A Vulnerability/Lethality Model for the Combat Soldier, A New Paradigm – Basis and Initial Development

N. Shewchenko[1], E. Fournier[1], M. Wonnacott[1], K. Williams[2], D. Filips[3], and L. Martineau[2]

[1]*Biokinetics and Associates Ltd., 2470 Don Reid Drive, Ottawa, Ontario, Canada K1H 1E1, Shewchenko@biokinetics.com*
[2]*Defence Research and Development Canada (DRDC) – Valcartier, 2459, boul Pie-XI Nord, Québec, Québec, Canada, G3J 1X5*
[3]*Innovative Trauma Care Solutions Inc., 122 Advanced Technology Centre, 9650 - 20 Ave., Edmonton, Alberta, Canada, T5W 0N9*

Abstract. Advances in vulnerability and lethality (V/L) modelling are being pursued for the analysis of mitigating strategies. Improving the prediction of morbidity and mortality from polytrauma, accounting for various threat effects and determining the effectiveness of protective systems for the combat soldier are some of the primary objectives. A new V/L paradigm is proposed for defining consistent injury severity assessments and ranking methods to allow for subsequent V/L and incapacitation analyses to be conducted. Advances in computational techniques, anatomical models and injury research have made it possible to improve the fidelity, specificity and accuracy of injury assessment methods. Further improvements are proposed by incorporating multiple injury ranking schemes, physiological parameters and temporal effects relevant to combat operations. The current paper presents the development of an assessment model, computational methods, and review of injury ranking methods and their limitations. The effects of penetrating, blunt force trauma, and blast threats are currently implemented in a relational database for integration with whole system V/L assessment models. The initial efforts employ an anatomically-based injury classification scheme for integration with a highly detailed human model representing major organs, circulatory, nervous and skeletal systems. The initial development and population of the injury assessment database show great potential for use with detailed human and protective system V/L assessment models to be conducted in future efforts where validation and enhancement of the processes are anticipated.

1. INTRODUCTION

Experience with recent combat casualties and victims from Iraq and Afghanistan have highlighted the occurrence of unique injury patterns and mechanisms. The resulting injury mechanisms and pathology typically involve polytrauma from blast overpressure, blunt impact, acceleration, ballistic and penetrating threats. In order to mitigate trauma through the development of effective protection systems, a thorough understanding of the threats, their interactions with soldiers and surrounding environment and resulting injuries is required. Limitations and effectiveness of existing protection systems must also be assessed to identify areas for study and improvement.

The assessment of weapons effects and protection systems has traditionally been limited to empirical approaches utilizing animals or synthetic surrogates for penetrating, blunt and blast-related trauma. The interaction and injury mechanisms of the threats are replicated with the objective of determining the overall outcome, whether it is operational or medical in nature. Assessment of survivability, lethality, vulnerability, incapacitation and medical interventions are examples of possible outcomes that are pertinent to the military environment.

With the use of computational techniques in the early 1970's for lethality analysis, analytical methods have evolved and paralleled much of the biomechanical studies. The computational methods were used to assess the effectiveness of weapons and included elements of threat interaction modelling in conjunction with injury severity assessment and eventually evaluation of its impact on the final performance objective. The evolution of injury assessment and scoring models over this time has also assisted in this effort with continued improvements occurring to this very day.

This paper describes the advances being made to the computational techniques employed at DRDC Valcartier for developing a human vulnerability/lethality (V/L) modelling tool. It is intended to employ the V/L Model to evaluate the effectiveness of personal protective equipment (PPE) in mitigating the effects of ballistic, blast and blunt impact threats. Existing injury predictive models and discrete shot line analyses can be improved upon with better anatomical detail and more comprehensive injury assessments. Recent knowledge of threat interactions, injury mechanisms, injury prediction criteria, and injury tolerance was obtained from literature published in the past decade, including those prompted from modern day conflicts in Iraq, Afghanistan, Croatia, Lebanon and the Gulf Wars.

The current V/L Model development effort is work in progress and comprises identifying and implementing injury assessment and scoring methods. Discussion of the threat injury mechanisms, resulting trauma as well as injury criteria and thresholds are presented along with their eventual implementation into a relational database for subsequent V/L analysis.

2. BACKGROUND

Existing models for survivability-lethality-vulnerability (SLV) prediction assess the interaction of conventional threats such as projectiles and fragments with the victim to determine their effect. The required models include that of the threat and delivery to the victim, their interaction with the anatomy and physiology, and injury outcome assessment. Prior to developing new models to address these requirements, knowledge can be gained from existing models with similar objectives.

