Scaling of animal and PMHS thoracic BABT data to live human data

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Abstract. The reduction of mass and the increase of soldier comfort and performance of armour systems are closely related and necessitates the optimization of those systems. Lighter weight materials and improved armour fabrication techniques are key to this objective. Another aspect of body armour optimization process concerns our knowledge of appropriate threshold to guide body armour design. Indeed, tests to assess the appropriate thresholds of injury are frequently done using either animals (either live or deceased) or PMHS (Post Mortem Human Subjects). We are assuming that the dynamic response and injury sensitivity of those surrogates is one to one compared to live human being. It has been shown in the past that it is not necessarily the case ([1], [2] and [3]). This paper investigates open literature data on the subject and determines the expected relationship between porcine (live or dead) and PMHS to live human. The relationship is then used to discuss and assess why, for similar impact loadings, experimental data on animals are resulting in injuries while field data are not showing the injurious response for live humans. As many available datasets concern blunt projectile impacts, the applicability of using those data for BABT studies is discussed.

1. INTRODUCTION

One aspect of body armour optimization process concerns our knowledge of appropriate threshold to guide body armour design. This knowledge can only be acquired through the use of Post-Mortem Human Subjects (PMHS) and live or post-mortem animals as a proxy to the response of live human subjects (LHS). This estimation is usually made by assuming that there is a one on one relation between PMHS and live or post-mortem animals to LHS. The present study uses available PMHS, Live Porcine Subject (LPS) and Post-Mortem Porcine Subjects (PMPS) data low mass high velocity and high mass-low velocity thoracic impacts to estimate the response of LHS. The range of impact conditions is selected to cover soft and hard thoracic armour BABT conditions. First a literature review is done to determine which data are available and how the automotive industry transfers data from animal to human subjects. Then, the available data are analysed and trends of selected dependent data for various relevant independent data are presented and discussed. Based on the relationships found, an estimate of LHS response is produced. Because the majority of porcine and PMHS thoracic response data used to assess LHS response concern blunt projectile impacts, a discussion on their validity for BABT studies is presented.

2. LITERATURE REVIEW

A literature review was made to determine the state of knowledge related to comparative impact biodynamic and associated injuries data for thoracic impacts on animals (live or post-mortem) and humans (live and post mortem). The results are presented in the following sub-sections:

2.1 Cardio-Pulmonary Resuscitation (CPR)

Although related to low rate impacts (0.25 to 2.4 m/s), data gathered using instrumented CRP defibrillators are particularly important as they are the only data set that relate live human response to PMHS and porcine response. Reference [1] to [6] have reported on measures of force-displacement-time data for a wide variety of subject mass and age. In particular they have come up with estimations of the stiffness and damping of anterior-posterior (AP) thoracic response to CRP maneuvers and scaled these data to pediatric size humans.

In [4], the authors measures CPR maneuvers response for live human (n = 91 adult, 61 males, average age = 70 years) compared to PMHS (n = 13, 6 males, average age = 71.2 years). They compared their force-displacement results to results from [5] and [6] (11 and 16 live human subjects). The area of load application was different for each dataset and no clear trend were seen related to thoracic stiffness. The authors found that the force-displacement response of the PMHS is statistically higher than for live human subjects, i.e. PMHS thoraces are stiffer than live human thoraces.

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On his side, Neurauter [3] measured stiffness and damping for live humans (90 patients, 18 to 92 years old) and 14 live porcine subjects (a group of 7 weighing 23-30 kg and a group of 7 weighing 34-46 kg) using an instrumented CPR defibrillator. Comparison of the human and animal data revealed similar chest stiffness and viscosity values at the beginning of the CPR episodes for 15 mm chest deformation, but at higher deformation (30 mm and 50 mm) porcine thoracic stiffness was significantly higher. Mean and median force-displacement response curve for the live pigs and live humans were compared and found to be similar.

2.2 High mass-low velocity impacts

In [7] and [8], Viano studied the response to low velocity (8.1 to 12 m/s), high mass (21 kg) thoracic impacts on live (7 sibling subjects, mass = 50.9 to 70.0 kg and 5 other subjects, mass = 49.9 to 59.0 kg) and post-mortem (4 sibling subjects, mass = 48.2 to 68.2) porcine subjects and compared these results to similar impacts on PMHS (Neathery [9]). Higher forces were measured at approximately mid-deflection for the post-mortem porcine subjects compared to the live porcine subjects but at higher and lower deflections, forces were essentially the same. Maximum compression, peak force and impact velocity were shown to be correlated with the AIS injury score and the number of rib fracture. Figure 24 of [8] shows the relation between the AIS injury level and the maximum thoracic compression for post-mortem porcine subjects, live porcine subjects and PMHS. The post-mortem porcine subjects' presents higher AIS scores compared to live porcine subjects and PMHS values are shown to be lower than those two.

