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Overview of Thoracic and Abdominal Blunt Impact Injury Models

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Abstract

Weapons systems deliver a variety of effects on human targets. One of the common effects is blunt trauma. It could result from ballistic impacts (Behind Armour Blunt Trauma – BABT) against either soft or hard ballistic body armour, from secondary blast effects (caused by non penetrating debris), from tertiary blast effects (caused by whole body displacement) or from impacts caused by kinetic energy non lethal weapons (KENLW). The design of a thoracic physical model that can deal with both KENLW blunt impacts and behind the armour blunt impacts would be beneficial to evaluate protection systems. Its development necessitates biomechanical data such that the model mimics the dynamic behaviour of the human body (e.g. biofidelic). Similarly, to assess impact severity using the thoracic physical model, trauma information that enables the definition of injury functions is required. Both types of data exist. They are covering a large number of impact conditions, mostly for KENLW type of impacts. It is therefore mandatory that all the data be assembled such that trends can be identified. This paper provides an overview of useful information to define biofidelic thoracic and abdominal physical models. Basic biomechanical data – maximum body wall deflection - are tentatively assembled using different parameters to provide general thoracic and abdominal impact response relations. Most of the data are valid for blunt rigid or soft impactors rather than for BABT and this is why a calibration/validation process is discussed. Injury thresholds for different types of injury are also defined to help in the calibration/validation process. The injury threshold discussed herein includes probability of lethality and probability of lung, heart, liver, kidney and bowel injuries.

Keywords: BABT, non-lethal weapon, blunt impact, injury thresholds, biomechanics

1 Introduction

DRDC Valcartier, NIST/OLES/NIJ (National Institute of Standards and Technology/Office of Law Enforcement Standards/National Institute of Justice), TSWG and Biokinetics and Associates are involved in the development of test methods to assess the performance of thoracic protection equipment and blunt impact kinetic energy non lethal weapons (KENLW). The test method described in reference [1] involves ballistic limit tests, proofing velocity tests and BABT evaluation tests. The BABT evaluation test method proposed uses a biofidelic thoracic membrane. That membrane has to be calibrated such that the dynamic characteristics of the membrane, under specific impact loads, are similar to that of either anesthetised animals or PMHS (Post-Mortem Human Subjects) for the widest range of impact condition possible. The test method uses a Laser Displacement Transducer (LDT) to measure the membrane displacement. One of the issues with the current BABT performance test methods is that it uses ballistic clay to assess BABT performance. It is known that ballistic clay has many issues, including that it does not have biofidelic compliance and that the backface deformation limit imposed by the standard does not correspond to actual injury limits [2]. Thus, to be significant, the proposed BABT performance test method has to incorporate injury threshold values that are based on both: thoracic membrane dynamics and animal/PMHS injury data.