Some past penetrating injury assessment models have focused on improving trauma care by providing better diagnostic tools for the medical community. One such model, TraumaSCAN provides a means to simulate and evaluate the consequences of injury to the thorax and abdomen [2]. The model tries to overcome the effects of missing or incomplete information on the extent of injury, patient vital signs and symptoms. The method uses an expert knowledge base in conjunction with detailed models of the human anatomy and probabilistic reasoning to arrive at an outcome. The use of Bayesian networks for reasoning lends itself well to diagnostic evaluation under conditions of uncertainty while accounting for dependent and independent relationships. While further validation is required and application to the military environment is unknown, the methodology has promise for analysis of qualitatively different parameters. It is, however, limited in anatomical detail due to the descriptive nature of the injured body regions.

Another approach taken by Rubin *et al.* to diagnose penetrating injuries incorporates descriptive information about anatomy with geometric organ information to provide a more comprehensive picture of the potential injuries and their sequelae [3]. The descriptive information, contained in ontologies, details potential implications with adjacent organs or those that are also likely to be affected. This is an alternate method for combining descriptive and geometric information but it is not considered to be advanced enough to provide an independent assessment of injury outcome.

ComputerMan is another injury penetration model that deviates from the generalized ballistic dose approach by employing wound ballistics knowledge with a detailed anatomical model [4-6]. The approach estimates the various tissues that are damaged along a wound tract for a given projectile velocity, orientation and trajectory. Each wound is coded for injury severity, initially with an index and then Abbreviated Injury Scale (AIS) [7]. The overall Injury Severity Score (ISS) [7] and Anatomic Profile Score (APS) [8, 9] are then evaluated [1]. Through a number of correlations, incapacitation is established. The anatomical model is constructed from cross sections of a human and the tissues within are mapped into a grid. A total of 108 sections and 297 organs or parts thereof are represented, Figure 1.

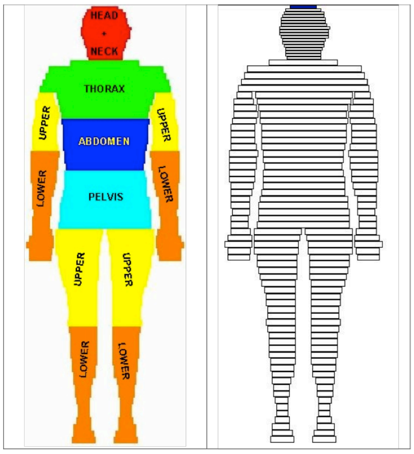

Figure 1: Depiction of the ComputerMan model segmentation.

A standardized casualty assessment model, Operational Requirements-based Casualty Assessment system (ORCA), has been developed by the U.S. Army Research Laboratory to study weapon-induced injury and soldier performance across a range of military platforms and tasks as well as weapon-induced threats (fragments, blast overpressure, acceleration, blunt trauma, directed energy, thermal and chemical contact/inhalation) [10, 11]. The accuracy of the ORCA model predictions depends greatly on the underlying simplifications and approximations made, in particular, the anatomical detail, interactions with various threats and corresponding rankings of injury severities. ORCA employs the same wound ballistic routines as ComputerMan. Both ORCA and ComputerMan employ discrete elements to coarsely represent the human anatomy with equally detailed information on the injury

[1] The ISS is based on the sum of the three maximum AIS values squared, across different body regions. The APS is based on the square root of the sum of the AIS scores squared for all serious injuries, *i.e.* AIS>3, in a body region thereby reflecting the affect of multiple injuries within a region.

outcomes. ORCA has the capability to assess injuries from blast and blunt impact threats which employ different computational models.

ORCA employs a standardized injury severity classification scheme to ensure compatibility with various analysis methods to be conducted. Penetrating threats are based on the Abbreviated Injury Scale (AIS) which is also the basis for overall body severity scoring methods including the Injury Severity Score (ISS), Anatomic Profile score (AP), Modified Anatomic Profile (MAP) [12] and Trauma and Injury Severity Score (TRISS) [13]. A unique feature of ORCA is the method to determine impairment to an individual's capabilities. An Elemental Capability Vector (ECV) is utilized which employs parameters for sight, hearing, mental, speech, physical capability and endurance. Time effects are also accounted for to recognize injury changes over time. Injury assessments are therefore carried out at 6 post-injury times (0 and 30 seconds, 5 minutes, 1 and 24 hours, and 3 days). Additional features for task requirements and individual characterization, such as the presence of PPE, are implemented.