In [10], Yaek did a validation study of the scaling process used in the car crash industry for pediatric aged subjects. Her approach was as follows:

a) Evaluate the geometry/material characteristics of porcine subjects and compare them to target pediatric human subjects.
b) Select representative porcine subjects representative of the 50th percentile human male subject as well as 10 years old, 6 years old and 3 years old human subjects and execute a series of pendulum tests to measure their response to lateral abdominal and lateral thoracic impacts. Impact mass and velocity were scaled to fit the scaled values used in the car crash industry
c) Define response corridors and compare them to: scaled down 50th percentile equivalent porcine subject and scaled down 50th percentile human subject

Her results indicated that the scaling process used for abdominal and thoracic side impacts is valid. She also demonstrated that the response corridor for porcine subjects and human subjects of the same total body mass are the same.

2.3 Low mass-high velocity impacts

Bir [11] executed 15 impacts on 7 PMHS thoraces. Impacts were located above the mid-sternum. The projectiles were: 140-g rigid PVC cylinders that impacted the subjects at 20 m/s (5 shots) and 40 m/s (5 shots) and 60-g rigid PVC cylinders that impacted the subjects at 60 m/s (5 shots). All projectiles were 37 mm in diameter. Their characteristics corresponded to typical KENLW (Kinetic Energy Non-Lethal Weapon) projectiles. Response corridors were determined along with the maximum thoracic compression (Cmax), the viscous criterion (VCmax), the blunt criteria (BC), AIS injury scores and number of rib fracture.

Prat and his colleagues, [12] to [15], presented results of a series of blunt impact experiment involving PMHS (n = 12, 5 males, 21 valid impacts, mass = 46 to 101 kg, average mass = 68.8 kg) and live porcine subjects (n = 19, average mass = 49 ± 1.5 kg) against two commercial KENLW projectiles weighing 31 g and 61 g (40 mm diameter). Both had a foam nose and a hard plastic pellet. Results presented included maximum thoracic deformation, Cmax, VCmax, BC and number of rib fracture. Impact location on the PMHS was the 4th left or right rib at the mid-clavicular line. On the porcine subjects, impact location was situated at the 7th right rib equidistant from the sternum and the spine. The conclusion of the principal document of this series [12] is as follows:

> *To conclude, both pigs and PMHS represent good surrogates for the human adult, which is the subject of interest for ballistic forensic assessment. Though PMHS provide good anatomic thoracic wall conformation, pigs allow for the study of pathophysiological responses to the impact. Because*

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only one type of impact was used in this study, we cannot build on acute correlation between pigs and PMHS for the thoracic wall response, but we can affirm that, under the same threat:

- *The motion of the pig's chest is greater than that of the PMHS*
- *Severity of the impact for a given Blunt Criterion is always higher for PMHS than pigs*
- *The bone in the porcine model is more elastic and less brittle than older PMHS bone.*

Pavier [14] did a series of test against porcine eviscerated hemi thoraces of 80 kg subjects using 2 short (42-g) and 2 long (78-g) projectiles made of two proprietary foam nose material. All projectile were 30 mm diameter. Dynamics of the thoracic deformation was measured and included the maximum thoracic deformation (Dmax). The authors demonstrate a relationship between the measured Dmax and the initial momentum of the projectile and showed similar relation using live porcine thoracic deformation from [12].

Finally, to study commotio cordis, Dau [16] did a series of experiments with an instrumented Lacrosse balls (64.7 mm diameter, 188.4 g for the 2 lowest impact speed and 214.5 g for the 2 highest impact speed) impacting at 13.4, 17.9, 22.4 and 26.8 m/s against:

- PMHS thoraces (7 subjects, 1 male, weighing 44.9 to 71.2 kg, mean 58.9 kg) on which a total of 23 impacts were done. PMHS thoraces were tested until injury occurred. As a result, between 2 and 8 impacts per PMHS were done.
- Live porcine subject thoraces (n = 17, weighing 21 to 45 kg, mean 32.9 kg) for a total of 187 impacts. Porcine thoraces were tested until normal cardiac rhythm could not be reached between shots. As a result, between 9 and 12 impacts per porcine subjects were done.

All impacts occurred over the center of the cardiac silhouette. For the porcine subjects, only the consolidated ventricular fibrillation risk (VF) function against impact characteristics and average thoracic response corridors are presented, while for the PMHS, detailed Cmax, VCmax and peak force data as well as average thoracic response corridors are presented. Comparison between live porcine and PMHS response shows that for low impact velocities (13.4 and 17.9 m/s), response are similar, while for the two highest impact velocities (22.4 and 26.8 m/s), the peak forces and peak deflections of the porcine subjects are higher than for the PMHS.

