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NORTH ATLANTIC TREATY ORGANIZATION



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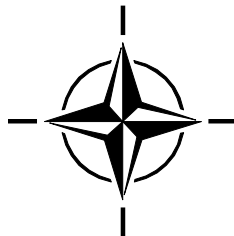
STO TECHNICAL REPORT

TR-HFM-338

# **Guidelines to Mitigate Military Occupational Brain Health Risks from Repetitive Blast Exposure**

**(Directives visant à atténuer chez les militaires les risques de santé cérébrale liés à une exposition répétée au souffle en contexte professionnel)**

The HFM-338 report identifies the best practices and knowledge to control, minimise, and mitigate the risk of developing brain-related health problems due to repetitive blast exposure.



Published June 2026

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- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensing Technology Panel
- TSI Technology and Science Incubation Panel

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## List of Acronyms

|         |                                                                                  |
|---------|----------------------------------------------------------------------------------|
| AI      | Artificial Intelligence                                                          |
| ALARA   | As Low as Reasonably Achievable                                                  |
| ANAM    | Automated Neuropsychological Assessment Metrics                                  |
| BEC     | Blast Exposure Count                                                             |
| BETS    | Blast Exposure Threshold Survey                                                  |
| BINT    | Blast-Induced Neurotrauma                                                        |
| BOP     | Blast Overpressure                                                               |
| bTBI    | Blast-Induced Traumatic Brain Injury                                             |
| BTB     | Blast Test Device                                                                |
| CASH    | Comprehensive Assessment Symptom History                                         |
| CFD     | Computational Fluid Dynamics                                                     |
| COTS    | Commercial Off-the-Shelf                                                         |
| CT      | Computed Tomography                                                              |
| CSF     | Cerebrospinal Fluid                                                              |
| DAMAGE  | Diffuse Axonal Multi-Axis General Evaluation                                     |
| DANA    | Defense Automated Neurobehavioral Assessment                                     |
| DoD     | Department of Defense                                                            |
| DOEHS   | Defense Occupational and Environmental Health Readiness System                   |
| DTI     | Diffusion Tensor Imaging                                                         |
| EEG     | Electroencephalography                                                           |
| EHR     | Electronic Health Record                                                         |
| EOD     | Explosive Ordnance Disposal                                                      |
| FAST-CT | Fast Automated Signal Transformation – Combat Training                           |
| FEA     | Finite Element Analysis                                                          |
| fMRI    | Functional Magnetic Resonance Imaging                                            |
| GBEV    | Generalized Blast Exposure Value                                                 |
| GCS     | Glasgow Coma Scale                                                               |
| GFAP    | Glial Fibrillary Acidic Protein                                                  |
| GOS-E   | Glasgow Outcome Scale-Extended                                                   |
| HFM     | Human Factors and Medicine                                                       |
| HLB     | High-Level Blast                                                                 |
| HPC     | Health Protection Criteria                                                       |
| HRV     | Heart Rate Variability                                                           |
| ICD-10  | International Statistical Classification of Diseases and Related Health Problems |
| IED     | Improvised Explosive Device                                                      |
| LLB     | Low-Level Blast                                                                  |
| MACE    | Military Acute Concussion Evaluation                                             |
| MEG     | Magnetoencephalography                                                           |
| ML      | Machine Learning                                                                 |

|            |                                                                       |
|------------|-----------------------------------------------------------------------|
| MoD        | Ministry of Defence                                                   |
| MOE        | Methods of Entry                                                      |
| MOS        | Military Occupational Specialty                                       |
| MRI        | Magnetic Resonance Imaging                                            |
| MSD        | Minimum Safety (Safe) Distance or Minimum Stack Distance              |
| mTBI       | Mild Traumatic Brain Injury                                           |
| NfL        | Neurofilament Light Chain                                             |
| NHTSA      | National Highway Traffic Safety Administration (United States)        |
| NSI        | Neurobehavioral Symptom Inventory                                     |
| OEL        | Occupational Exposure Limit                                           |
| PET        | Positron Emission Tomography                                          |
| PPE        | Personal Protective Equipment                                         |
| PRT        | Procedural Reaction Time                                              |
| PTSD       | Post Traumatic Stress Disorder                                        |
| RAC        | Risk Assessment Code                                                  |
| R&D        | Research and Development                                              |
| RPQ        | Rivermead Post-Concussion Symptoms Questionnaire                      |
| RTG        | Research Task Group                                                   |
| SEG        | Similar Exposure Group                                                |
| SME        | Subject Matter Expert                                                 |
| SOF        | Special Operations Forces                                             |
| SOP        | Standard Operating Procedure                                          |
| SRT        | Simple Reaction Time                                                  |
| STO        | Science and Technology Organization                                   |
| TAP        | Technical Activity Proposal                                           |
| TBI        | Traumatic Brain Injury                                                |
| TBICoE     | Traumatic Brain Injury Center of Excellence                           |
| TMS        | Transcranial Magnetic Stimulation                                     |
| TNT        | Trinitrotoluene                                                       |
| TOR        | Terms of Reference                                                    |
| TPI        | Total Positive Impulse                                                |
| US CONQUER | United States Combat and Training Queryable Exposure/Event Repository |
| USSOCOM    | United States Special Operations Command                              |
| VOMS       | Vestibular Ocular Motor Screening                                     |
| WAHTS      | Wireless Automated Hearing-Test System                                |

# Glossary

|                                        |                                                                                                                                                                                                                                                                                                                                                                                                          |
|----------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Biofidelic Surrogate</i>            | A physical or computational model designed to accurately replicate the anatomical and physiological responses of the human body to blast forces.                                                                                                                                                                                                                                                         |
| <i>Blast Event</i>                     | A scenario in which a rapid release of energy (for example from an explosive detonation or firing of weapons) results in the generation of a blast wave [1].                                                                                                                                                                                                                                             |
| <i>Blast Exposure</i>                  | Blast exposure occurs when a shockwave interacts with a person's body.                                                                                                                                                                                                                                                                                                                                   |
| <i>Single Blast Exposure</i>           | Exposure to an isolated blast event.                                                                                                                                                                                                                                                                                                                                                                     |
| <i>Repetitive Blast Exposure</i>       | Exposure to more than one blast event.                                                                                                                                                                                                                                                                                                                                                                   |
| <i>Cumulative Blast Exposure</i>       | The sum of exposures/events that occurred over a defined period.                                                                                                                                                                                                                                                                                                                                         |
| <i>Lifetime Blast Exposure</i>         | Cumulative exposure over an individual's life.                                                                                                                                                                                                                                                                                                                                                           |
| <i>High-Level Blast (HLB) Exposure</i> | Blast exposure generally experienced in combat settings as a result of incoming or enemy-inflicted munitions, such as IEDs, rocket-propelled munitions, etc. [2].                                                                                                                                                                                                                                        |
| <i>Low-Level Blast (LLB) Exposure</i>  | Blast exposure generally but not exclusively occurring within operational and training environments from outgoing (user directed) munitions [2].                                                                                                                                                                                                                                                         |
| <i>Occupational Blast Exposure</i>     | Blast exposures experienced in the course of performing one's job [2].                                                                                                                                                                                                                                                                                                                                   |
| <i>Blast Injury</i>                    | Direct tissue damage and its downstream effects resulting from a blast overpressure wave coupling into the body. High-level blast and low-level blast may both be associated with blast injury. Low-level blast may be associated with sub-clinical injury that may result in cumulative, clinically apparent symptoms over time [3], [4], [5], [6], [7]. Types of blast injury are listed in Table 2-1. |
| <i>Blast Overpressure (BOP)</i>        | The pressure above ambient atmospheric pressure. Units for overpressure are the same as for pressure. Overpressure is sometimes called gauge pressure or static pressure [8].                                                                                                                                                                                                                            |
| <i>Peak Overpressure</i>               | The maximum value of overpressure at a given location, which is generally experienced at the instant the shock (or blast) wave reaches that location [1].                                                                                                                                                                                                                                                |
| <i>On-Body Overpressure</i>            | Overpressure at a particular point on the body, also known as body load.                                                                                                                                                                                                                                                                                                                                 |

|                               |                                                                                                                                                                                                                                                                                                                                                                         |
|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Incident Overpressure</i>  | Used here to describe the blast overpressure that may be recorded in free space, such that its recording does not perturb the blast field. This overpressure is normally approximated in explosive trials by the use of streamlined pressure sensors [1].                                                                                                               |
| <i>Reflected Overpressure</i> | The pressure caused by the reflection of a shock wave from a surface or interface (change in medium). This pressure is maximum when the incident shock velocity is perpendicular to a non-responding surface but is not a monotonic function of the incident angle [1].                                                                                                 |
| <i>Blast Wave</i>             | A shock wave which decays immediately after the peak is reached. This decay occurs in all variables, including pressure, density, and material velocity. The rate of decay is, in general, different for each of the parameters [8].                                                                                                                                    |
| <i>Contextual Information</i> | Information about the blast exposure event, environment, and personnel involved.                                                                                                                                                                                                                                                                                        |
| <i>Health Hazard</i>          | An existing or likely condition inherent to the operation or use of materiel that can cause personnel death, injury, illness, disability, and/or reduced job performance. It is important to distinguish between hazards inherent in the normal use and maintenance tasks and those hazards related to equipment failures, mishaps, or human errors [9].                |
| <i>Health Surveillance</i>    | The regular or repeated collection, analysis, and interpretation of health-related data and the dissemination of information to monitor the health of a population and to identify potential risks to health, thereby enabling timely interventions to prevent, treat, or control disease and injury; includes occupational and environmental health surveillance [10]. |
| <i>Overpressure Impulse</i>   | A parameter that indicates a measure of the load in a blast wave. It is defined as the area under the pressure (expressed as force per area) vs. time function [1].                                                                                                                                                                                                     |
| <i>Positive Impulse</i>       | The integral of the pressure–time trace during the positive phase over a selected waveform duration.                                                                                                                                                                                                                                                                    |
| <i>Total Positive Impulse</i> | The overpressure impulse of the positive phase of the overpressure over the entire waveform duration from a single blast exposure. It can include multiple peaks from reflected waves when present. Equation:                                                                                                                                                           |