The soldier vulnerability model, VeMo-S is also being developed to assess injuries, incapacitation, mission capability reduction, lethality, ammunition effectiveness and protective equipment effectiveness against fragments and small arms [1]. Assessments are based on the physical disruption of 400 elements approximating critical organs, muscles, tissues, bones, nerves and vessels caused by the permanent cavity of the threat, Figure 2. Ballistic dose and bodily insult determine the risks of injury. Time-to-fail was also incorporated into the injury risks assessments for discrete time intervals (0 and 30 seconds, 5 and 30 minutes). While physiological and psychological effects are not taken into account, blunt trauma assessment is being considered for cases with multiple penetrating and non-penetrating projectiles.

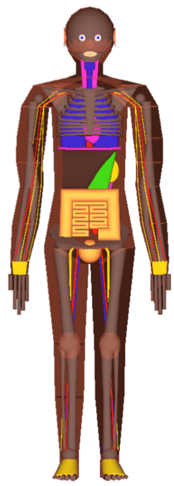

Figure 2: Soldier vulnerability model, VeMo-S [1]

3. V/L MODEL APPROACH

Assessment of injury outcomes from ballistic, blunt impact and blast threats requires knowledge of the relationships between the threats, interaction with the human anatomy, physiology, and sequelae resulting from the insult. As an initial approach toward this objective, an anatomical approach was chosen, appreciating that physiological parameters must be introduced at a later time to improve overall injury assessment accuracy.

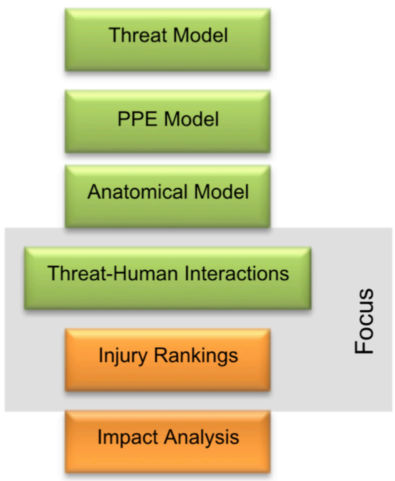

Figure 3: Injury assessment approach.

An overview of the critical elements required to fulfill the program objectives is illustrated in Figure 3. The threat and personal protective equipment (PPE) computational models define the insult seen by the soldier while the anatomical model represents the critical tissues required to assess injury outcome. Interactions between the threats and tissues are defined by various prediction methods. Final assessment of the outcome is determined by ranking the injury severities and determining the overall impact on operational or medical performance objectives. Military objectives may include survivability, lethality, vulnerability and incapacitation whether it applies to the soldier or weapon systems.

The focus of the current program deals with understanding the fundamental threat-human interactions and developing injury rankings for implementation with supporting threat and anatomical models, implementation and impact analysis methods provided by the Survivability and Lethality Assessment Modelling Software (SLAMS) tool in development at DRDC Valcartier.

3.1 Anatomical Model

In an effort to improve the threat-human interaction models and predictions, a higher fidelity anatomical model was developed, V-Man [14]. The V-Man model is based on a highly detailed commercial 3-dimensional anatomical male Zygote™ model [15] and is widely considered to be the most comprehensive and best-crafted three-dimensional dataset available today Figure 4. Each model/system within the dataset maintains true to life human shape with accurate proportion and positioning of the anatomical systems. Skeletal, integument, circulatory, reproductive, respiratory, lymphatic, urinary, digestive, nervous, and muscular systems are represented. The tissues are defined by three-dimensional geometric surfaces that can be integrated with other computational modules for interrogation and analysis.

The sole use of an anatomical model will limit the ability to assess trauma due to the lack of physiological assessment factors that may influence the injury outcome. Ideally, the physiological systems would be assessed to aid in the prediction of mortality or morbidity (*i.e.* endocrine, immune, haematologic, coagulation, acid/base balance, thermoregulatory, metabolic, electrolyte regulation, circulating blood volume, neurally-mediated responses, other pathophysiological responses). However, their inclusion with the Zygote™ model is not currently possible and, as such, the current focus remains with anatomically-based injury predictions. The Zygote is also currently limited in terms representing the population (age, sex, stature, somatotype) and cannot be manipulated for assuming different postures.