2.4 Summary of findings

This literature review indicates that a relationship between animal (live or post-mortem) and PMHS response to thoracic impact exits. The exact nature of the relationship is not clear although some trends can be underlined:

- Yaek [10], clearly demonstrate that PMHS and live porcine response are comparable for subjects with the same total body mass under the same impact conditions. She also validated the use of scaling laws to scale thoracic response for different subject size. Unfortunately, these demonstrations were done for side impacts and for high mass-low impact velocity (~10 m/s) impacts.
- For lower mass-higher impact velocity impact conditions, Prat [12], conclusion mentions that the motion of the pig's chest is greater than that of the PMHS. This seems contrary to Yaek conclusion. The difference can be explained if we consider that the range of mass of the porcine subjects (49 ± 1.5 kg) is quite different from the range of mass of the PMHS (46 to 101 kg). Scaling of thoracic response to body mass might reduce the observed difference.
- Still for low mass-high impact velocity impact conditions, Dau [16] shows that as the projectile impact velocity increases, the discrepancy between the PHMS and porcine response increases, porcine thoracic dynamic being higher. This fits well the conclusion from [12], but again, the difference between the PMHS body mass (44.9 to 71.2 kg) and the porcine subject's body mass (21 to 45 kg) might explain the observed difference.
- In [3], Neurauter compared live porcine subject to live human thoracic stiffness. Response for both species were found to be different for larger deformation (live porcine thoraces being stiffer than live human thoraces). Porcine subject's mass range (23-46 kg) was most likely lower than that of the 90 human patients (mass data not available). These data were generated for very low loading rates.
- Only CPR data from [4] compares thoracic response of live humans to PMHS. In this case, subject's mass data is not available. The authors observed that PMHS thoraces are stiffer than live human thoraces. Similar to above, these data were generated for very low loading rates.

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If a relationship between live or post-mortem porcine thoracic response and PMHS/live human thoracic response exists, clearly the rate of application of the force and the subjects mass have to be considered.

3. OPEN LITERATURE DATA ANALYSIS

Analysis of the above mentioned open literature data is presented in the following sections. For the response related dependent variables VCmax (m/s), Cmax (mm/mm) and Dmax (mm), the independent variables studied are: Energy (E, in J), Energy per unit area for the impactor (E/A, in J/cm^2), Impulse (I, in Ns), Impulse per unit area for the impactor (I/A, in Ns/cm^2), Impact velocity (V, in m/s), Blunt Criterion (BC[1]) and mV/W/D (projectile momentum, in Ns scaled by animal mass W, in kg and projectile diameter D, in cm). For all variables, the projectile mass (m) is in kg. The independent variable mV/W/D is used here since it was used in [18] as a preliminary variable and enables scaling to the impact to the animal size and impact surface.

For the injury severity related data, dependent variables # Rib Fx (number of rib fractures) and # Rib Fx/A (# Rib Fx scaled to the projectile impact area, in cm^2) are used. The independent variables studied are, with the same units as above: E, E/A, I, I/A, V, BC, mV/W/D, VCmax and Cmax.

For all curve discussed the coefficient of determination (R^2) is calculated and presented in the figures and an ANOVA (ANalysis Of VAriance) is done on the fitted equation parameters to assess if the curves for the different subject groups (PMHS, PMPS and LPS) are statistically different. The data fitting process was done using MS Excel LINEST function from which the standard error estimate can also be found. Statistically significant difference is reached if p-value of the test is less than 0.05.

3.1 Dynamic response related dependent variables correlation

Error! Reference source not found. presents VCmax versus projectile momentum data. Data used for LPS are from [12] and data used for PMHS are from [12], [11] and [16]. Consequently, all data used are for low mass-high velocity impacts. No VCmax data are available for PMPS. It can be observed that response for LPS is higher than for PMHS, but an ANOVA of the equation parameters shows that they are not statistically significant, i.e. both curves are essentially the same (equation: $y = Ax^B$, for A, $p = 0.162$, for B, $p = 0.238$). This is due to the large scatter of the PMHS data. Therefore, for the same projectile momentum, LPS present similar VCmax values compared to PMHS.

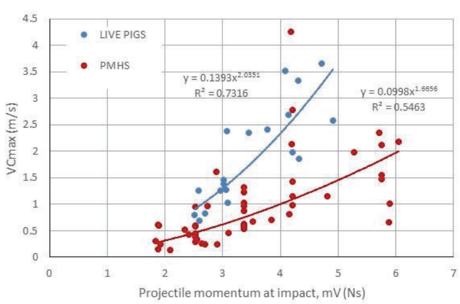

Figure 1 – VCmax (m/s) versus projectile momentum (Ns) for live porcine subjects and for PMHS

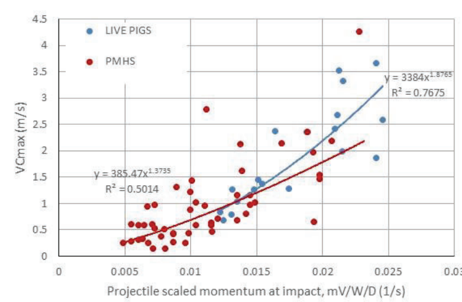

Figure 2 – VCmax versus mV/W/D (1/s) for live porcine subjects and for PMHS

Error! Reference source not found. presents VCmax versus mV/W/D. Data used for LPS are from [12], data used for PMHS are from [12], [11] and [16]. Consequently, all data used are for low mass-high velocity impacts. No VCmax data are available for PMPS. The relationship between VCmax and BC (not shown) did not produced good correlation. Animal mass and projectile diameter scaling of the projectile momentum data have not changed the outcome: both curves are essentially the same (equation: $y = Ax^B$, for A, $p = 0.061$, for B, $p = 0.058$). The same conclusion can be given for VCmax versus BC data (not presented here).