*$x[n]$  is the overpressure waveform;*

*$y[n] \subseteq x[n]$ , for when  $x[n] > 0$*

$$\text{Total Positive Impulse} = \sum_{n=1}^M y[n] * \Delta t$$

### *Cumulative Impulse*

A measure of load from a blast wave experienced by an individual over a defined period from multiple exposure events. It is calculated by summing the Positive Impulse values or the Total Positive Impulse values. These impulse values may be determined from a single sensor or when multiple sensors are being used by taking the maximum of the impulse values from these sensors.

### *Risk Level*

The characterisation of risk as either High, Serious, Medium, or Low [11].

### *Warfighter Brain Health*

The physical, psychological, and cognitive status that affect a warfighter's capacity to function adaptively in any environment and affects readiness, operational capability, mission effectiveness, and the goal to achieve overmatch or superior lethality [12].

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# Guidelines to Mitigate Military Occupational Brain Health Risks from Repetitive Blast Exposure

## (STO-TR-HFM-338)

### Executive Summary

Blast and the resultant overpressure (Blast Overpressure – BOP) exposure can cause negative effects to Force Health and Readiness. Such exposures can pose a significant occupational risk among military members both from enemy action and during training from the operation of artillery, shoulder-launched munitions, mortars, high-calibre weapons, and explosives. Most blast exposures over a career are usually experienced in training. Repeated exposure to Low-Level Blast (LLB) can be detrimental to brain health. The cumulative effects of LLB exposure on brain health is of concern. This is distinct from the acute brain effects observed with exposure to a single, high-level blast. Monitoring and documenting Blast Overpressure (BOP) exposure is critical to better understanding the effect on brain health, and to best protect troops throughout and beyond their military careers.

Concerned NATO allies formed a multidisciplinary team of military and civilian specialists within the biomechanical and biomedical fields, as well as from the fields of military occupational exposure and implementation domains to develop ‘Guidelines to Mitigate Military Occupational Brain Health Risks from Repetitive Blast Exposure’ as part of NATO STO-TR-HFM-338 Human Factors and Medicine (HFM). The objective of this team was to identify the best practices as well as produce knowledge to control, minimise, and mitigate the risk of developing brain-related health problems due to blast exposure.

The HFM-338 aims to achieve this through the development of three products:

- 1) **Blast Interim Exposure Guidelines** that may be used today to mitigate the risk of adverse brain health effects;
- 2) **Operational Guidelines** that detail the development of four capabilities including: 1) blast exposure monitoring; 2) capture of health; 3) performance information; and 4) data; analysis of blast exposure, health and performance effects, mitigations and health management strategies;
- 3) **Research and Development Guidelines** that identify critical research focus areas which, once addressed, will help us better monitor and understand warfighter brain health.

Warfighter brain health in this report is defined as the physical, psychological, neurological, and cognitive status that affect a warfighter’s capacity to function adaptively in any environment and affects readiness, operational capability, and mission effectiveness. The goal is to achieve overmatch or superior lethality by maximising brain health. The three products were designed to offer a comprehensive approach to implementing actions now while continuing to investigate key and targeted research areas that support a better understanding of blast exposures and brain health effects. However, each product can be used as a standalone tool to help drive key capabilities.

**Product 1: Blast Interim Exposure Guidelines** provide interim guidance for blast exposure threshold values to mitigate the risk of adverse brain health effects. The Guidelines include a description of the state of knowledge regarding blast overpressure exposure threshold values, which can be used to inform occupational exposure limits. The product also includes a review of the interim brain health protection criteria and peak overpressure methods, with a focus on level of evidence, applicability for short and long-term brain health effects, and usability. This product shows the current state of science

and found a 28 kPa (4 psi) peak on-body overpressure, a cumulative impulse of 219 kPa\*ms (31.7 psi\*ms), and a Generalized Blast Exposure Value (GBEV) of 200k – 400k as thresholds for blast exposure to limit the risk of adverse brain health effects.

**Product 2: Operational Guidelines** provide a practical and detailed overview of the recommended structure and progression to develop a National Blast Exposure Mitigation Program. The Operational Guidelines are divided into three sections: Guidelines Overview, Detailing the Operational Guidelines, and Examples. The Guidelines Overview section provides a concise overview of the capabilities that are further divided into sub-capabilities. Six levels are described for every sub-capability, indicating the advancement of guideline implementation. The Detailing the Operational Guidelines section provides a more thorough narrative description of each item provided in the Overview. The Examples section provides practical examples of how the capabilities, sub-capabilities, and levels function in practice, and how the different capabilities are connected. The Examples also highlight that a country need not operate at a consistent level across capabilities and sub-capabilities, rather it can tune the program to fit their specific national need. This product was written with the intent to identify critical areas required for a comprehensive blast exposure mitigation program.

**Product 3: Research and Development Guidelines** identify and discuss significant research gaps that, once addressed, will enable further advancement of a blast exposure mitigation program. This product has eight research focus areas related to one or more of the capabilities detailed within Product 2: Operational Guidelines. Each research gap is further detailed with a description and justification of gap importance, the general approach to solving the research gap, and the goals and outcome of solving the research gap.

Finally, Research Task Group (RTG) HFM-338 concludes with a call for action by NATO and allied partners to adopt and implement strategies to mitigate military occupational brain health risks from blast exposure in order to reduce effects to readiness, operational capability, and mission effectiveness for the warfighter.

# **Directives visant à atténuer chez les militaires les risques de santé cérébrale liés à une exposition répétée au souffle en contexte professionnel (STO-TR-HFM-338)**

## **Synthèse**

L'exposition au souffle et à la surpression qui en résulte (surpression du souffle ou BOP en anglais) peut avoir des effets négatifs sur la santé et l'état de préparation des forces. De telles expositions peuvent constituer un risque professionnel important chez les militaires, tant lors d'une action ennemie que pendant l'entraînement, en raison du fonctionnement de l'artillerie, de munitions tirées à l'épaule, de mortiers, d'armes de grand calibre et d'explosifs. La plupart des expositions au souffle au cours d'une carrière ont généralement lieu pendant l'entraînement. Une exposition répétée à un souffle de faible niveau (LLB) peut nuire à la santé cérébrale. Les effets cumulés de l'exposition à un LLB sur la santé cérébrale sont préoccupants. Il ne s'agit pas de la même chose que les effets cérébraux aigus observés après l'exposition à un seul souffle de haut niveau. La surveillance et la documentation de l'exposition à la surpression du souffle (BOP) sont essentielles pour mieux comprendre l'effet sur la santé cérébrale et pour protéger au mieux les troupes tout au long de leur carrière militaire et au-delà.

Les alliés concernés de l'OTAN ont formé une équipe multidisciplinaire de spécialistes militaires et civils dans les champs de la biomécanique et de la biomédecine, ainsi que dans les domaines de l'exposition professionnelle militaire et de la mise en œuvre, afin d'élaborer des « Directives visant à atténuer chez les militaires les risques de santé cérébrale liés à une exposition répétée au souffle en contexte professionnel » dans le cadre du STO-TR-HFM-338 de la Commission sur les facteurs humains et la médecine (HFM) de l'OTAN. L'objectif de cette équipe était d'identifier les meilleures pratiques et de produire des connaissances afin de maîtriser, minimiser et atténuer le risque de développer des problèmes de santé cérébrale à cause de l'exposition au souffle.

Pour cela, le HFM-338 élabore trois produits :

- 1) Des directives provisoires d'exposition au souffle qui peuvent être utilisées aujourd'hui pour atténuer le risque d'effets néfastes sur la santé cérébrale ;
- 2) Des directives opérationnelles qui détaillent le développement de quatre capacités, à savoir :
  - 1) la surveillance de l'exposition au souffle ;
  - 2) la capture d'informations et de données relatives à la santé et aux performances ;
  - 3) l'analyse de l'exposition au souffle et des effets sur la santé et les performances ;
  - et 4) les stratégies d'atténuation et de gestion de la santé ;
- 3) Des directives de recherche et développement identifiant les domaines critiques de recherche qui, une fois traités, nous aideront à mieux surveiller et comprendre la santé cérébrale des combattants.