Table 1 Summary of thoracic and abdominal biomechanical and injury data

Ref	Impact mass range	Impact velocity range	Biological reactor used	Location of impact	Biomechanical response parameters	Injury data
	(g)	(m/s)				
[3]	1750	7.14 to 19.05	Dog	Lateral, left, at 5th costal interspace and mid clavicular line	Dmax/Cmax/Fmax/Amax/Vmax/VCmax	MAIS AIS-85 score
[4,5,6]	30 & 140	20, 40 & 60	PMHS	Frontal, above center of sternum	D(t), F(t), VCmax, BC	Skeletal AIS score (sternum, rib fractures)
[7]	140 & 380	19.7 to 72	Swine	Frontal Mid-sternum & lateral right	Dmax, Cmax	Sternal injury (fracture) and cardiac injury description
[8]	3000 to 69	5.8 to 81.2	Swine	Right lateral thorax over diaphragmatic lobe of lung	Dmax, Cmax, t95	Quotient of lung injury Qi
[9, 10, 11]	21000 - 4900	8.1 to 30.7	Swine	Frontal Mid-sternum	Cmax/Fmax/Amax/Vmax/VCmax/Dmax	Heart rupture, VF, AIS-84 score
[12]	80 & 53	32 to 52.1	Swine	Lateral, right between 6th and 8th ribs	Dmax	Rib fracture
[13]	1600 - 23600	4.4 to 14.6	PMHS	Frontal, 4th interstitial space	Cmax, Fmax	AIS-76 score, no. of rib factures
[14]	45 & 50	45.2 to 76.6	PMHS & swine	Epigastric, liver & bowel regions	F(t)/D(t)/Fmax/Dmax/VCmax/AIC/BC/ED	AIS-?? Score for bowel and liver
[15]	23500	4.3	PMHS	Level of the 6th rib anteriorly on the right side	F(t), D(t), Fmax, Dmax	AIS-90 score and injury details
[16]	52 to 377	15.9 to 85.8	Swine	5 cm cranial to prepuce in males subjects	D90, t90	Bowel/intestinal injury descriptions
[17]	45 & 95	35 (approx.)	Swine	Between 11th and 9th intercostal space		Complete injury description
[18]	227	10.9 to 45.7	Goats	Thorax & liver regions		Lung,/heart/liver injury description
[19]	167 & 500	14 to 66	Goats	Heart, kidney, between 7th and 13th rib		Complete injury description
[20]	300 & 430	27.0 to 58.4	Goats	Liver region	Dmax	
[21]	63 to 382.8	18.9 to 91.4	Dogs	Mid-lateral point to the right side of the thorax		No. of rib fractures, survival
[22]	8.2 & 17	58 to 179	Swine	Thorax, liver & kidney area		Thorax injury description, survival
[23]	3.23	162 to 280	Swine	Heart, liver & kidney area		Injury description, survival
[24]	264	15.9 to 34.2	Swine	Thorax, liver & kidney area		Injury description, survival
[25]	30	50.8 to 94.4	Swine	Heart, liver & kidney area		Injury description, survival
[26]	11.7	58.2 to 149.4	Swine	Thorax, liver & kidney area		Injury description, survival
[27]	190	16.7 – 34.5	Swine	Thorax, liver, spleen & kidney area		Injury description, survival
[28]	43 to 210	18.3 to 85.7	Goats	Thorax & liver area		Survival

Dmax: Maximum thoracic deflection, D(t): Thoracic deflection versus time, Cmax: Maximum thoracic compression, Vmax: Maximum thoracic wall deformation velocity, Fmax: Maximum force applied to the thorax, F(t): Force applied to the thorax versus time, Amax: Maximum acceleration applied to the thorax, t95: Time to reach 95% reduction in projectile velocity, t90: Time to reach 90% reduction in projectile velocity, D90: Displacement at 90% reduction in projectile velocity, VCmax: Viscous criterion, BC: Blunt criterion, AIC: Abdomen Injury Criterion, ED: Energy dissipated, Qi: Quotient of lung injury. It is the injured lung weight/predicted normal lung weight, VF: Ventricular Fibrillation

Finally it will be shown that there is a relation between impact characteristics (projectile mass, velocity, diameter, animal mass, i.e. the blunt criterion - BC) and parameters that can be measured directly on the thoracic membrane such as maximal deformation but also the viscous criterion. This step is essential to provide confidence that calibration and validation of the membrane can be done.

This paper proposes an overview of thoracic and abdominal biomechanical and injury data that can be used to calibrate the proposed membrane and to generate injury threshold data for a range of impacts: from KENLW impacts to soft body armour impacts to rigid body armour impacts. It also proposes consolidated relationships between impact characteristics and thoracic/abdominal wall displacement or injury probability for different impact conditions, different animals and different impact directions. Finally, the relationship between impact characteristics and parameters that can be measured using the membrane will be done.

2 Overview of biomechanical/injury data and calibration/validation process

A literature survey was done to identify papers and reports that related to thoracic and abdominal biomechanical data and thoracic and abdominal injury data for a large range of impacts characteristics. Table 1 presents a summary of those data, including the projectile's mass, velocity, the animal type, the location of the impact, the biomechanical response parameters reported and the injury data available. The range of data (mass-velocity) for all those data is shown in Figure 1 and Figure 2.

