60-cal, 15 mm diameter, 3.7 gram rubber ball by impacting it with 326 m/s and 346 m/s speeds using thorax surrogate 3-RCS. VC_{max} calculated for former and later impact cases were 0.20 and 0.09 respectively. High speed rubber ball impact produced lesser chest displacement (consequently, lesser VC_{max}), when compared to lower speed impact with the same projectile. This discrepancy in the VC_{max} might be due to the limitations of 3-RCS as mentioned by DuBay and Bir (Bir, 2000; DuBay & Bir, 1998) and Dau (2012).

A dynamic transient impact analysis was carried out by impacting the MTHOTA with the 60-cal rubber ball at 325 m/s. Due to high impact speed of the projectile, MAT_057 and MAT_027 (Mooney_Rivlin_Rubber material model) didn't give any useful results as within very less time the projectile got eroded. Without ERODE option active, it is not possible to carry out impact simulations involving foam and thermo-plastic elastomers. Therefore, Plastic_Kinematic material model was used for the projectile.

Various stages of projectile impacting the MTHOTA are shown in the “Fig. 21”. Relative displacement of the impact plate with respect to the plate-4, as a function of time is shown in the “Fig. 22”.

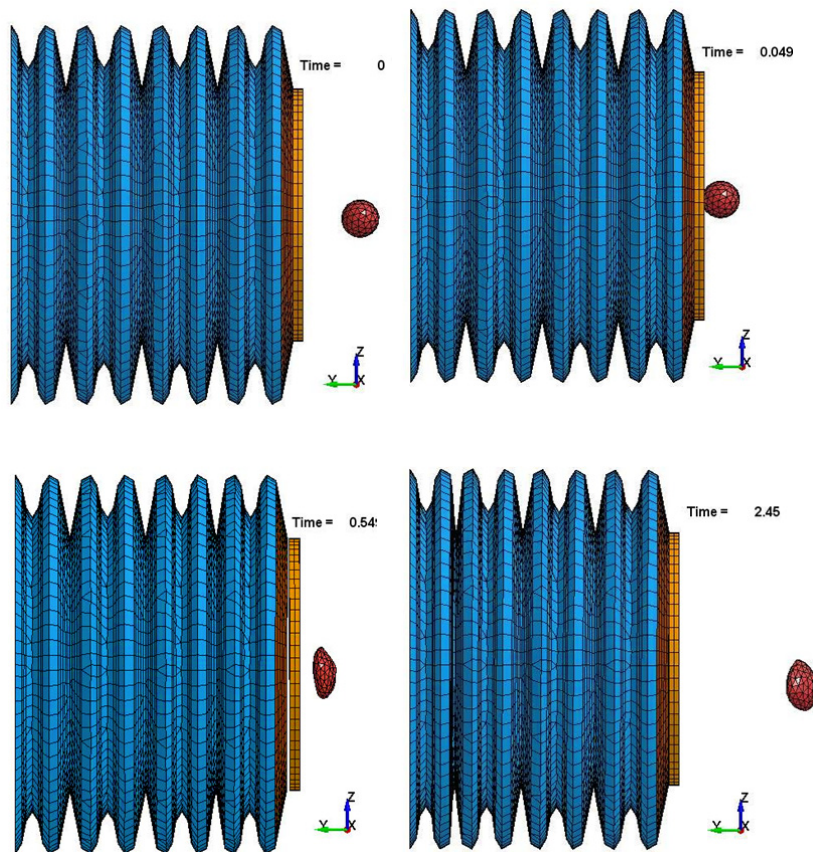


Fig. 21 Various stages of thorax surrogate (MTHOTA) and .60 calibre rubber ball projectile impacting with the speed of 326 m/s (from left to right 0.049 ms, 0.5 ms and 2.45 ms impact duration respectively)