Dans le présent rapport, la santé cérébrale d'un combattant est définie comme l'état physique, psychologique, neurologique et cognitif qui influence la capacité d'un combattant à fonctionner de manière adaptative dans n'importe quel environnement et influe sur l'état de préparation, la capacité opérationnelle et l'efficacité de la mission. Le but est de parvenir à un meilleur résultat ou à une létalité supérieure en maximisant la santé cérébrale. Les trois produits ont été conçus pour offrir une approche complète de la mise en œuvre d'actions dès maintenant, pendant que les recherches se poursuivent dans des domaines

clés et ciblés qui facilitent la compréhension de l'exposition au souffle et des effets sur la santé cérébrale. Cependant, chaque produit peut être utilisé comme un outil autonome pour favoriser les capacités clés.

**Produit n° 1** : les directives provisoires d'exposition au souffle proposent des valeurs temporaires de seuil d'exposition au souffle, afin d'atténuer le risque d'effets néfastes sur la santé cérébrale. Les directives incluent une description de l'état des connaissances sur les valeurs de seuil d'exposition à la surpression du souffle, qui peuvent être utilisées pour éclairer les limites d'exposition professionnelle. Le produit comprend également un examen des critères provisoires de protection de la santé cérébrale et des méthodes de surpression de crête, mettant l'accent sur le niveau de preuve, l'applicabilité aux effets à court et long terme sur la santé cérébrale et la facilité d'utilisation. Ce produit, qui expose l'état actuel de la science, mentionne une surpression maximale sur le corps de 28 kPa (4 psi), une impulsion cumulée de 219 kPa\*ms (31,7 psi\*ms) et une valeur généralisée d'exposition au souffle (GBEV) de 200 k à 400 k comme seuils d'exposition au souffle pour limiter le risque d'effets néfastes sur la santé cérébrale.

**Produit n° 2** : les directives opérationnelles fournissent une présentation pratique et détaillée de la structure et de la progression recommandées pour élaborer un programme national d'atténuation de l'exposition au souffle. Les directives opérationnelles sont divisées en trois sections : 1) présentation des directives, 2) détail des directives opérationnelles, et 3) exemples. La section de présentation des directives donne une vue d'ensemble concise des capacités, qui sont divisées en capacités secondaires. Six niveaux sont décrits pour chaque capacité secondaire et indiquent l'avancement de la mise en œuvre de la directive. La section détaillant les directives opérationnelles décrit plus minutieusement chaque élément indiqué dans la présentation. La section portant sur les exemples fournit des exemples pratiques de la manière dont les capacités, capacités secondaires et niveaux fonctionnent dans la pratique et de la manière dont les différentes capacités sont reliées. Les exemples soulignent également qu'un pays n'a pas besoin que ses capacités et ses capacités secondaires soient de même niveau, mais qu'il peut ajuster le programme pour répondre à ses besoins nationaux particuliers. Ce produit a été rédigé dans l'intention d'identifier les domaines critiques nécessaires à un programme complet d'atténuation de l'exposition au souffle.

**Produit n° 3** : les directives de recherche et développement identifient et traitent des lacunes significatives de la recherche qui, une fois comblées, permettront la progression ultérieure d'un programme d'atténuation de l'exposition au souffle. Ce produit examine huit domaines de recherche liés à une ou plusieurs des capacités détaillées dans le produit n° 2 : directives opérationnelles. Chaque lacune de la recherche est détaillée et comporte : une description et une justification de l'importance de la lacune, la démarche générale permettant de combler cette lacune et les objectifs et résultats attendus.

Enfin, le groupe de recherche (RTG) HFM-338 appelle l'OTAN et ses partenaires alliés à adopter et mettre en œuvre des stratégies visant à atténuer les risques professionnels liés à l'exposition au souffle pour la santé cérébrale des militaires, afin de réduire les effets sur l'état de préparation, la capacité opérationnelle et l'efficacité de la mission pour le combattant.

## Chapter 1 – INTRODUCTION

### 1.1 JUSTIFICATION

Blast exposure is an important concern for military personnel due to its potential to cause significant harm. Military personnel are at risk of experiencing blast exposure due to the nature of their work, such as during live fire training or involvement in operations [1]. This includes exposure to explosions, heavy weapons firing, and other types of training, as well as combat-related hazards.

It is important to note that the effects of blast exposure can be cumulative, meaning that repeated exposure to Low-Level Blast (LLB) over time may result in long-term adverse brain health outcomes [2] even if no immediate injury is visible. Single Blast (HLB) exposures can also inflict adverse brain health outcomes. Both HLB and repetitive LLB brain health outcomes are thought to be a significant risk factor for military personnel who are regularly exposed to blast events [2].

Long-term adverse brain health outcomes can lead to a range of cognitive and behavioural problems, including memory loss, difficulty concentrating, mood changes, and mental health disorders [3], [4]. These symptoms can significantly affect the ability of military personnel to perform their duties effectively and can negatively affect the warfighter's home life and life after service. Additionally, changes in brain structure and function have been observed alongside alterations in brain biomarkers in blast exposed personnel [5], [6], [7], [8]. The risk of injury from repetitive blast exposure may also be influenced by several individual demographic and anthropometric factors, and pre-existing medical conditions.

Given the risks associated with blast exposure, it is essential that military personnel take steps to protect themselves whenever possible, including the use of protective gear, training on blast safety, and minimising exposure to potential hazards. Monitoring the blast exposure as well as the status of brain health with validated methods is vital to mitigate the risk of development of long-term injury as well as providing important research data to study the long-term health effects, understand dose-response for repetitive exposures over time, and to develop strategies to mitigate these effects.

This topic requires a multidisciplinary approach and spans from threat to long-term health consequences, physics and biomechanics of the actual physical exposure to blast load, Traumatic Brain Injury (TBI)/brain health diagnostics, epidemiology, and knowledge of military operational procedures. Furthermore, it is a problem which extends NATO-wide, since there is a similarity in blast exposures from weapon training across countries. However, there are large differences in attention paid to this topic across countries. As such, it is a relevant research topic for the NATO Human Factors and Medicine panel.

### 1.2 SCIENTIFIC OBJECTIVES

The general objective for RTG HFM-338 was to develop expert-based guidelines which may be used to reduce the risks of developing acute and long-term adverse brain health outcomes from blast exposures. This general objective is divided into three more specific objectives:

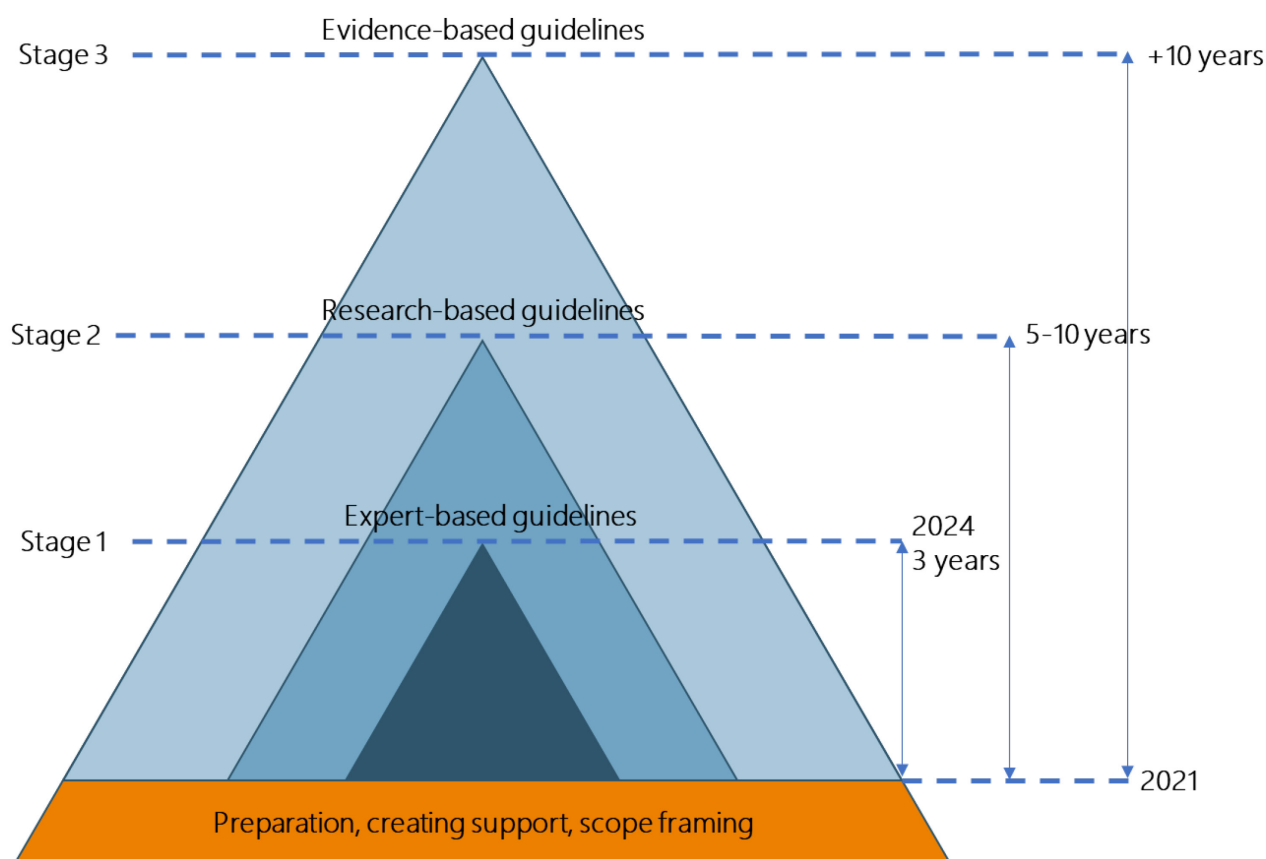
- **Define Interim Exposure Guidelines:** State-of-the-science exposure limits to mitigate the risk of developing acute and long-term adverse brain health outcomes from blast exposures.