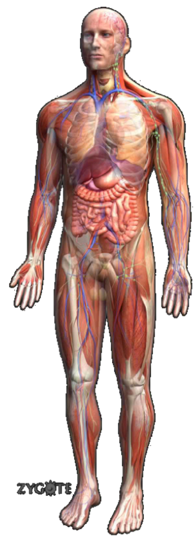

Figure 4: Zygote™ human model.

3.2 Injury Severity Scoring

Injury severity scoring is the process by which complex anatomical and physiological information is reduced to a single ranking. The intent of the score is to accurately quantify the degree to which an individual has been wounded to help determine the impact on medical, operational or strategic performance objectives. The reality is, however, that achieving a high degree of accuracy is unrealistic considering the complexity and variability of the human system, assumptions that are made, and loss or absence of important information for the ranking process. As a result, a multitude of injury ranking scoring systems have been proposed in the literature to address specific objectives and are not always consistent in their methods or rankings. The basis and application of these systems are critical to their implementation into the V/L Model.

Current injury scoring systems can be loosely structured into one of three categories; 1) anatomical; 2) physiological; and, 3) combined/predictive. They can also be classified as consensus based or data-driven. These scoring systems are used for a variety of applications including the triage of pre-hospital patients, making transfer decisions between hospitals, predicting outcomes, improving the quality of programs, making clinical decisions, and retrospectively evaluating injury prevention programs [16].

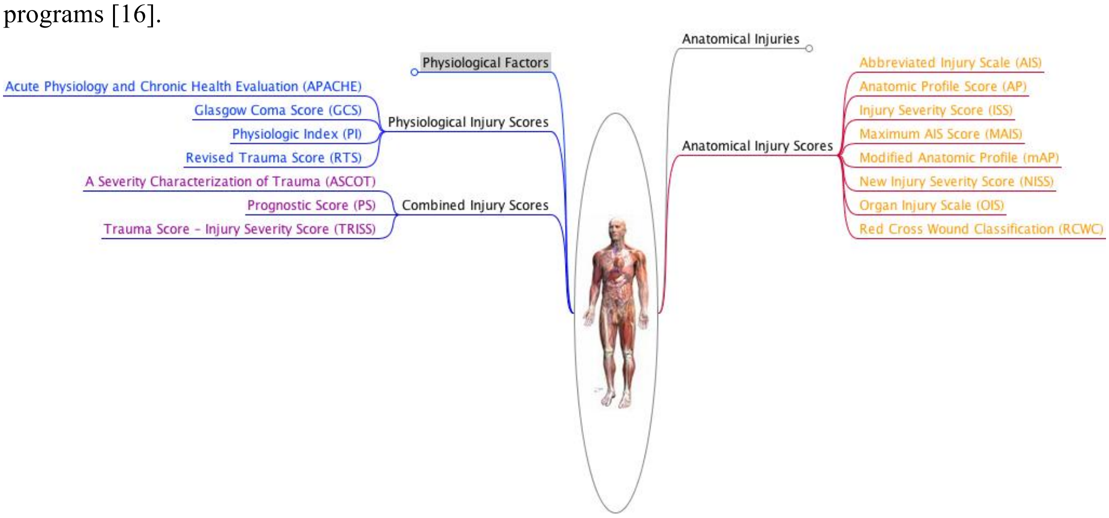

Figure 5: Trauma scoring schemes involving anatomical and physiological assessments.

Anatomy-based injury scoring systems are generally based on the extent and location of tissue disruption, the nature of the injured tissue, and the sensitivity to mechanical injury of the tissue in relation to mortality/localized amputation without consideration for physiological variables. Anatomical injury scores can be further divided into localized injury scores which consider only one tissue region and are generally based on the probability of amputation and/or recovery, and global anatomically-based injury rankings which consider the body as a single unit and scores are generally ranked with respect to threat-to-life. Several anatomical scoring methods are depicted in Figure 5.

Physiologically-based injury scores are primarily used for pre-hospital triage, evaluating the efficacy of treatment, and predicting outcomes. Systolic blood pressure, respiratory rate, heart rate, arterial pressure, and percentage of oxygenated blood are typical measures to assess the effect of an injury on function. Physiologically-driven scales are focused on the response of the body to trauma.

Combined trauma scores calculate the probability of survival based on both anatomical tissue disruption and physiological factors. These scales tend to have a better applicability in research settings and are not commonly found in hospital settings due to their complex calculation.