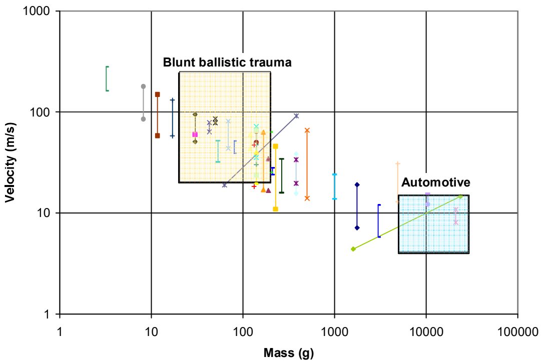

Figure 1 - Range of mass & velocity of data presented in Table 1 for thoracic impacts

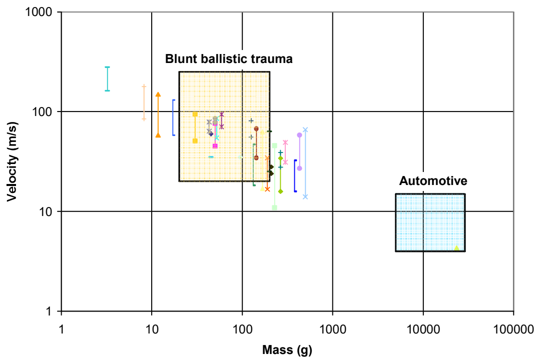

Figure 2 - Range of mass & velocity of data presented in Table 1 for abdominal impacts

Overlaid over the references mass-velocity data, regions of interest for automotive and blunt ballistic impacts [6] are shown. It should be noted that many of the data were generated using KENLW systems. It shows that many data exist within the right mass-velocity range that can be used to calibrate the proposed thoracic membrane and to generate injury thresholds. Data are available for a range of targets with a range of body weight. Impact location shows the most variability, some being defined precisely, while others are being defined generally as an impact area.

Amongst the biomechanical response parameters available, maximum deflection (and maximum compression) is the most common parameter. It will therefore be used to generate the calibration data presented in the next section. Although ballistic clay also uses maximum deflection as injury parameter with all its known limitations, remember that ballistic clay is not a calibrated medium, hence maximum deformation measured in clay cannot be related to any type of injuries. This is what we are trying to avoid by calibrating our membrane. A parameter like VCmax would have been the ideal choice for calibration, but unfortunately, VCmax data does not exists for the spectrum of interest. Body armour related data [29 - 36] are presented in Table 2. They will not be used for the generation of the biomechanical data relations but it is planned that they will be used for validation of the membrane for soft and hard body armour. Part of the issues in doing such validation is to access the armour used to generate the injury data. In some cases foreign body armour systems have to be used [30, 31, 32], in other cases, experimental body armour systems [29] were used and finally, in the case of soft body armours tests done in the 70's, old body armour systems have to be acquired. Furthermore, for some data, the descriptions of components of the body armour are defined using generic names or do not relate to specific items that can be traced back. The proposed process to calibrate (steps a) to c)) and validate (steps d) and e)) the thoracic membrane would be:

a) Reproduce impact conditions presented in the references shown in Table 1 on the thoracic membrane.
b) Measure the dynamic behaviour of the thoracic membrane and correlate its response to the intended response based on relations presented in section 3.
c) Similarly, correlate the thoracic membrane response to the injuries based on relations presented in section 4.
d) Reproduce impact conditions from references [29 - 36] and measure thoracic membrane response.
e) Compare expected response and expected injuries based on steps b) and c) to actual response as described in the references.

Table 2 Hard and soft body armour data

Ref	Impact mass range	Biological reactor used	Location of impact	Data available
[29]	Hard BA (UHMWPE)	PMHS	Frontal, middle of sternum	Amax, Fmax, AIS-98 score
[30]	Hard BA (AL_2O_3/B_4C + vest + TAB)	Swine	Lateral thorax	Amax, Vmax & Dmax, pulmonary & myocardial contusion, rib fractures, survival
[31]	Hard BA (AL_2O_3 +vest+TAB)	Swine	Lateral thorax	Summary of injuries
[32]	Hard and soft BA	Animal, PMHS & incidents	Various	Injury description
[33]	Soft BA	Swine	Left thoracic wall at mid-axillary line	Injury description
[34]	Soft BA	Goat	Left chest above cardiac silhouette	Thoracic injury descriptions
[35]	Soft BA	Goat	5th intercostal space, 12 inch from dorsal midline	Thoracic injury descriptions
[36]	Soft BA	Goat	Thorax area	Thoracic injury descriptions

3 Biomechanical dynamic characteristics for membrane calibration

The objective of this section is to establish biomechanical dynamic characteristic curves for the largest projectile impact conditions possible for both, thoracic impacts and abdominal impacts such that the thoracic membrane can be calibrated with the largest quantity of impact conditions possible.