## INTRODUCTION

- **Formulate Operational Guidelines:** Practical guidelines which may be used by military personnel and leaders to act in limiting the risks of developing acute and long-term adverse brain health outcomes from blast exposures. These guidelines need to be applicable for all NATO countries and align with the requirements and demands of the military leaders to address their responsibility as the employer.
- **Define Research and Development Guidelines:** These contain the research gaps and provide direction to future research which may be used to improve the interim exposure guidelines and the operational guidelines.

### 1.3 STRATEGY

The strategy to cope with the risks of blast exposure and adverse brain health outcomes within a military setting is based on a three-stage development of guidelines in the upcoming 10 – 15 years (Figure 1-1). These include three levels of guidelines, where the scientific evidence increases over time.



**Figure 1-1: Evolution of Blast Exposure Guidelines from Expert-Based to Research-Based to Evidence-Based Over a 10+ Year Period.**

### **1.3.1 Stage 1: Expert-Based Guidelines**

The development of these Stage 1 expert-based guidelines has been based on the current state of science known to experts in the field of blast exposure monitoring and adverse brain health outcomes in military training and operations. There is a level of opinion present in expert-based guidelines which may be derived from the individual expert's knowledge and training. These guidelines provide an expert-based framework for military personnel and leaders to develop procedures to minimise exposure and associated risk of adverse brain health outcomes in the short and long term. This RTG HFM-338 report outlines these expert-based guidelines.

### **1.3.2 Stage 2: Research-Based Guidelines**

The research-based guidelines will enhance effective collection of data and the development of necessary tools for documentation of exposure levels, diagnostics, and procedures to monitor the cumulative exposure and associated health status over a longer period. This will result in specific knowledge on the acute and long-term adverse brain health outcomes linked to exposure history and will presumably lead to more advanced research-based guidelines. These improved research-based guidelines will result in more effective procedures for monitoring, clinical assessment, and documentation, which will reduce risk while ultimately enabling development of evidence-based guidelines in Stage 3.

### **1.3.3 Stage 3: Evidence-Based Guidelines**

Evidence-based guidelines are supported by a mature literature with studies of differing levels of evidence. Evidence is graded using various methodologies, e.g., the Cochrane Grading of Recommendations Assessment, Development, and Evaluation (GRADE), and ranked from low to high in quality. High-quality evidence is weighted more highly than lower quality evidence in formulating guidelines. The application of the guidelines provided by Stage 1 and 2 in the context of high quality observational and clinical studies will generate data over time, which will allow long-term brain pathology to be linked to the cumulative exposure of each individual warfighter. This will lead to the development of evidence-driven guidelines to control the risk of adverse brain health outcomes due to blast exposure.

Rapid advancement through these three stages of guideline development will be accelerated by collaborative, multi-nation allied research and sharing of collected data between countries.

## **1.4 OUTLINE AND RATIONALE OF REPORT**

The report is structured in six chapters. The current chapter, Chapter 1 provides the introduction of the report, detailing the justification, objectives, strategy, and outline of the report.

Chapter 2 provides relevant background information needed to understand the report. This chapter includes information on blast exposures, monitoring, and on the potential for injury.

Chapter 3 describes the Interim Exposure guidelines with expert-based selected threshold methods that may be used to limit exposure and to reduce the associated risks of adverse brain health effects.

Chapter 4 describes the Operational guidelines, a wide range of practical guidelines, which will support reducing the risk of adverse brain health effects. These guidelines include four capabilities:

## INTRODUCTION

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- Blast Exposure Monitoring
- Capture of Health and Performance Information and Data
- Analysis of Blast Exposure, Health, and Performance Effects
- Mitigations and Health Management Strategies

Chapter 5 details the Research and Development guidelines, listing a range of research gaps and proposed methodologies to fill those gaps. Addressing these research gaps is essential to inform refinement of the interim exposure guidelines in Chapter 3, and the operational guidelines in Chapter 4.

Chapter 6 summarises the report, listing the main outcomes and general recommendations.

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## Chapter 2 – BACKGROUND RISK TO BRAIN HEALTH

Whether exposure to Blast Overpressure (BOP) could be related to alterations in brain function (Blast-Induced Neurotrauma – BINT) has been a matter of discussion since World War I (WWI). Reports of the so-called shell shock syndrome (described in *The Lancet* by C.S. Myers (Feb 13 1915, pp. 316-320) and summarized in Ref. [1]) where soldiers that had been close to detonations but did not have any visible wounds to the head frequently presented with amnesia, poor concentration, headache, tinnitus, hypersensitivity to noise, dizziness, and tremor.

Despite uncertainties in underlying pathology and pathophysiological mechanism, the clinical medical problem with this disorder became significant to such an extent that up to 10% of British battle casualties were categorized as shell shock-related and 32,000 British war pensions were awarded for shell shock. The term shell shock fell out of favor and the British Government banned the term at the beginning of the Second World War; soldiers that were near explosions continued to present a variety of symptoms that were generally categorized as post-concussion syndrome.

Modern time awareness of BINT stems from the high numbers of reported Mild Traumatic Brain Injury (mTBI) in recent conflicts starting in Afghanistan and Iraq. The use of Improvised Explosive Devices (IED) in these conflicts resulted in a growing number of military personnel having been exposed to BOP, which was considered one explanation to the high number of reported mTBI [2] (Figure 2-1). Improvements in body and vehicle protection and a resulting decreased mortality but greater morbidity in Traumatic Brain Injury (TBI) was also a plausible explanation for the observed increase in the number of mTBI [3]. Similar to the previous WWI observations, the early studies of BOP-related TBI in modern conflicts observed an overlap of concussion-like symptoms and PTSD/depression [4]. Separating the contributions of the different parts of the blast exposure (primary, secondary, tertiary blast, Table 2-1) from each other and from physical, blunt impact is important to understand underlying pathophysiological mechanisms and consequences of BINT. For example, MacDonald et al. showed specific brain imaging findings related to axonal injuries in U.S. military personnel that had been exposed to blast and showed symptoms of mTBI; however, these individuals were also exposed to other blunt impact, complicating the possibility to separate the different mechanism of injury [5]. Multiple more recent studies have attempted to separate out the specific contribution of especially the primary blast to BINT. These have shown promising findings on regulation of brain injury markers [6], [7], [8], [9], specific brain imaging findings [10], [11], [12], and cognitive changes [13]. The current scientific clinical knowledge about BINT suggest symptoms in the hours and days after repetitive BOP exposures, particularly those of higher intensity, may share features with mTBI, i.e., impairment of memory, particularly working memory, confusion, altered consciousness, slow thinking, slowed reaction time, headache, etc. Similar to mTBI, initial acute symptoms may diminish. However, cumulative repetitive exposure over time is associated with increased changes in brain structure and function, altered brain biomarkers, and an increase in symptoms relating to mental health, such as depression, anxiety, mood alteration, irritability, etc. Additionally, operators with higher levels of cumulative exposures seem to show a lower threshold for the manifestation of signs and symptoms following blast exposure than personnel with lower lifetime levels of exposure.