The AIS assessment method has been selected for evaluating anatomical tissue disruption in the V/L Model due to its good level of detail and whole body application to blast overpressure, blunt force, and penetrating trauma. Furthermore, it is the basis for most other anatomical injury scoring systems, is widely implemented, and can be cross-referenced with previous studies. However, the ability for AIS to distinguish between survivors and non-survivors is shared with many other scoring classification schemes. Where AIS is lacking in detail, more in-depth anatomical scoring systems may be utilized though these values will be correlated to corresponding AIS values for input into the trauma scoring.

Polytrauma in the V/L Model is to be scored with New Injury Severity Scale (NISS) and the Red Cross Wound Classification (RCWC) which is calculated to provide additional detail with respect to visible anatomical disruption. The RCWC will also provide increased information relating to wounds within the military community. The NISS has been selected because it has been found to be the most accurate AIS-based predictor of trauma mortality in the civilian and military contexts [17].

Other AIS-based polytrauma scores that can easily be calculated include the ISS, Maximum AIS (MAIS), and the MAP. A more recent Revised Injury Severity Score (RISS) shows promise as it is noted to outperform both ISS and NISS [18]. These will be implemented in future efforts due to their ease of calculation and value, in providing insight into the V/L Model assessments.

Recognizing the limitations of an anatomically based scales, consideration of physiological parameters (*e.g.*, change in blood pressure, blood loss, level of consciousness, respiratory rate, etc.) and time to treatment and type of medical intervention available could increase confidence in the injury rankings. However, the practicality and utility of including physiological response in a predictive manner remains to be determined in light of physiological variability, ability to predict the responses and validity in representing the mean population. When physiological variables are quantifiable within the V/L Model, physiological rankings such as the Physiologic Index (PI), A Severity Characterization of Trauma (ASCOT), Trauma and Injury Severity Score (TRISS), Revised Trauma Score (RTS), and Glasgow Coma Scale (GCS) may be explored for overall assessment.

The need for consistent injury taxonomy and scoring has also been instrumental to human systems integration studies including the US Army's Manpower and Personal Integration (MANPRINT) program. Application to a wide range of injury severities, from acute to chronic, for a wide range of domains was required [19]. Anatomical scoring systems and combined anatomical-physiological based systems were recommended with consistency provided by use of the military version of the AIS.

3.3 Injury Interactions

A method for accurate quantification of extent of the trauma produced by blunt impact, ballistic and blast threats has many potential benefits, including improved allocation of medical resources and the ability to predict the outcome of trauma, including incapacitation and lethality. Computer models that have the ability to accurately predict these outcomes have unencumbered potential within the military setting in determining the effects on operational effectiveness of various personal protective equipment (PPE) and situational strategies.

The following encompasses the injury mechanisms and recommendations for potential injury ranking systems to be used within the V/L Model, both currently available and prospective directions for future research.

3.4 Penetrating Injuries

Penetrating type injuries involve four mechanisms based on Patrick [20] and Kneubuehl [21]. It should also be noted that the permanent cavity may result from the expansion and disruption of tissue during formation of the temporary cavity.

- Penetration wound: the tissue through which the projectile passes, and which it disrupts or destroys;
- Permanent cavity: the volume of tissue destroyed by the passage of a projectile;
- Temporary cavity: the maximum expansion of the wound channel by stretching due to the transfer of energy during passage of the projectile; and,
- Fragmentation: projectile pieces or secondary fragments of bone which are driven outward from the permanent cavity into surrounding soft tissue.

The susceptibility of human tissues and organs to penetrating injuries depends greatly on the elastic nature of the tissues with some capable of withstanding the expansion from large temporary cavities (*e.g.* muscle, vessels, lungs, bowel) while others have little tolerance to these tensile loads (*e.g.* kidneys, brain). Wound classification systems based on kinetic energy or projectile velocity can overemphasize the importance of velocity in determining the wounding potential of a projectile as the missile and tissue characteristics typically determine the nature of the wound. Bullet mass in combination with its profile, shape and material construction often determines a bullet's penetrative ability, including whether it will penetrate tissue to the depth of vital structures. Bullet construction determines whether the bullet will deform or fragment, while bullet shape and centre-of-mass decide when, and if, the bullet will yaw (tumble) in its path through tissue. The thickness of the body part and density of the tissue establish if the bullet will perforate the body region or have sufficient time to yaw, while tissue elasticity and density determine the ability of the tissue to withstand temporary cavitation [22, 23].