[1] Blunt Criterion, BC is defined in [17] as: $BC = \ln(E/(W^{1/3} \times T \times D))$, where E is the projectile energy in J, W is the animal mass in kg, T is the thoracic wall thickness in cm and D is the projectile diameter in cm. The thoracic wall thickness is estimated in [17] using the following formulas: $T = k \times W^{1/3}$ where $k = 0.751$ for pigs, $k = 0.593$ for women and $k = 0.711$ for men.

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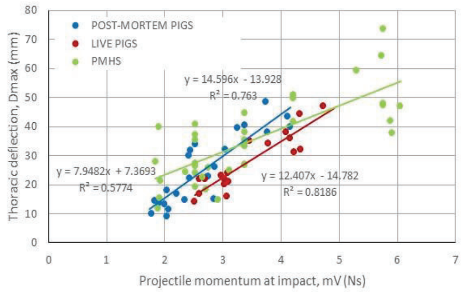

Figure 3 – Maximal thoracic deformation versus initial projectile impulse for LPS and PMPS, reproduced from [14], with PMHS ([12], [11] and [16]) data overlaid.

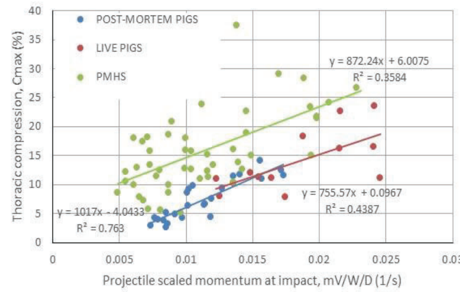

Figure 4 – Cmax versus mV/W/D for LPS, PMPS and PMHS. Data for LPS are from [12], data for PMHS are from [12] and [11] and finally, data for PMPS are from [14].

Pavier [14] shows that for PMPS and LPS, the projectile initial momentum correlates to the maximal thoracic deformation, Dmax. The figure reproduced from [14] is presented in Figure 3 with PMHS data from [12], [11] and [16] overlaid on top. The average body mass of the LPS in [12] is 49 kg and it is 80 kg for PMPS in [14] while for PMHS, it is 69.3 kg in [12], 79.3 kg in [11] and 58.8 kg for [16]. Despite the different average body mass of the datasets and the large variation of the PMHS data, analysis shows a statistically significant difference between both types of porcine subjects and PMHS (PMHS vs LPS: $y = Mx + B$, for M, $p < 0.01$, for B, $p < 0.01$), while it shows no statistically significant difference between LPS and PMPS (PMPS versus LPS: $y = Mx + B$, for M, $p = 0.170$, for B, $p = 0.452$). Therefore, under the same projectile momentum, PMHS thoraces deforms differently than porcine subjects, either live or post-mortem. Another ANOVA (correlation not shown here) shows that thoracic compression (Cmax) versus projectile momentum curves are not statistically significant between PMHS, PMPS and LPS. Scaling of the projectile momentum with the subjects' body mass and projectile diameter (mV/W/D), Figure 4 shows that maximal thoracic compression curves are not statistically significant between PMHS, PMPS and LPS (PMHS vs PMPS: $y = Mx + B$, for M, $p = 0.245$). Again, this is due to the large scatter of the PMHS data.

For VCmax and Cmax data, attempts were made to reduce variability of the PMHS data by using only one dataset at a time (either [12] or [11] or [16]) to see if significant difference between PMHS and porcine data fit could be observed. No significant differences were observed. In conclusion, comparison of thoracic response data for a variety of blunt impact conditions shows that:

- VCmax values for thoracic impacts on LPS and PMHS are similar (not statistically different) for a given scaled (mV/W/D or BC) or unscaled (mV) projectile impulse
- Cmax values for thoracic impacts on LPS, PMPS and PMHS are similar (not statistically different) for a given scaled (mV/W/D or BC) or unscaled (mV) projectile impulse.
- Post-mortem human subject Dmax is different of porcine subjects (live or post-mortem) Dmax. No difference is found between live and post-mortem porcine subject responses.