3.1 Thoracic impacts

From all the references mentioned in Table 1 data were extracted and plotted against a series of parameters, based primarily on the Blunt Criterion (BC) and on variations of the BC. The blunt criterion is an energy-based parameter developed by Sturdivan [20, 37]. It relates physical target and projectile characteristics to the probability of lethality using the Blunt Criterion defined as:

$$BC = \ln\left(\frac{E}{W^{1/3}TD}\right)$$

$E = 1/2mV^2$ = Blunt impactor's kinetic energy (J)
m = Blunt impactor mass (kg)
V = Blunt impactor velocity (m/s)
W = Animal weight (kg)
T = Animal body wall thickness (cm) = $kW^{1/3}$. Value of k varies with animal species.
D = Diameter of the blunt impactor (cm)

The animal weight and animal body wall thickness are target related parameters while impact energy and diameter are projectile related parameters. From that equation, it becomes clear that an impactor with a large area (D) will result in a lower BC and therefore a lowest probability of lethality. Also, a lighter target (W) will be more sensitive to BABT than a heavier target, against the same projectile and using the same armour.

In most of the references specified in Table 1, the body wall thickness is unknown and was evaluated as specified in [37]. It is interesting to note that if the body wall thickness equation inserted in the BC equation, BC becomes:

$$BC_m = \ln\left(\frac{k_a E}{W^{2/3} D}\right)$$

In the last equation, k_a is a constant that depends on the animal species. Figure 3 presents the maximal body wall deformation plotted versus BC for the data from references [3, 5, 7, 8, 9, 10, 11, 12, 13] with the values k as defined in [37]. It is interesting to note that Bir data for PMHS [5], Niu data for swine [12] and Cooper data also for swine [7, 8] are reasonably well aligned. Those data include frontal thoracic impacts for PMHS and both, lateral and frontal impacts for swine thoracic impacts. Viano data for PMHS [13], Kroell data for swine [9, 10 & 11] and Baosong data for dog [3] are either above or below Bir, Niu and Cooper data. Since Viano and Kroell data were obtained for impacts with very large masses at very low impact velocities comparative to the impact characteristics of blunt ballistic impact. It was thus decided to remove Kroell and Viano data for our curve fit, especially that very low coefficient of correlation (R) were obtained when those data were used.

Table 3 shows the best curve fits for different dependent and independent variables using the above mentioned data. Fits using maximum deformation were slightly better than fits with maximum compression. A total of 3 parameters were used for the curve fit, i.e. 2 parameters for the equation (A and B) and one parameter for the animal species (k or k_a) – PMHS, dog and swine. To constrain the curve fit process, it was assumed that k (or k_a) for swine is fixed to 1.0 such that data from PMHS and dog are converging toward swine data.

Amongst the different independent variables tested (including BC and BC_m), the best results were for a modified version of BC and BC_m that includes a ratio of the projectile mass to the animal body weight. It is believed that the ratio scales the data for the different animal masses and projectile masses present in the data. Figure 4 presents the data points and the curve fit for the best of the 3 fits presented in Table 3.