## DOD Numbers for Traumatic Brain Injury Worldwide

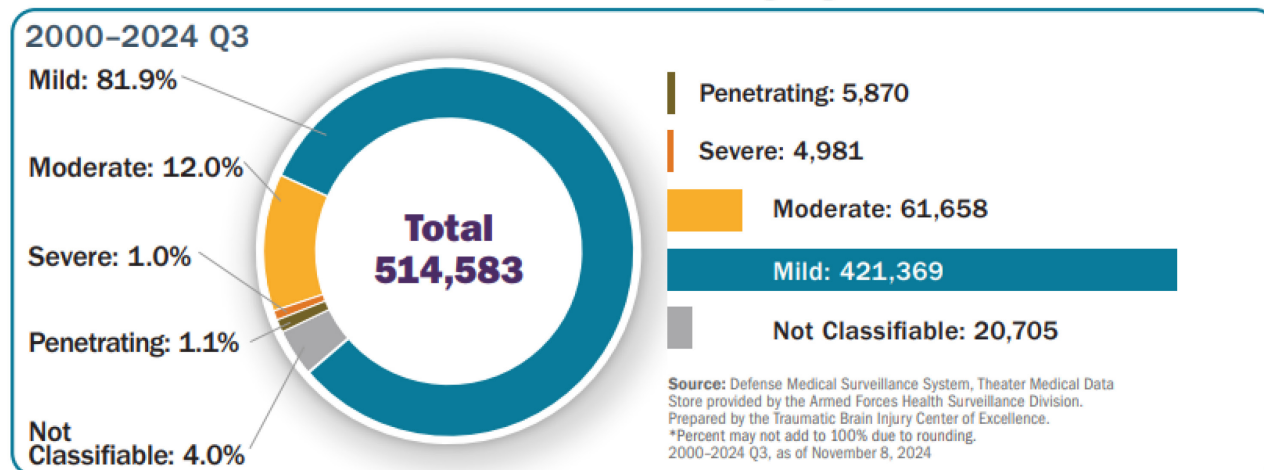


Figure 2-1: U.S. DoD Number of Traumatic Brain Injury Worldwide. (<https://health.mil/Military-Health-Topics/Centers-of-Excellence/Traumatic-Brain-Injury-Center-of-Excellence/DOD-TBI-Worldwide-Numbers>).

Table 2-1: Description of Different Categories of Blast Injury.

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Primary Effects of Blast:</b> Injury resulting in direct tissue damage from the shock wave coupling into the body.                                                                                                                                                                                                                                                                                                                                                  |
| <b>Secondary Effects of Blast:</b> Injury produced by primary fragments originating from the exploding device (preformed and natural (unformed) casing fragments, and other projectiles deliberately introduced into the device to enhance the fragment threat); and secondary fragments, which are projectiles from the environment (debris, vehicular metal, etc.).                                                                                                  |
| <b>Tertiary Effects of Blast:</b> Displacement of the body or part of the body by the blast exposure causing acceleration/deceleration to the body or its parts, which may subsequently strike hard objects causing typical blunt injury (translational injury), avulsion (separation) of limbs, stripping of soft tissues, skin speckling with explosive product residue, building structural collapse with crush and blunt injuries, and crush syndrome development. |
| <b>Quaternary Effects of Blast:</b> Other “explosive products” effects including heat (radiant and convective), and toxic toxidromes from fuel, metals, etc., causing burn and inhalation injuries.                                                                                                                                                                                                                                                                    |

These intensified clinical and experimental research efforts in combination with the technical development of wearable blast sensors (measure of BOP exposure) during the last 10 – 15 years, as well as structured self-report tools for the assessment of cumulative BOP exposures since 2020, have resulted in a growing body of data on the blast wave and its role in BINT (primary effect). This, in turn, has increased the understanding of the importance to better understand the affect of BINT on warfighters’ health and performance.

The fact that the primary effect of BOP exposure, without secondary effects (penetrating injury from fragments) or tertiary effects (e.g., movement of the head) can result in BINT, has resulted in multiple actions in the military medical field. One example is the U.S. Department of Defense (DoD) and the Department of Veterans Affairs (VA) in 2021 requesting a diagnosis code specifically for blast injury of the brain from the International

Classification of Disease, 10th Revision (ICD-10) Coordination and Maintenance Committee. ICD-10 is the International Statistical Classification of Diseases and Related Health Problems, which is the global World Health Organization (WHO) standard for diagnostic health information. It was pointed out in this request that the level of evidence of a direct primary blast wave effect on the brain is now sufficient to refer to it as a unique clinical entity which merits a unique diagnosis code, even though details of its fundamental injury mechanisms are not fully understood. This request led to the decision by the World Health Organization (WHO) to classify brain injuries from primary blast exposure as a unique clinical entity according in the International Classification of Disease (ICD) system; in 2022 ICD-10 established the code S068A for Primary Blast Injury of the Brain [14], [15].

Parallel to this developing knowledge of primary BOP exposure being a source of BINT, our understanding of the brain effects of repeated exposure from low-level primary BOP, over short (e.g., training exercises) or long (e.g., deployment, range safety officers) periods of time has evolved. The vast majority of such BOP exposures for individual military personnel have been in the training environment. Advantageously, this environment is also much easier to capture properties of the BOP exposure and collect relevant health data as compared to the deployed/combat environment. This has shifted the focus of the BOP health research field toward the training environment with repeated low-level BOP exposure and the cumulative effects of those exposures on medical outcomes. There are now numerous studies utilizing more standardized setups for capture of BOP exposure and acute health outcomes. For example, breaching exercises with explosives has gathered important new data on primary BOP exposure health effects [16], [10], [17], [7].

One other major result of the increased understanding and concern about the effects of BOP exposure and its role in BINT and brain health of service members was the United States Congress legislating Section 734 of the National Defense Authorization Act for Fiscal Year 2018. This law required the U.S. Secretary of Defense to conduct an extensive longitudinal medical study on blast pressure exposure of members of the Armed Forces. The overarching goal of Section 734 studies was to demonstrate that it is possible to capture blast information from weapon systems utilizing wearable blast sensors, store that information safely, and improve DoD's understanding of the brain health effects of BOP exposure from commonly used weapon systems to better inform policy for risk mitigation, unit readiness, and health care decisions. This study was part of a larger U.S. DoD Warfighter Brain Health Initiative (WBHI), a joint strategy and action plan between operational and medical forces. The focus is to:

- 1) Optimize Warfighter brain health, specifically cognitive and physical performance.
- 2) Identify known and emerging brain threats in military environments, such as blast.
- 3) Detect brain injury immediately when it occurs to combat its effects on warfighters, their families, line leaders, commanders, and their communities at large.

The WBHI strategy has five lines of effort and 53 activities to support end-to-end solutions for the warfighter. The blast work outlined in this report is organized under Line of Effort 2: Identify, Monitor, and Mitigate Brain Exposure [18], [19] (see Figure 2-2).



# DOD WBHI: Optimizing Brain Health Through Five Lines of Effort (LOEs)

**Mission:** Act rapidly to provide products, practices, and policies to directly impact warfighter brain health and performance

**End State:** Optimize warfighter brain health and performance to maximize Joint Force superiority and lethality in all operating environments

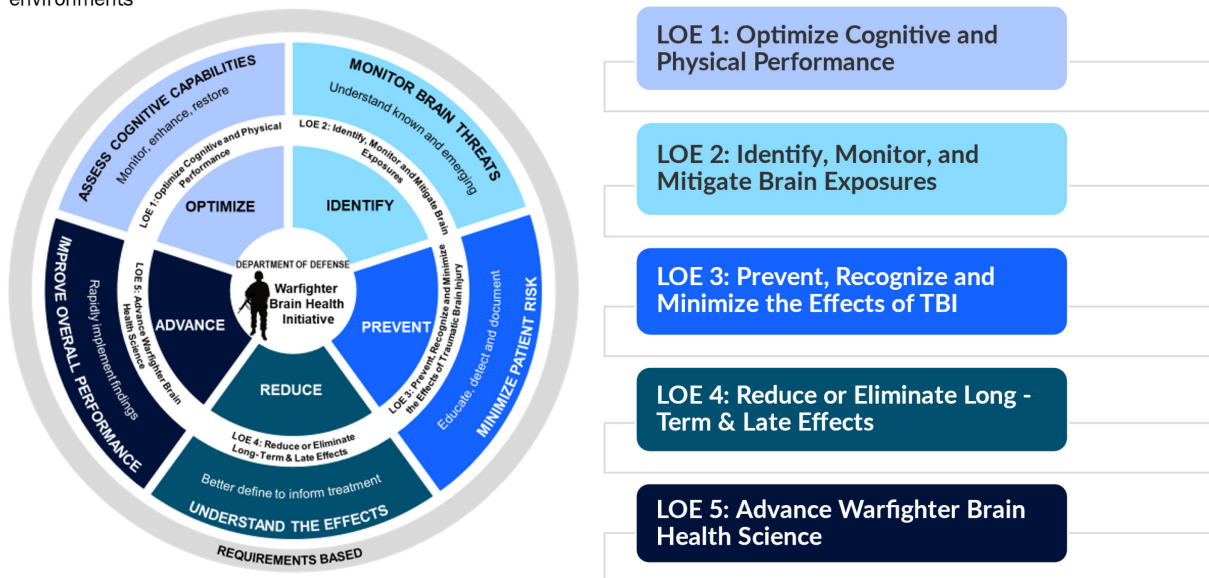


Figure 2-2: Outline of the U.S. Warfighter Brain Health Initiative.

A major goal in the field of BOP-related BINT is to better understand the threshold and dose–response relationship between BOP exposure and resulting BINT, especially for exposure in the Low-Level Blast (LLB) range, which naturally has broad implications in various weapon systems and their associated safety regulations. Interim safety recommendations for BOP exposure were developed based on literature studies as part of the U.S. National Defense Authorization Act (NDAA) for Fiscal Year 2018, Section 734 effort. The published studies in the field are still limited but several trends regarding reaction time, neurocognitive performance, etc. were commonly reported to be associated with exposures above 4 psi (28 kPa), which was therefore the threshold recommended to relate to until further studies reveal a more detailed understanding of the dose–response relationship between LLB BOP and BINT [19]. This interim recommendation, at present, 2024, also integrated in the U.S. Department of Defense requirements for managing brain health risks from BOP.