3.2 Injury severity related dependent variables correlation

Figure 5 presents number of rib fracture versus Cmax data for LPS, PMPS and PMHS. Data for LPS are from [12] and [8], data for PMHS are from [12] and [11] and finally, data for PMPS are from [14] and [8]. The data cover a wide range for impact conditions covering low mass-high velocity impacts and high mass-low velocity impacts. Direct comparison between curves shows they are all statistically different. Notice also that the R^2 for PMPS (0.97) and LPS (0.71) are high, whereas it is low (0.52) for PMHS.

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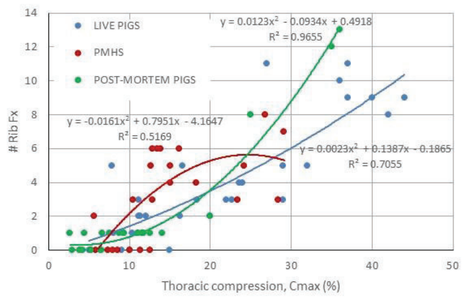

Figure 5 – Number of rib fracture versus Cmax for live and post-mortem porcine subjects and for PMHS

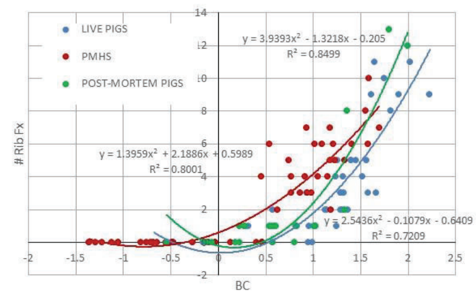

Figure 6 – Number of rib fracture versus BC for live and post-mortem porcine subjects and for PMHS

Figure 6 presents number of rib fracture versus BC for LPS, PMPS and PMHS. Data used for live pig are from [12] and [8], data used for PMHS are from [12], [11] and [16] and finally, data for post-mortem porcine subjects are from [14] and [8]. Again, impact conditions cover low mass-high velocity impacts and high mass-low velocity impacts. Direct comparison between curves shows that PMHS curve is statistically different from both, PMPS and LPS curves and the difference between PMPS and LPS curves is also statistically different. Notice also that the R^2 for each curve is high (0.72 for LPS, 0.80 for PMHS and 0.85 for PMPS).

To conclude, comparison of injury severity (number of rib fracture) for a large variety of blunt impact conditions shows that:

- The BC independent variable enables significant discrimination between PMHS, PMPS and LPS injury response. Also, for each subject types, high correlation is found with BC.
- The Cmax independent variable enables significant discrimination between PMHS, PMPS and LPS injury response. Also, for porcine subjects, high correlation is found with Cmax, but it is not the case for PMHS.
- No correlation is found between the number of rib fracture and VCmax.

4. DISCUSSION

For a given projectile momentum (scaled or unscaled to animal mass), scaled dynamic thoracic response (Cmax and VCmax) are the same between human and porcine subjects. This is due, in part to the large variability of the PMHS response as it can be seen in **Error! Reference source not found.** to Figure 4. Normalisation of the data presented above for a given body mass (50th percentile male, 77.7 kg) following the process detailed in [19], [20] and [21] results in slight decrease of the PMHS response variability. For Dmax, Cmax and VCmax, use of normalisation does not improve the correlation coefficient of the different thoracic response variables for the different subjects, nor does it enable differentiation between PMHS, PMPS and LPS responses. In Yaek [10], dynamic thoracic response of PMHS is found to be the same as the dynamic thoracic response of LPS when data are scaled to the same body mass. Similarly here, it is observed that the dynamic thoracic response of PMHS cannot be differentiated from porcine dynamic thoracic response. Part of the observed PMHS data variation is due to the different projectile compliance used in [11], [12] and [16] and also variation in impact location on the subjects' thorax, which also results in varying compliance. Nevertheless, the current analysis of the dynamic response data seems to support the observations made by Yaek [10] for high mass-low velocity impacts and expands the applicability of Yaek's conclusion to low mass-high velocity data.

Thoracic injury severity response (# of rib fracture) is found to correlate with BC. Furthermore, distinct responses can be observed for PMHS versus PMPS versus LPS. It is found that for the same impact severity, PMHSs' show higher number of rib fracture compared to porcine subjects. Also, PMPSs' show higher number of rib fracture than LPSs' for the same insult. As expected, post-mortem subjects (human or porcine) are more sensitive to impacts than live subjects. In [8], Viano showed that it is the case for high mass-low velocity impacts and in [12], Prat reached a similar conclusion for low mass-high velocity impacts. Results shown here seem to show that it is also the case for a wider range of impact conditions. An estimate of impact sensitivity for LHS is shown in Figure 7. It is calculated assuming that the difference between post-mortem and live porcine subjects is the same as the difference between PMHS

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and LHS. An analysis of Figure 7 shows that the expected number of rib fracture (and therefore the severity of the injury) for a LHS is higher than for either a PMPS or a LPS. For BC values higher than 1.56, the expected severity of injury for LHS is lower than for PMPS and LPS. An impact with a BC value of 1.56 is quite severe as it is is higher than most BABT related impact severity (see next section).