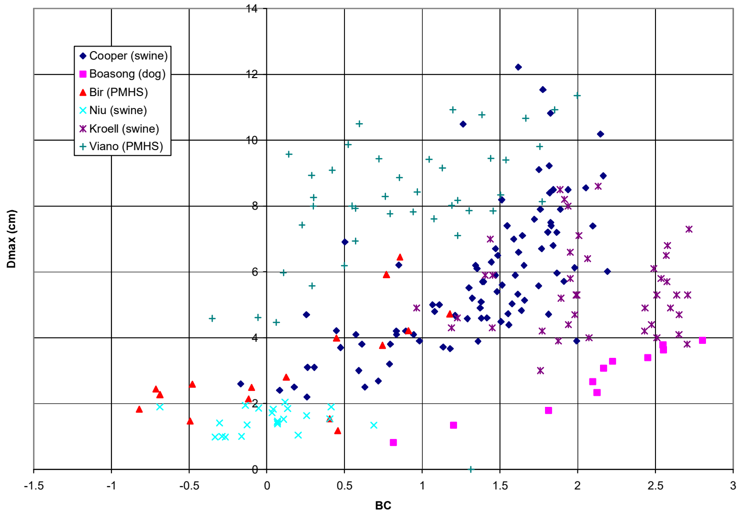

Figure 3 Maximal displacement versus BC

Table 3 Curve fit parameters for thoracic impact related maximal deformation

Independent Variable (x)	Dependant Variable	Equation	A	B	$k_{a\ PMHS}$	$k_{a\ dog}$	$k_{a\ swine}$	R
$\ln\left(\frac{k_a E}{W^{2/3} D}\left(\frac{m}{W}\right)^{1/3}\right)$	Dmax	$D_{max} = Ae^{Bx}$	8.093	.5758	2.1121	.0426	1.00	0.899

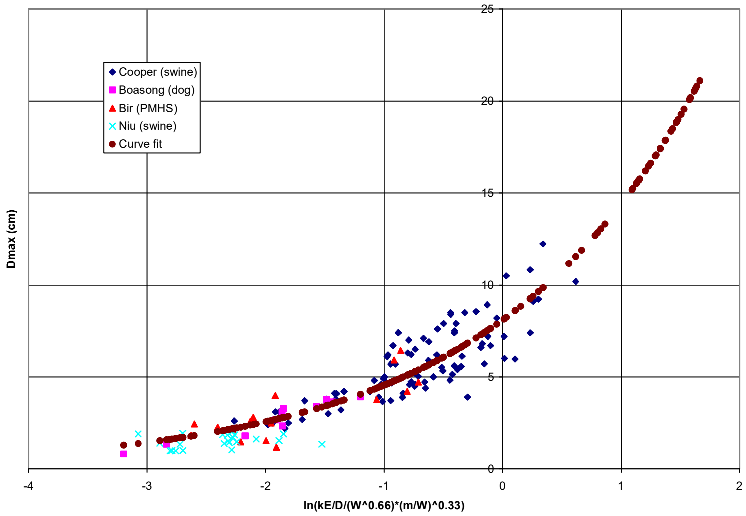

Figure 4 Curve fit of maximal displacement versus a modified version of BC_m for thoracic impacts.

3.2 Abdominal impacts

For abdominal impacts a process similar to the one presented for thoracic impact was performed. Data used are coming from Cripps [16] for bowel impacts on swine, Bir [14] for bowel and liver impacts on swine and in PMHS, OTA [20] for liver impacts on goats and from Yoganandan [15] for epigastric impacts on PMHS. Variations of the BC did not show up as the best fits for those data. Instead, the following ratio was found to give the best results:

$$\frac{k_a mV}{WD}\left(\frac{m}{W}\right)^{1/3}$$

The animal mass and projectile diameter are still present in the parameter while the kinetic energy of the projectile is replaced by its momentum. Notice also the presence of the projectile mass-animal mass scaling ratio. Table 4 presents the curve fit parameters for the bowel and liver impacts and for the bowel impacts alone excluding data from Yoganandan [15]. Figure 5 shows the curve fit along with the data points. Notice the large variations in the goat data. They were removed because those data resulted from low velocity high mass impacts incompatible with the other more relevant data.

Biomechanical response data (thoracic wall compression) presented by Cripps [16] were different to the other data sets. Indeed, for that reference, the compression data were evaluated relative to the 'internal' abdominal depth whereas the other references presented their compression data relative to the 'external" abdominal depth. Since the exact correction factor was unknown, Cripps data were corrected during the fitting process by using a value of k_a different to the other swine data ($k_a = 4.906$ for bowel and liver fit, $k_a = 2.772$ for bowel only fit compared to $k_a = 1.0$ for other swine data). Finally, it should be noted that a physically significant curve fit from the liver data alone could not be found.