Assessment of penetrating injuries must account for the bullet trajectory and depth of penetration into tissue. The approach taken with the V/L Model is intended to assess the injury severity based on anatomical disruption of tissue. As such, anatomical descriptors of tissue damage from the AIS method will be used as the preferred method over sole use of energy based models (*i.e.* Kokinakis and Sperrazza [24], Sturdivan [25]). Information on penetration depth, projectile dynamics, permanent and temporary cavities is still required to determine which anatomical interactions will occur for a given penetration and is planned to be provided by an empirically based threat model being developed at DRDC Valcartier. While not discussed further here, there are several hundred injury criteria within the AIS and anatomically detailed scales that are applicable to tissue disruptions from penetrating trauma.

3.5 Blunt Impact Injuries

Blunt trauma comprises any injury sustained from non-penetrating impact to the body by an object or physical attack and is often referred to as blunt force trauma. Motor vehicle accidents, falls, impact from blunt objects or being thrown against rigid surfaces are known sources of this type of injury in theatre. The term blunt trauma may encompass concussions, abrasions, contusions, ruptures, lacerations, and bone fractures.

In trauma related to interactions with blunt objects (*e.g.*, large projectiles, vehicle accidents, body thrown against a surface by blast wind), the slower loading rates result in energy transfer to the body in the form of compression, tensile, and shear stresses and strains. This may result in structural deformation (focal and distributed) of the body and translation and rotation of the body, in part or as a whole with dynamic loads imposed on the body or internal tissue. For most cases, the body experiences all types of local and global energy transfer [26]. Furthermore, blunt trauma related to indirect and inertial loading can also lead to dynamic effects on the body with related stresses and strains in the whole body and internal tissues.

Injury functions and criteria estimating the severity of blunt trauma injuries have been primarily derived from experimental tests on cadavers or animals, and occasionally on human volunteers. It is important, however, to recognize that there are many inherent problems with the development of injury criteria, including sample size, age of cadaver subjects, scaling from animal to human tolerances or cadaver to living human tolerances, and transfer of the loads to 'real-world' events. Further, limitations in sensor technology and test dummy biofidelity have resulted in injury criteria which correlate to kinetic and kinematic parameters (forces and movement) of the surrogate rather than tissue stresses or strains.

Blunt trauma injury assessment criteria differ from anatomically-based ones in that the injury outcome is typically more global in nature and addresses the survivability of the test subject taking into account the physical injury and sequelae. Physiological effects are therefore indirectly reflected in many of the injury criteria.

For implementation into the V/L Model, the blunt trauma injury criteria have been mapped to the anatomical body regions of the AIS. In many cases where probabilistic estimates are available, thresholds were determined to correspond with the occurrence of a specific AIS injury severity. The simplification allows the injury rankings to be consistent with those for penetrating injuries and with combined anatomical or anatomical/physiological scoring methods.

3.6 Blast Injuries

The study of blast injuries has been noted to be a phenomena of the 20th Century due to the increased usage and effectiveness of explosive type weapons in current events [27]. With this, primary blast overpressure injuries have been observed in addition to more traditional modes which included internal and external tissue damage from penetrating and non-penetrating threats as well as trauma from blast winds propelling the body. Documentation of primary blast injuries from past military conflicts is remarkably sparse with very few cases noted. Lack of data or incomplete records can be attributed to this and is partly due to the focus on penetrating and other immediate life-threatening injuries. The primary focus of blast injuries for the V/L Model will be those that result from exposure to blast overpressure, recognizing that the blast event may result in polytrauma. Penetrating injuries from fragments, non-penetrating trauma, and blast wind effects are dealt with elsewhere in the model. As with other injury modes, the blast injury criteria are mapped to the body regions and scores of the AIS. Many of the published criteria for blast overpressure are derived from experiments with biological, animal and human surrogates and, as such, incorporate aspects of the insult (magnitude, duration) and associated risks of injury outcome for specific AIS levels. For example, the Bowen curves (with recent revisions by Bass and Rafaels [28, 29]), Stuhmiller [30] and Axelsson [31] injury functions are examples of thoracic overpressure injury assessment methods that can be mapped to AIS scores.