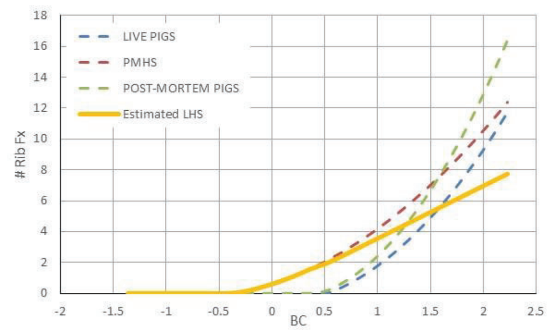

Figure 7 – Estimate of # of rib fractures versus BC for LHS (= PMHS – (PMPS-LPS)). LPS, PMHS and PMPS curves are the same as in Figure 6 with negative # of rib fracture values removed. LHS curve equation is $0.2765x^2 + 2.6194x + 0.6385$

The relationship shown above for LHS does not explain why, for similar impact loadings, experimental behind armour data on animals are resulting in injuries while operational data are not showing injurious response. The assumption made above might not be true. In order to assess the truthfulness of that assumption, thoracic blunt impact injury data from theaters of operation would be necessary.

4.1 Severity of KENLW impacts relative to BABT related impacts

The conclusions made above are mostly based on data related to KENLW projectile impacts. Although BABT and KENLW projectile impacts are both considered as blunt impacts, they are not necessarily equivalent. Literature contains a large number of thoracic BABT test results that involve the use of specific alumina and UHMWPE armours against a variety of projectiles, including 12.7 mm Ball, 7.62 mm Ball and 5.56 mm Ball projectiles, [22] to [33]. As these tests involve the use of LPS some comparison can be drawn at least on the severity of the impacts generated in both scenarios. To enable comparison, it is necessary to translate the complex projectile-armour interaction into an equivalent projectile. Assuming conservation of momentum just before and just after impact on the armour and assuming that the armour surface pushed against the thorax corresponds to the surface of the bruise left on the animal, it is possible to calculate an effective mass, an effective velocity and an effective BC value for a given BABT event. Figure 8 presents effective BC versus effective mass for BABT ([22] to [33]) and KENLW ([11], [12], [16]) events. The use of BC to assess impact severity accounts for both, the severity of the impact and the size of the animal and therefore enables a direct comparison of impact severity.

It can be seen that the severity level (BC value) for each type of event is generally equivalent and it is lower than BC = 2.0. The impact with a BC value of 2.85 was obtained for a very light animal (20 kg only). The effective projectile mass range for BABT experiments is much larger than for KENLW impacts, i.e. impacts should be done with heavier blunt projectile to cover the full range. Finally, severity of impact for typical 7.62 mm Ball round corresponds to the upper end of KENLW impact severity, i.e. impacts with typical KENLW projectiles should be done at higher velocity to reach the level required to simulate BABT impacts.

5. CONCLUSIONS

Dynamic and injurious response of PMHS and porcine thoraces to blunt impacts for a wide range of impact conditions were studied with the objective to determine the expected thoracic response of live human subjects. The study showed that dynamic thoracic response of PMHS and porcine subjects are difficult to differentiate due to the large variations in PMHS response data available. The injury severity for PMHS, post-mortem porcine subjects and live porcine subjects with respect to impact BC was shown to be statistically different. This enables the estimation of the thoracic response of live humans by assuming that the difference between post-mortem and live porcine subjects is the same as the difference

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between PMHS and live human subjects. It is predicted that LHS would have more severe injuries than PMPS and LPS for similar impact for a wide range of impact severity. Clearly, BABT related injury data from the field must be used to verify the assumptions used to assess live human subject response. In addition, it is demonstrated that the range of blunt impact tests on animal and PMHS test should be expanded to cover the full range of BABT injury severity and that those tests should be done against animals with the same body mass as the subjects to be protected. The data presented cannot explain the observed difference in BABT injury severity between laboratory animals and humans.

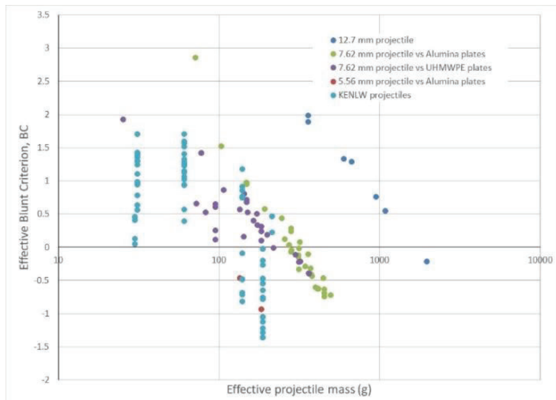

Figure 8 – Estimate of effective BC versus effective impact mass on the thorax of LPS and PMHS for KENLW projectile and BABT events

REFERENCES

[1] Maltese, M.R., Arbogast, K.B., Wang, Z. & Craig, M.T., Scaling Methods Applied to Thoracic Force Displacement Characteristics Derived from Cardiopulmonary Resuscitation, National Highway Traffic Safety Administration, 22nd International Technical Conference on the Enhanced Safety of Vehicles, 13-16 June 2011, Washington, D.C., USA.