Table 4 Curve fit parameters for abdominal impact related maximal deformation

Body area	Independent Variable (x)	Dependant Variable	Equation	A	B	$k_{a\ \text{PMHS}}$	$k_{a\ \text{goat}}$	$k_{a\ \text{swine}}$	R
Bowel & liver	$\frac{k_a mV}{WD}\left(\frac{m}{W}\right)^{1/3}$	Cmax	$D_{max} = Ax^B$	3.100	.4429	.9043	6.148	1.00	0.942
Bowel only				5.532	.5174	.7848	-	1.00	0.965

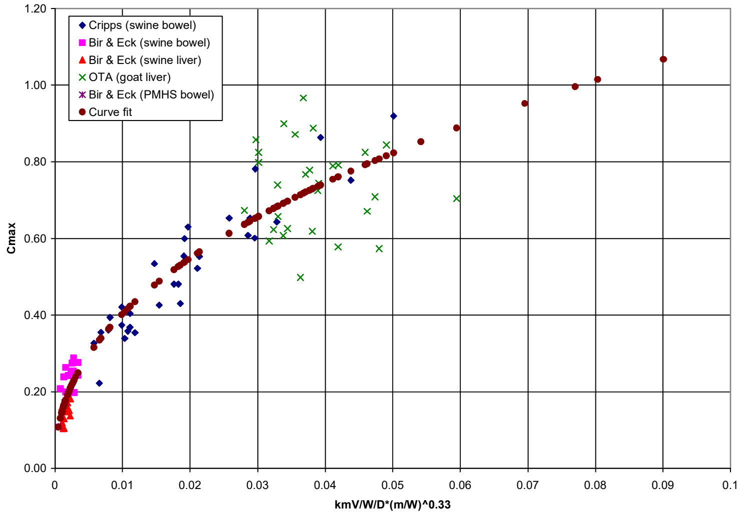

Figure 5 Curve fit of maximal compression for abdominal impacts.

4 Injury threshold data

All references presented in Table 1 were scanned to find either injury data or AIS data. Available data in each reference are presented in Table 1. When only injury descriptions were found, they were transformed into an AIS-2005 score [38, 39]. Depending on the presentation of the data, the AIS-2005 score was done either for each organ, or for the total injury. Earlier AIS scores were specified in some references, but it was assumed that they are similar to the current AIS-2005. Impact area was specified more or less precisely depending on the reference and analysis was done according to the general impact location. In some references, ventricular fibrillation [7, 9, 10, 11], heart rupture [7, 9, 10, 11, 22, 23, 24, 25, 26, 27], liver fracture [14 ,17, 18, 19, 22, 23, 24, 25, 26, 27, 28] and death [9, 10, 11, 19, 22, 23, 24, 25, 26, 27, 28] were also specified. Independent variables used to create the injury threshold curves were: BC, BC_m and BC_{scaled}, defined as:

$$BC_{scaled} = \ln\left(\frac{E}{W^{2/3}D}\left(\frac{m}{W}\right)^{1/3}\right)$$

It was not possible to use VCmax as an independent variable since most of the references mentioned in Table 1 do not present viscous criterion data. The data were fitted using a logistic equation:

$$P = \frac{1}{\left(1 + e^{-(A+Bx)}\right)}$$

Where x is the independent variable and A & B are the logistic equation parameters. Table 5 presents the best fit parameters for the different impact location and injury type. The table is divided in 3 parts: the first relates to death probability when impact occurs over the specified organ, the second relates to probability of injuries to the specific organ and the third part relates to the probability of maximum AIS (MAIS) level when impact occurs over the specific area.

In addition the velocity at which 50% probability of injury is predicted to occur is presented at the last column of Table 5 for a typical 140 g projectile, 3.7 cm diameter against a 70 kg man. Based on those data, the heart and liver regions are the most sensitive.