Altogether, the emerging and accumulating understanding of the adverse brain health effects and BINT as result of BOP is steadily growing and prompts the need for NATO members and NATO as a whole to develop guidelines regarding brain health risks from BOP.

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## BACKGROUND RISK TO BRAIN HEALTH

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## **Chapter 3 – INTERIM EXPOSURE GUIDELINES**

### **3.1 INTRODUCTION**

This chapter describes the state-of-the-science of blast exposure threshold values. These values may be used to mitigate the risk of adverse brain health effects due to Low-Level Blast (LLB) exposure. The values discussed are intended for short- and/or long-term brain health effects.

At the time of writing, there is no international consensus on the blast exposure threshold values associated with adverse short- or long-term brain health effects caused by single or cumulative exposures. Multiple countries use an unprotected eardrum rupture criterion to calculate the Minimum Safe Distance (MSD) for explosive demolition charges. There is no such calculation for brain health effects since the brain injury response to blast exposure remains poorly understood. This chapter provides more insight into the threshold values that may be used based on the current state of science.

Published and soon-to-be published research was gathered. From this research, three approaches for acute and chronic threshold determinations emerged that were selected. This list is not exhaustive and may evolve over time:

- 1) Peak Overpressure
- 2) Cumulative Impulse
- 3) Lifetime History of Blast Exposure (Generalized Blast Exposure Value – GBEV).

Additionally, a risk assessment framework, based on current efforts within the US Department of Defense (DoD), was identified and outlined as a notional structure which may use these types of thresholds in a risk assessment procedure.

These threshold methods are evaluated in Section 3.2 for their level of evidence, applicability for short- and long-term brain health effects, and usability. The risk assessment framework is described in Section 3.3. Section 3.4 summarises the interim exposure guidelines.

RTG HFM-338 found the single exposure 28 kPa (4 psi) peak on-body overpressure, a cumulative impulse over a single day of 219 kPa\*ms (31.7 psi\*ms), and a GBEV of 200k – 400k as thresholds for blast exposure to limit the risk of adverse brain health effects. These recommendations are made in the context of an evolving understanding of the adverse brain health effects of single and repeated exposures. As such, this guidance is subject to change based on guidance supported by new and emerging evidence.

### **3.2 THRESHOLD METHODS**

This section explores three different approaches for blast exposure thresholds. Each approach includes a description of the method, the threshold value, the level of evidence, applicability, and usability, and discussion and conclusion.

### 3.2.1 Peak Overpressure

#### Method

Current research provides emerging evidence of adverse health and performance effects (e.g., headache, ringing in ears, neurocognitive performance degradation, sleep disturbance, dizziness) from acute exposures to LLB. Until the relationship between BOP and brain health effects are more fully understood, it is recommended that military units in training manage the risk of exposures exceeding 4 psi (28 kPa) as part of training planning and execution. The US Interim Recommendation for Blast Overpressure Exposure Safety for Brain Health uses a blast exposure safety guidance of 4 psi (28 kPa) peak overpressure as a threshold, based on published blast exposure data and health and performance outcomes [1]. The recommendation does not explicitly state the method of overpressure measurement that should be used. However, the referenced literature predominantly used on-body overpressures, often using the highest recorded peak overpressure event of the set of wearable sensors. Therefore, RTG HFM-338 concluded that a recommendation based on such referenced data should specify a peak on-body overpressure threshold.

#### Threshold Value

4 psi (28 kPa) peak on-body overpressure (highest point recorded in a shock waveform as measured or simulated at a point on the body) for a single exposure.

#### Level of Evidence

Currently, published studies supporting this level are limited, but several trends can be observed from the findings. Symptomatology (e.g., headache, concentration problems, taking longer to think, etc.) were commonly reported, associated with exposures above 4 psi (28 kPa) peak on-body overpressure [2], [3], [4]. Reaction time alterations, a metric for neurocognitive performance, were reported for exposures above 4 psi (28 kPa) peak on-body overpressure in three studies; however, two other studies did not find such alterations for similar exposures [4] – [8]; 4 psi (28 kPa) peak on-body overpressure is lower-bound and based on a combination of neurocognitive performance and symptom reporting.

In August of 2024, the US Deputy Secretary of Defense published a Memorandum titled, ‘Department of Defense Requirements for Managing Brain Health Risks from Blast Overpressure’ [1]. This Memorandum rescinded the Memorandum titled, ‘Interim Guidance for Managing Brain Health Risk from Blast Overpressure’ [9], published in November of 2022 by the US Assistant Secretary of Defense (Readiness). It establishes US DoD requirements and direction for the management of health risks to US DoD personnel from exposures to BOP. This Memorandum stated that, until the relationship between BOP and brain health effects is more fully understood, US DoD Components will manage the risk of blast exposures exceeding 4 psi (28 kPa) as part of training planning and execution, and will apply risk management procedures described in US DoD Instruction (DoDI) 6055.01, ‘Safety and Occupational Health (SOH) Program’ [10]. It specifically states that the policy is not meant to preclude or unreasonably restrict commanders from conducting mission-essential weapons training but instead establish requirements for practical risk management action to mitigate and track BOP exposures. It also maintains the interim BOP exposure safety guideline of 4 psi (28 kPa).

### **Applicability for Short- and/or Long-Term Brain Health Effects**

The threshold value is based on data focused on short-term brain health effects. The long-term effects of repetitive exposure are the subject of ongoing research [11] – [14].

### **Usability**

While not specified in US policy, the preponderance of the evidence that supports the guideline is based on body-load data from wearable blast sensors, often using the highest recorded event of the set. The peak overpressure threshold can be used, with multiple assessment methods described in Section 4.4.1.3 Methods and Technologies from Blast Exposure Monitoring Capability. These include documented overpressure signatures from weapon systems and explosives, wearable blast sensors, static blast sensors, and advanced modelling tools. However, these methods are operating at different levels, and each method has its caveats. It is recommended to use the best method available, defined by the most usable and most representative of peak overpressure measured on the body. When methods are used that do not capture on-body overpressure, careful attention should be paid to how the method, and associated overpressures, translate to the on-body overpressure and the associated threshold. The caveats of the different methods for blast exposure monitoring are described in more detail in Section 4.4.1.3.

### **Discussion**

Different methods of assessing whether an individual has exceeded 4 psi (28 kPa) can be used. A wearable blast sensor will measure on-body overpressures at locations of the body, a static pencil probe will measure incident pressures at a given location (when properly positioned), and simulations or a reference table listing exposures may provide all types of overpressures (on body, incident, and reflected) but it will be representative of a single scenario which may or may not be indicative of future exposures. Each assessment method and type of overpressure requires understanding of what is being measured. In many cases, use of multiple techniques is warranted to leverage the respective strengths of each. Strengths and weaknesses of each method are detailed in Section 4.4.1.3.

The scientific evidence for the threshold level is limited but growing and primarily based on acute short-term brain health effects. The long-term brain health effects from exposures exceeding 4 psi (28 kPa) remain unknown, but using such a threshold is a start to limit exposures.

Linking a peak overpressure threshold to an impulse value may improve this single exposure guideline. Impulse, having both components of peak pressure and duration, may be a candidate metric for improving future thresholds. Emerging data are starting to provide the first threshold values (see Cumulative Impulse Section 3.2.2).

Investigations should be conducted on military personnel from various nations who are exposed to blast overpressure to identify other symptoms associated with blast exposures. The peak overpressure exposures measured on the soldiers and symptoms could be compared to support the defined 4 psi (28 kPa) peak overpressure on-body threshold that is reported in the literature [14], [8], [3] – [7].

### **Conclusions**

The use of a single exposure guideline at 4 psi (28 kPa) peak on-body overpressure is a useful first step to begin helping military personnel reduce their overpressure exposures using an easy-to-understand metric. While other guidelines may be more comprehensive, this guideline stands out for its simplicity and usability (primarily

## INTERIM EXPOSURE GUIDELINES

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when wearable blast sensors are used). Adopting this guideline, along with using the tools to identify those exceeding the guideline, will allow leaders, medics, and troops to immediately begin controlling/limiting above-threshold exposures in training.

### 3.2.2 Cumulative Impulse

#### Method

Cumulative positive impulse may be calculated from blast overpressure histories, as measured on, or estimated for, an exposed individual. Blast positive impulse is defined as the integral of the positive phase of the overpressure vs. time waveform. Total positive impulse refers to the value of the blast positive impulse when it is calculated over the entire waveform duration. Individual blast overpressure histories may be obtained from wearable blast sensors on the exposed personnel or estimated from other pressure sensors deployed in the blast environment. If multiple wearable blast sensors are used, blast impulse may be chosen as the sensor yielding the maximum positive impulse value or as the average positive impulse from all body worn sensors. Blast positive impulse could also be derived from overpressure history estimates obtained from modelling of the blast environment. Cumulative positive impulse is typically obtained from the summation of positive impulses over multiple exposure events, over a defined period (a day, multi-day training event, etc.), for a single individual.