4. V/L DATABASE DEVELOPMENT

The means through which the threat interactions, injury assessments and rankings are documented will play an important role in the vulnerability-lethality analysis process. A software tool to easily manage the various body regions, injury ranking schemes, injury interactions and calculations as well as providing a convenient interface to external analysis modules is required. Prior survivability and vulnerability approaches which codify a fixed set of rules and decisions is not practical in the current effort due to the large datasets involved, the complicated interactions between parameters, and the need for information tracking and management. To address these requirements, a relational database was implemented to document the rules and operations associated with different body regions and insult from various threats and to provide a structured approach for queries. This approach is in contrast to data storage and mining applications for which databases are typically used.

The relational database was developed to handle a wide range of injury functions and criteria including those that were dichotomous, stepwise, and continuous in nature. In all cases, the injury assessments were mapped to the ordinal scale provided by the AIS 2005 thereby providing continuity.

The hierarchy of the database follows that of the anatomical regions defined by the AIS which fall into one of three categories;

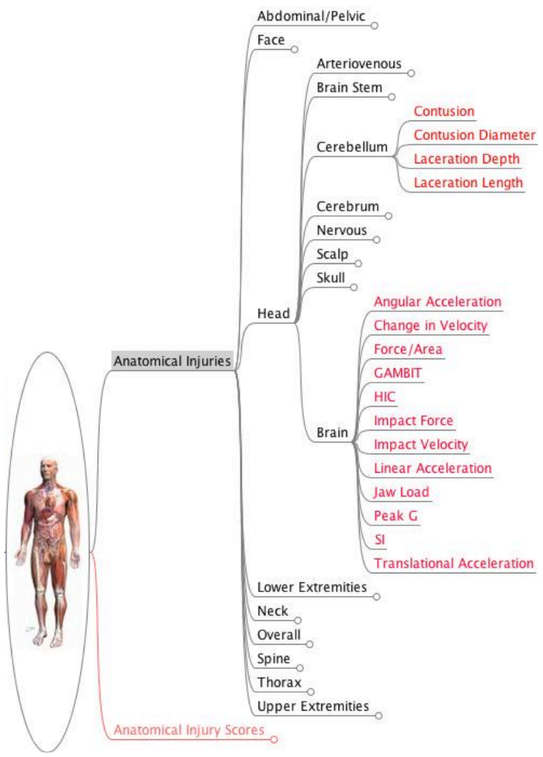

Figure 6: Sample anatomical injury metrics employed in the V/L model.

1) whole body; 2) organ; and, 3) tissue or sub-region, as depicted in Figure 6 for the head. There are currently over 700 injury criteria addressing penetrating, blunt impact and blast threats. Multiple injury ranking methods for a body region/organ/tissue are possible but only one method can be selected as the preferred ranking method for a given body region or sub-region. The database also has computational capabilities to combine or compute additional criteria based on multiple individual assessments in order to provide whole body evaluations.

The V/L database is intended to interface with the SLAMS (Survivability and Lethality Assessment Modelling Software) developed by DRDC which will provide the threat, armour and anatomical models for input into the database, as well as the impact analysis to determine systems effectiveness, operational impact or mission kill decisions.

5. SUMMARY AND RECOMMENDATIONS

The objective of the program was to develop a computational method for assessing injury outcome from penetrating, blunt impact and blast threats in the military environment. The method is intended to be implemented as part of a personnel or global analyses involving vulnerability/lethality and incapacitation assessments. Typical examples may include mortality assessment from penetrating wounds to more complex systems involving polytrauma from blast and ballistic threats in various air/land/sea platforms encompassing personal protective equipment.

Assessment of the injury severity is based on an anatomical approach with threat interaction prediction models and published injury rankings. Initial efforts identified the injury mechanisms (penetrating, blunt impact, blast) and associated criteria with implementation into a relational database. The database permits management and definition of the injury criteria, and assessment of their effects for local and global body regions from polytrauma. A number of limitations with the published criteria were noted that may affect accuracy of the analysis. These include missing information on injury mechanisms, criteria and rankings; inconsistencies with ranking objectives, calculation methods, ranking schemes, use of surrogates, empirical vs. analytical methods, and level of validation; sole use of anatomically-based injury assessments; lack of consistency of threats across studies; relevance of threats to those in current day conflicts; and, inconsistencies among empirical studies regarding the time of injury assessment, animal/human scaling methods, and specimen pre-conditions. In all cases, the injury scores must be mapped to a single scale, *i.e.* AIS 2005, for consistency and the ranking methods should be reviewed by military and medical experts to ensure their relevance and completeness for their intended application. Further to this effort, the military version of the AIS scoring system (AIS-2005-MIL, [32]) should be implemented in place of the civilian scale to reflect combat injuries, conditions and scenarios. Multiple injuries from polytrauma should also consider recent summary injury severity scoring systems such the RISS.