Table 5 Injury threshold best fit

Impact location/ organ	Injury type	Independent variable	A	B	R	No. data points	$V_{50\%}$ (m/s)
Liver	Death	BC_{scaled}	.8115	2.988	0.45	102	62
Thorax & heart	Death	BC_m	-3.299	1.597	0.45	209	84
Liver	Liver AIS $\geq$ 2	BC_{scaled}	2.568	2.180	0.50	72	47
Liver	Liver AIS $\geq$ 4	BC_m	-4.666	2.486	0.61	72	77
Heart	Heart rupture	BC_{scaled}	-1.507	1.266	0.49	149	129
Bowel	Bowel AIS $\geq$ 2	BC_m	-6.083	6.481	0.59	45	48
Lungs	Lung AIS $\geq$ 3	BC_m	-2.623	2.476	0.53	79	51
Lungs	Lung AIS $\geq$ 4	BC_{scaled}	-2.180	29.12	0.58	79	74
Kidney	Kidney AIS $\geq$ 2	BC_m	-1.707	1.622	0.48	54	51
Liver	MAIS $\geq$ 3	BC_m	-3.225	2.719	0.65	110	54
Liver	MAIS $\geq$ 4	BC_m	-5.999	3.235	0.67	110	76
Heart	MAIS $\geq$ 3	BC_{scaled}	4.425	3.696	0.70	11	39
Kidney	MAIS $\geq$ 3	BC_m	-3.090	1.842	0.50	54	69

5 Correlation between BC and VCmax

To complete the process described in section 2, it is essential that a relation between the parameters for which we have the most data - BC and its variations - and the thoracic or abdominal wall dynamics – Cmax, Vmax or VCmax - exists. This is because only the membrane dynamics will be measured during actual testing. Note that the relation between variations of BC and Cmax was demonstrated in section 3, but for the BC related injury thresholds, it is necessary to transform them to another parameter which is related to the membrane dynamics. Relationships between injury and variations on BC have been demonstrated in section 4, but a relation with VCmax would be more meaningful as VCmax is known to be related to injury severity. Sturdivan et al. [37] have published data that demonstrate a relation between VCmax and BC for relatively large mass, low velocity impacts. Other specific data presented in Table 1 demonstrate similar relationships as seen in Figure 6 and Figure 7.

This gives hope to the authors that a calibration of the membrane based solely on maximum deformation as well as variations of the BC will provide good results during the validation process and injury thresholds definitions process as the BC is related to VCmax and both are related to injuries.

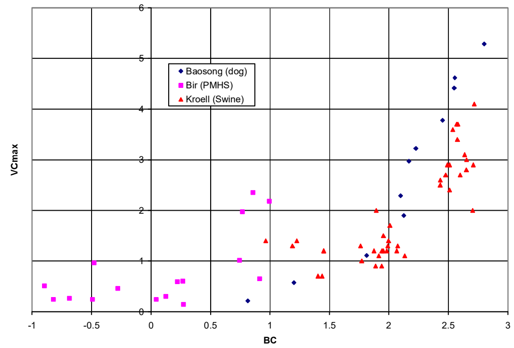

Figure 6 – VC_{max} vs BC relation for thoracic impacts

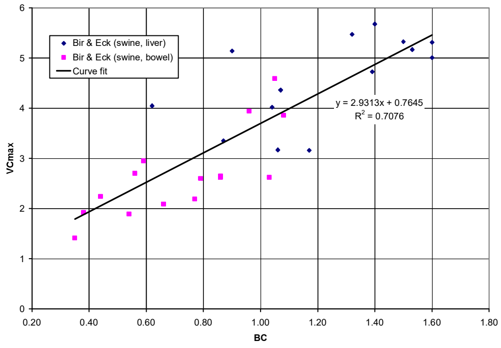

Figure 7 - VC_{max} vs BC relation for abdominal impacts

6 Conclusion

This paper demonstrated that a large body of biomechanical data and injury data exists that can be used to design, calibrate and validate a biofidelic BABT device - thoracic membrane – from KENLW impacts to soft body armour and up to hard body armour. These data have been used to extract biomechanical calibration curves for thoracic and abdominal impacts. The same data have been used to extract injury thresholds that can be used as limits for test methods. Finally relations between the viscous criterion and the blunt criterion are demonstrated.

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