#### Threshold Value

Recent evidence, reported below, suggest that a 50% risk of acute cognitive effects may occur at a cumulative positive impulse value of 31.7 psi\*ms (219 kPa\*ms), calculated as the sum of all total positive impulses measured for each individual wearable blast sensor over a period of a single day. The wearable blast sensor with the highest cumulative impulse reading is compared with the threshold. The measured cognitive changes represent an acute effect, which may or may not translate into long-lasting effects or chronic impairment. This proposed threshold also does not account for multiple successive days of exposure. It is also not directly applicable to incident pressure recording in an environment, as it was derived using sensors recording on-body overpressure (i.e., overpressure applied on the body surface). It was also derived from computing total positive impulse over a given recording duration, which is specific to the sensor technology used in the underlying research.

#### Level of Evidence

Peak overpressure alone is an incomplete description of the loading exerted by a blast wave on personnel. While peak overpressure quantifies the magnitude of the loading, impulse is a better correlate of overpressure exposure over time, as it indirectly accounts for how long the loading from the blast is applied, how blast reflections from the surrounding may influence loading, and how the decay from the peak overpressure to ambient overpressure occurs.

There is indirect evidence that suggests that blast impulse should be considered in the prediction of brain injury risk from exposure to blast. Connected fields of research have established that the resistance of structures, including the human body, to external loading is generally a function of loading magnitude and duration of application. For man-made structures, failure thresholds are typically defined in the pressure–impulse plane (also referred to as PI curve), where combinations of peak pressure and impulse values are correlated to a given level of damage [15]. Burn injury models are also defined as a function of temperature and duration of exposure [16]. In the field of head injury biomechanics, multiple proposed injury criteria (e.g., head injury criteria, head impact power) are a function of the loading impulse, which indirectly accounts for duration of load application by considering head velocity (i.e., integration of acceleration over time) in their correlation to injury risk

(e.g., brain injury criterion, DAMAGE [17]). Blast injury criteria for organs other than the brain, derived from animal and cadaveric experiments, have been defined as iso risk curves in the pressure–impulse plane. Eardrum rupture thresholds [18] and lung injury thresholds [19] are defined as a series of possible combinations of peak pressure and positive phase impulse values.

For loading from blast waves, duration of loading may also have additional implications. During blast exposure, the development of the transient overpressure field around the body is on the same timescale as the propagation velocity of the blast wave. For example, for short-duration blast waves, overpressure on one side of the body may have time to decay completely before the blast wave reaches the other side of the body. Similarly, a long-duration blast may engulf the body in a zone of overpressure. These result in significantly different loading scenarios from the perspective of the body.

Despite the aforementioned evidence suggesting that impulse is an important parameter in the description of blast loads, only a few researchers have attempted to directly relate blast impulse to a risk of neurobehavioural impairment. In a recent review of the evidence supporting the use of a 4 psi (28 kPa) maximum peak overpressure threshold, it was reported that only six of the 14 published research articles that quantified blast exposure concurrently with brain health and performance effects had considered average or cumulative impulse. Upon further analysis, only four had used impulse within the context of a dose–response correlation analysis [20].

**The following is a review of relevant literature to provide a more detailed description of the study:**

- **Lavalle et al.** [5] measured changes in the neurocognitive performance of 202 participants involved in a breaching course. The course involved 2 – 4 total exposures per individual, with peak individual overpressure ranging from 2.57 psi (17.7 kPa) to 9.17 psi (63.2 kPa) and **cumulative impulse ranging from 15.05 to 47.2 psi\*ms (103.8 to 325.4 kPa\*ms)**, measured from a wearable pressure gauge worn on the shoulder. The authors attempted to correlate blast characteristics to changes in DANA performance, administered before, immediately after (5 min), and a short-time after (25 min – 2h) the last blast exposure. Changes in Simple Reaction Time (SRT), Procedural Reaction Time (PRT), and Go-no Go assessment were regressed against continuous models and dichotomous models of blast characteristics. While continuous and dichotomous (over/under 5 psi (34 kPa)) descriptions of peak overpressure showed statistically significant correlation to changes in PRT, cumulative impulse did not show significant correlation. However, it is important to note that overpressure measurements were taken from a single sensor only, which is claimed to represent incident overpressure due to the orientation of the participant relative to the blast. Therefore, true loading characteristics may not have been monitored properly, as reflected impulse may not scale linearly with incident impulse estimates.
- **Carr et al.** [8] performed an extensive list of neurobehavioural assessments and neuroimaging on 31 participants (26 students and five instructors) before, during, and after a six-day explosive breaching course. Given the nature of the exposures, which involved blast propagation in a complex environment, cumulative impulse was chosen as the best characteristic to quantify exposure. In this study, students and instructors were exposed to 40 low-level blasts, **with an average total cumulative impulse of 51 and 43 psi\*ms (352 and 296 kPa\*ms), respectively**. Although self-reported symptoms (22 queried) increased in 44% and 88% of the student and instructor participants post exposure, the authors conclude that the study did not yield clear evidence of neurological impairments. However, when observing the instructor sub-group relative to the student sub-group, clear effects were observed on task performance necessitating memory demand. The authors suggest that a long history of blast exposure expected from breaching instructors may increase the likelihood of developing acute neurological symptoms after blast exposures.

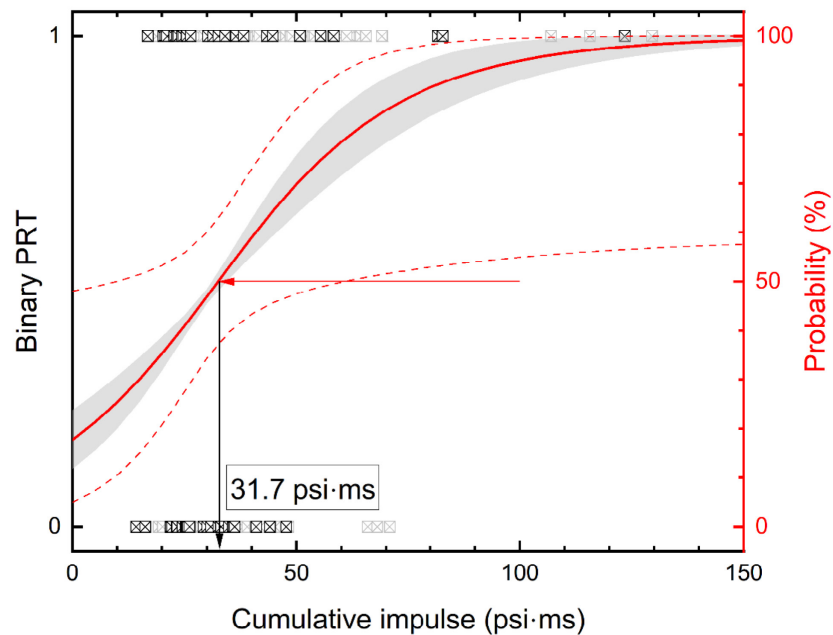
- Woodall et al.** [13] investigated neurocognitive symptoms and pupillary light reflex response in 11 mortarmen and four non-exposed controls. Of the 11 mortarmen, four were operating a 120 mm mortar, three were operating an 81 mm mortar, and four were range officers during the six-day period of training where measurements were taken. Exposures were measured from four wearable blast sensors worn on the sides of the helmets and on each shoulder. 120 mm mortarmen, 81 mm mortarmen, and range officers were exposed to an average peak overpressure of 2.1 – 5.8 psi (14.5 – 40.0 kPa), 1.2 – 2.6 psi (8.3 – 17.9 kPa), and 1.3 – 2.6 psi (9.0 – 17.9 kPa), respectively, depending on their position. The average cumulative impulse was 788 and 560 psi\*ms (5433 and 3861 kPa\*ms) for 120 mm and 81 mm mortarmen, respectively. The author found a high prevalence of neurocognitive symptoms (headaches, forgetfulness, slow thinking, sleep disturbance, etc.) in all exposed participants relative to controls. They also observed that mortarmen had smaller pupil diameters and slower pupillary responses when compared to controls. The authors also found pupillary responses negatively trended with blast exposure, where slower pupil response was associated with increasing average peak overpressure and increasing cumulative impulse, even for mortarmen with average peak overpressure exposures below the 4 psi (28 kPa) threshold. The authors conclude that these results suggest systemic neurological issues in mortarmen, and that brain health and performance effects may occur in mortarmen even when average peak overpressure exposure remains below 4 psi (28 kPa). The study however suffers from a lack of pre-exposure performance baseline and remarkably high cumulative impulse values. While it hardly informs on acute blast exposure thresholds, it potentially highlights an extreme situation of neurological effects occurring for large cumulative impulse values with average peak overpressures remaining below 4 psi (28 kPa).
- Thangevelu et al.** [7] investigated changes in neurocognitive performance, symptoms reporting, and serum biomarker concentrations in 15 law enforcement personnel engaged in a three-day long training course involving firings of 0.50 calibre rifles. Wearable sensors mounted on the shoulder of the participants were used to quantify low-level blast exposures. Participants fired between four and 50 rounds per day from different positions. For Days 1, 2, and 3, the mean peak overpressures were 3.9, 3.8, and 4.5 psi (26.6, 26.3, and 31.2 kPa), respectively, and cumulative daily impulse were 42.2, 19.3, and 34.1 psi\*ms (291, 133, and 235 kPa\*ms), **respectively**. Symptoms reporting was found to be inconsistent and results from the DANA assessment post exposure were not substantially affected by the overpressure exposure. However, daily elevation in A $\beta$  peptides (A $\beta$ -40 and A $\beta$ -42) were associated with higher peak overpressure and higher cumulative impulse. Additionally, the A $\beta$  peptides elevation at the end of Day 3 had a statistically significant correlation with the three-day cumulative impulse, indicating a potential cumulative effect, whereas it did not correlate significantly with peak overpressure summation. The authors observed that A $\beta$ -40 and A $\beta$ -42 elevation can be affected by other factors but remain ‘important pathological components in chronic neurodegenerative disease progression’ [21].