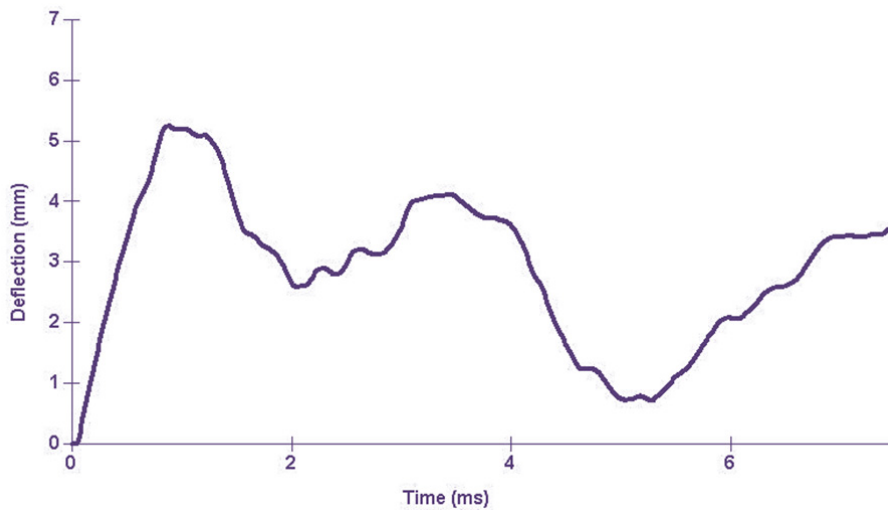


Fig. 22 Dynamic deflection of the impact plate with respect to the plate-3 when MTHOTA impacted with .60 calibre rubber ball projectile at 326 m/s impact speed

From the Fig. 22, the maximum relative displacement of the impact plate with respect to the plate-3 was 5.25 mm at 0.849 ms impact duration. Method-2 of VC_{max} calculation described in previous sections yields 0.23, which is well correlated with the results presented in a technical report by DuBay and Bir (1998).

4. Conclusions

From the corroborative impact simulations carried out using MTHOTA as the surrogate, it is evident that MTHOTA emulates human thorax. Force response, deflection response and VC_{max} values were in very good agreement with those obtained from the cadaver tests as force-time response, deflection-time response and VC_{max} values were in very good agreement with those obtained from the cadaver tests. MTHOTA is further validated for the two impact cases presented by Nsiampa using the full human thorax model. Though FE model thorax of Nsiampa et al., (2011a, 2011b and 2012) has got some internal organs, it doesn't provide any organ specific injuries and only provides VC_{max} . The major disadvantage with this model is high computational time and also VC_{max} depends upon the impact point. Therefore, more number of impact simulations need to be carried out so that average VC_{max} values can be used. MTHOTA facilitate the accurate calculation of the VC_{max} with only one simulation, without any ambiguity. As VC_{max} is well correlated with thoracic injuries on Abbreviated Injury Scale, MTHOTA serves the purpose of validating the non-lethal ammunition, chest protectors etc.

MTHOTA is not computationally demanding. Because, the surrogate MTHOTA consisted only of 7543 shell elements, 723 solid brick elements, 7 components (foam sheet, rigid impact plate, corrugated sheet, 4 plates) and 4 contact interfaces (including the interface between projectile and MHTOTA's impacted surface). Therefore, the solution time is very less. Due to the simple model, MTHOTA also offer ease in setting up the simulation preprocessing files.

Only physical surrogate (3-RCS), which is developed for the evaluation of the trauma caused by blunt ballistic impacts, requires costly experimental set up and cumbersome evaluation process. Due to limitations of 3-RCS mentioned in the previous sections, more number of impacts would be required either to get the proper deflection response or to perform sampling or averaging to obtain the values of VC_{max} . Major disadvantage with physical surrogates is the requirement of the prototypes of the products of interest, which is another costly and cumbersome affair. MTHOTA require only one impact simulation as there is no ambiguity in the impact point and doesn't require any prototypes.

Though the material data used in FE model of the surrogate MTHOTA were real, due to the shape of the corrugated sheet, MTHOTA is not manufacturable. At the same time, it is not difficult to make a new manufacturable design based on the same concept.

Development and validation of MTHOTA, therefore, undoubtedly paves a way for developing application specific simple surrogates (both FE and physical models), which will be very handy during the development stage of the concerned products.

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