It is proposed that further improvements to trauma assessment accuracy can be achieved by incorporating whole body anatomical, physiological information and any preconditions including victim's details such as age and sex. The TRISS and ASCOT may provide a good foundation for development of a more comprehensive injury assessment methodology. Validation of the revised method should employ large scale and current military casualty and trauma databases representing a range of injury severities and exposure to a wide range of threats including blunt impact, penetration and overpressure. Comparisons can also be made with the Red Cross Classification of War Wounds to validate the injury assessments with a trauma scale more commonly used in theatre. Conceptually, the total trauma assessment can be calculated as follows:

$$\text{Total Trauma} = \Sigma\text{Anatomical Trauma} + \Sigma\text{Physiological Responses} + \text{Preconditions} \qquad (1)$$

The anatomical trauma could be calculated via a more anatomically encompassing scale, such as the Penetrating Trauma Index (PTI) [33], including each standard body region (head/neck, thorax, abdominal/pelvic, extremity, and external). Each anatomical body region would be given a tissue risk factor, which will be multiplied by an injury factor as determined by the extent and location of tissue disruption. These injury rankings will likely be based on the AIS. Total anatomic injury will be the summation of individual anatomic injury scores although simplifications may be required to improve the predictive power.

Physiological responses could be calculated based on anatomical disruption and will include factors deemed influential in mortality and incapacitation based on expert medical opinion. A total physiological score will be calculated as the summation of individual physiological scores. It remains to determine how the physiological scores will be assessed but it is anticipated that some expert knowledge database will be employed. Data-derived scores, such as the International Classification for Diseases Injury Severity Score (ICISS) provide more accurate mortality prediction than consensus-derived scores such as the NISS do when considering solely anatomical injury, but offer little advantage if age and physiological status are taken into account [34].

A further limitation of the current approach is the exclusion of time-lapse effects that may be important for more accurate injury assessments or long-term evaluations. Physiological response of the body, level of casualty trauma care and timing of medical interventions can all effect the assessments. As such, a revised injury assessment and ranking approach is presented in Figure 7. Upon initial insult from the threat, the anatomical/threat interactions and damage metrics are used as input to the injury assessment and scoring routines. An individual and total injury outcome score is determined at this time. Additional analysis can be conducted at different time intervals taking into account physiology, medical interventions and even recovery or escalation of the injury. These factors can then be used to modify the damage metrics or as input for physiological ranking methods before subsequent assessment and scoring of the injuries. The process can be repeated until the desired time period has been reached at which time vulnerability and survivability assessments can be conducted.

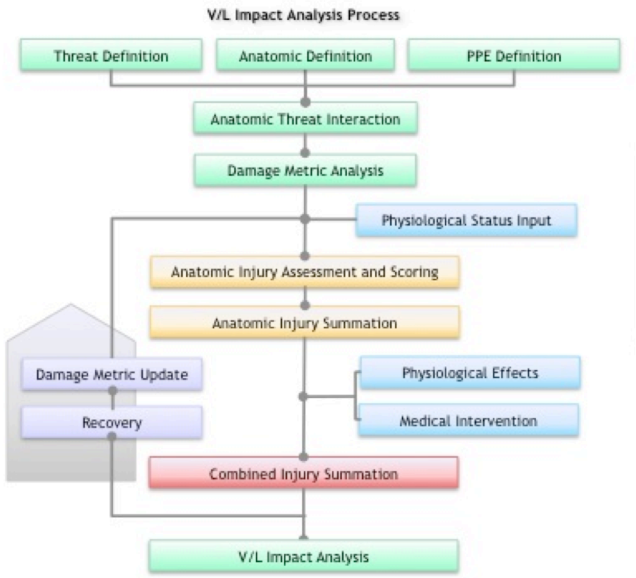

Figure 7:. Proposed comprehensive V/L analysis process.

The models and concepts presented in the paper are an initial effort in the development of a comprehensive V/L Model. Injury models and ranking methods were identified from the literature and remain to be integrated with the detailed anatomical computer model. It is envisaged that penetrating, blunt impact and blast threat models would be used with the anatomical model and injury database to provide an overall injury assessment for subsequent impact analysis on operational, mission, equipment or strategic objectives.

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