[2] Maltese, M.R., Arbogast, K.B., Nadkarni, V., Berg, R., Balasubramanian, S., Seacrist, T., Kent, R.W., Parent, D.P., Craig, M. and Ridella, S.A., Incorporation of CPR Data into ATD Chest Impact Response Requirements, Ann Adv Automot Med. 2010 Jan; 54: 79–88.

[3] Neurauter, A., & al. Comparison of mechanical characteristics of the human and porcine chest during cardiopulmonary resuscitation, Resuscitation, Vol. 80, 2009, pp 663-469

[4] Arbogast, K.B., Maltese, M.R., Nadkarni, V.M., Steen, P.A. & Nysaether, J.B., Anterior-Posterior Thoracic Force-Deflection Characteristics Measured During Cardiopulmonary Resuscitation: Comparison to Post-Mortem Human Subject Data, Stapp Car Crash Journal, Vol. 50, November 2006, pp. 131-145

[5] Gruben, K., Guerci, A., Halperin, H., Popel, A. & Tsitlik, J., Sternal force-displacement relationship during cardiopulmonary resuscitation, Journal of Biomechanical Engineering, Vol. 115, 1993, pp. 195-201.

[6] Tsitlik, J., Weisfeldt, M., Chandra, N., Effron, M. Halperin, H. & Levin, H., Elastic Properties of the human chest during cardiopulmonary resuscitation, Crit. Car. Med., Vol. 11, No. 9, 1983, pp. 685-692

[7] Viano, D.C., Warner, C.Y., Thoracic Impact Response of Live Porcine Subjects, Paper 760823, Proceedings of the 20th Stapp Car Crash Conference, New York, Society of Automotive Engineers, Inc., 1976

[8] Viano, D.C., Kroell, C.K. and Warner, C.Y., Comparative Thoracic Impact Response of Living and Sacrificed Porcine Siblings, SAE Technical Paper 770930, 1977.

[9] Neathery, R.F., Kroell, C.K. and Mertz,, H.J., Prediction of Thoracic Injury from Dummy Response, Paper 751151, Proceedings of the 19th Stapp Car Crash Conference, New York, Society of Automotive Engineers, Inc., November 1975

https://doi.org/10.52202/078352-0026

[10] Yaek, J., Biofidelity Assessment Of 6-Year-Old Anthropometric Test Devices (ATDs) And Scaling Laws In Lateral Impact, Wayne State University Doctoral Dissertation, Paper 1902, Jan. 2017.

[11] Bir, C. A., The Evaluation of Blunt Ballistic Impacts of the Thorax, Wayne State University Doctoral Dissertation, 2000

[12] Prat, N., Rongerias, F., de Freminville, H., Magnan, P., Debord, E., Fusai, T., Destombe, C., Sarron, J.C., and Voiglio, E.J., Comparison of thoracic wall behavior in large animals and human cadavers submitted to an identical ballistic blunt thoracic trauma, Forensic Science International, 222 (2010)

[13] Prat, N., Rongerias, F., Voiglio, E., Magnan, P., Destombe, C., Debord, E., Barbillon, F., Fusai, T. & Sarron, J.C., Intrathoracic Pressure Impulse Predicts Pulmonary Contusion Volume in Ballistic Blunt Thoracic Trauma, The Journal of Trauma, Vol. 69, No. 4, October 2010.

[14] Pavier, J., Langlet, A., Eches, N., Prat, N., Bailly, P. and Jacquet, J.F., Experimental study of the coupling parameters influencing the terminal effects of thoracic blunt ballistic trauma, Forensic Science International, 252, 2015, pp. 39-51

[15] Pavier, J., Langlet, A., Eches, N., and Jacquet, J.F., On ballistic parameters of less lethal projectiles influencing the severity of thoracic blunt impacts, Computer Methods in Biomechanics and Biomedical Engineering, Vol. 18, No. 2, 2015, pp. 192-200.

[16] Dau, N., Development of a biomechanical surrogate for the evaluation of commotio cordis protection, Wayne State University Dissertations, Paper 407, 2012

[17] Sturdivan, L.M., Viano, D.C., Champion, H.R., 'Analysis of Injury to Assess Chest and Abdominal Injury Risks in Blunt and Ballistic Impacts', Journal of Trauma, Volume 56, No. 3, March 2004.

[18] Clare, V.R., Lewis, J.H., Mickiewicz, A.P. and Sturdivan, L.M., Blunt Trauma Data Correlation, Report number EB-TR-73016, Edgewood Arsenal, Maryland, USA, May 1975

[19] Mertz, H.J., Irwin, A.L., Melvin, J.W., Stalkner, R.L., Beebe, M.S., Size, Weight and Biomechanical Impact Response Requirements for Adult Size Small Female and Large Male Dummies, Society of Automotive Engineers, Paper 890756, 1989

[20] Irwin, A.L., Mertz, H.J., Elhagediah, A.M., Moss, S., Guidelines for Assessing the Biofidelity of Side Impact Dummies of Various Sizes and Ages, Stapp Car Crash Journal, Vol. 46, November 2002, pp. 297-319.

[21] ISO/TR 12350:2013, Road vehicles – Injury risk curves for the evaluation of occupant protection in side impact tests, Edition 2, October 2013.

[22] Gryth, D., Maj. 'Hemodynamic, Respiratory and Neurophysiological Reactions after High-Velocity Behind Armor Blunt Trauma', Thesis for Doctoral Degree, Karolinska Institutet, Sweden, 2007.

[23] Drobin, D., Gryth, D. Maj., Persson, J.K.E., Rocksén, D., Arborelius, U.P., Olsson, L-G., Bursell, J. and Kjellström, B.T., 'Electroencephalogram, Circulation, and Lung Function After High-Velocity Behind Armor Blunt Trauma', Journal of Trauma, Vol. 63, No. 2, pp 405-413, August 2007.

[24] Gryth, D. Maj., Rocksén, D., Persson, J.K.E., Arborelius, U.P., Drobin, D., Bursell, J. and Olsson, L-G., 'Severe Lung Contosion and Death after High-Velocity Behind-Armor Blunt Trauma: Relation to Protection Level', Military Medicine, Vol. 172, pp 1110-1116, October 2007.

[25] Gryth, D. Maj., Rocksén, D., Arborelius, U.P., Drobin, D., Persson, J.K.E., Sondén, A., Bursell, J., Olsson, L-G., Kjellström, B.T., Bilateral vagotomy inhibits apnea and attenuates other physiological responses after blunt chest trauma, J Trauma, Vol. 64, No. 6, Jun 2008, pp 1420-1426.

[26] Rocksén, D., Gryth, D., Druid, H., Gustavsson, J. and Arborelius, U.P., 'Pathophysiological effects and changes in potrassium, ionised calcium, glucose and haemoglobin early after severe blunt chest trauma', Injury, Int. J. Care Injured, 43 (2012), 632-637

[27] Gryth, D., Rocksén, D., Drobin, D., Druid, H., Weitzberg, E., Bursell, J., Olsson, L-G., Arborelius, U.P., Effects of fluid resuscitation with hypertonic saline dextrane or Rigner's acetate after nonhemorrhagic shock caused by pulmonary contusion, J Trauma, Vol. 69, No. 4, Oct. 2010, pp 741-748

[28] Sondén, A., Rocksén, D., Riddez, L., Davidson, J., Persson, J.K., Gryth, D., Bursell, J. and Arborelius, U.P., 'Trauma Attenuating Backing Improves Protection Against Behind Armor Blunt Trauma', The Journal of Trauma, Vol. 67, No. 6, December 2009

 https://doi.org/10.52202/078352-0026

[29] Riddez, L., Rocksén, D., Dondén, A., Persson, J.K., Gryth, D., Bursell, J. & Arborelius, U.P., 'Increased Protection Against Behind Armour Blunt Trauma using Trauma Attenuating Backing (TAB)', Proceedings of the Personal Armour System Symposium 2006, Leeds, UK, 19-22 September 2006.

[30] Johansen - Trial Report 02/97 - Behind Armour Blunt Trauma, Danish Army Combat School, Trials and Safety Branch, 24-28 February 1997

[31] Sarron, J.C., Destombe, C., Da Cunha, J., Martinez, Vassout, P., Magnan, P., Blessures thoraciques par balle de guerre sous protection balistique individuelle – Étude comparative de trois plaques de protection – Essais conduits à Oksbøl (Danemark) par le groupe de travail TG001 du groupe OTAN HFM 024, PEA 980823, DGA/DSP/STTC/DT-SH, décembre 2000

[32] Sarron, J.C., Destombe, C., Da Cunha, J., Martinez, Vassout, P., Lésions Thoraciques fermées par balles de guerre – Étude comparative de deux plaques de protection : céramique et polyéthylène, PEA 980823, Contrats DGA 98028, 9810075 et 98040, septembre 1999

[33] Sarron, J.C., Destombe, C., Da Cunha, J., Morin, Chene, Vassout, P., Magnan P., Gravité des blessures non-penetrantes du thorax protégé par in gilet pare-balles en fonction de l'énergie d'impact d'une munition de calibre 7.62 – Étude de seuils lésionnels, PEA 980823, DGA/DSP/STTC/DT-SH, février 2003

https://doi.org/10.52202/078352-0026