Recently, **McEvoy et al.** [11], [22] conducted a study combining a mice model and live-fire recording on military personnel. Mice were exposed to controlled repeated (4 – 5) low-level blast within a tube for 11 consecutive workdays, during which the authors assessed neurobehavioural changes at two time points using a righting (RT) reflex measure. This measure was used to identify a subset of candidate blast overpressure metrics that could effectively correlate with the observed neurobehavioural outcome on the mice. Using a robust statistical approach, the study demonstrated that cumulative impulse, exposure counts, and cumulative peak overpressure were significantly associated with RT changes. The portion of the study involving military personnel was carried during a six-week special operation forces breaching course, for which the large majority of the exposure was during Week 4. It involved 23 students, 13 instructors, and 10 controls with no low-level blast exposures. Low-level blast exposures were from a mix of flash bang grenades and detonation cord

breaching charges. The mean number of exposures for students was 115.6 with mean peak overpressure of 1.3 psi (8.7 kPa) and mean impulse of 1.4 psi\*ms (9.7 kPa\*ms). The Neurobehavioral Symptom Inventory (NSI) was used to assess neurobehavioural symptoms before and after the exposures. Various regression models were studied in an attempt to correlate changes in NSI to blast characteristics, baseline NSI ratings, total time in a low-level blast occupation, and time in service. Through Bayesian analysis of those regression models and subsequent statistical treatment, it was found that cumulative impulse after Week 6 showed credible evidence of an effect on NSI score, while baseline NSI was found to have a certain effect on the Week 6 NSI score. Generally, only multi-variate regression models including cumulative impulse and baseline NSI were significant in predicting final NSI score. Importantly, it was found that instructors displayed a more significant dose-response relationship, despite being exposed to lower overpressures and less impulse compared to trainees. This indicated that a considerable low-level blast exposure history is an important risk factor for the appearance of acute symptoms.

More recently, **Carr et al.** [23] evaluated acute cognitive effects among 310 soldiers involved in wall demolition/explosive breaching training. This study was observational in nature, occurring during standard training protocols, given that exposing personnel to blast solely for research purposes does not meet ethical requirements among NATO member nations. In this study, acute cognitive deficit was assessed using DANA PRT (Defence-Automated Neurobehavioural Assessment – Procedural Response Time) at the beginning and end of a training day. Throughout training, individualised on-body blast exposure was quantified using a set of three to eight wearable pressure sensors mounted on each warfighter. Peak pressure and total positive impulse values were used as the main exposure metric. Cumulative positive impulse was obtained by summing the total positive impulse over a day of training for each individual wearable blast sensor and selecting the highest one.

Risk curves were generated through binary logistic regression, classifying soldiers between those with statistically significant acute cognitive slowing and those without slowing, as measured using PRT. A single predictor risk curve derived for cumulative impulse is shown in Figure 3-1.



**Figure 3-1: Probability Curve of a Single Predictor using Cumulative Impulse.**

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A single predictor risk threshold based on cumulative impulse was defined by the value where there was a 50% or greater probability of cognitive impairment in the measured sample. The exposure threshold determined through this method, specific to explosive breaching, yielded a value of 31.7 psi\*ms (219 kPa\*ms) for cumulative impulse.

The authors of the study defined a combined risk map linking peak overpressure to cumulative impulse (not included in this report). The HFM-338 did not adopt the combined risk map due to the limited dataset. The map suggests that lower peak pressure exposure can be combined with greater cumulative impulse exposure and remain within acceptable risk levels. Conversely, greater peak pressure exposure can be combined with lower cumulative impulse exposure to remain within acceptable risk levels. This is a well-established approach that could be applied independently to different exposure environments or over an entire dataset that includes multiple exposure environments. However, it is important to note that the dataset at the origin of the risk map is not necessarily well distributed across the map space and therefore, the applicability of the risk map at the lower and upper boundaries is uncertain. The authors of the study mentioned that the original intent was to generate a generalised risk map by pooling a larger dataset that included multiple exposure environments and profiles. However, this idea was abandoned due to apparent inconsistencies between the individual datasets. A dataset unique to grenade exposures, for example, appeared to generate a significantly different risk map to the one devised from the breaching dataset. This observation suggests that environment/scenario-specific maps may be required to properly capture the risk of acute cognitive impairment from repeated exposures to blast.

### Applicability for Acute and/or Long-Term Brain Health Effects

Evidence that supports the definition of an exposure threshold as a function of cumulative impulse were built from observations of neurobehavioural effects or other brain health proxies following an acute exposure to low-level blasts. They are indicative of a potential immediate or acute response but do not necessarily reflect risk of developing or contributing to chronic brain health effects. Linkages between an acute exposure to low-level blast exceeding the proposed threshold and any long-term neurocognitive impairment remains tenuous. The logical approach, given what is currently known with regards to the cumulative impulse metric, is to use a threshold that minimises the risk of acute neurobehavioural effects, with the perspective of reducing the risk of development of chronic effects. The risk thresholds described here were derived for exposures within a training day. The application of this method to effects from chronic exposure is pending work.

### Usability

The cumulative impulse requires insight in every blast exposure during a training day. Multiple assessment methods described in Section 4.4.1.3 Methods and Technologies from Blast Monitoring capability can be used to derive the blast exposure; however, this specific method was developed using on-body overpressure from specific wearable blast sensors. When methods are used which do not use these wearable blast sensors, careful attention should be paid to how the method and associated overpressures translates to the on-body overpressure and the associated threshold.

### Discussion

At this time, the injury risk function developed in the work of Carr et al. [23] represents the most usable research that accounts for the contribution of cumulative impulse to the level of risk of impairment. The threshold value of 31.7 psi\*ms (219 kPa\*ms), associated with a 50% risk level, represents the level where the statistical confidence is the highest. However, it is important to note that this risk level may be deemed too high and therefore, different groups may choose to use daily cumulative impulse values that are lower.

Also, the applicability of the injury risk function from [23] for conditions differing significantly from breaching/demolition training scenarios should be considered with caution. More specifically, the application of the risk curve for larger number of exposures to very low peak overpressure, or for very lower number of exposures to high overpressure, remains tentative.

It is important to identify the limitations to the usability of the risk curve defined in [24]. First, the study used on-body overpressure measured from wearable blast sensors. These represent on-body overpressure and should not be confused with incident overpressure measurements/estimates obtained from an overpressure mapping exercise. The proposed risk curve should only be used in conjunction with on-body overpressure measurements, or estimates obtained from simulation. All of the caveats outlined in usability for the peak overpressure threshold apply. Second, the calculation and summation of single blast positive impulse requires a common methodology to yield consistent results across different data collection and monitoring efforts. This may be difficult to achieve since the study reported in [23] used sets of three to eight sensors but does not appear to be consistent throughout. Averaging of positive impulse over three or eight sensors will likely yield a different value, depending on their position on the body. In general, the application of the proposed threshold requires the computation of an average total positive impulse over multiple locations on the body, therefore a maximum number of sensors is recommended to maximise the accuracy of this average value. Other limitations related to logistics, cost, and data management may drive decisions on the number of sensors being used. While most published reports have used three sensors distributed on the body, other sensor configurations may be exploited to compute an average total positive impulse value compatible with the proposed threshold. The duration over which positive impulse is calculated from an individual overpressure waveform is critical and should be consistent with the method used in the work supporting the definition of the risk curve. That work used the total positive impulse, where the collected data was limited to 17 msec (post rising edge) based on the sensor used. Application of this threshold to other types of blast exposure should consider potential reflections in the environment and the appropriate waveform duration to include in a positive impulse calculation so only exposures potentially linked to brain injury are included.

Adequate post-processing of the raw sensor signals is also required to avoid potential errors due to a shift in sensor baseline or due to low signal-to-noise ratio. The process for cumulative positive impulse calculation should be automated sufficiently to allow for monitoring over short timeframes, such as day-to-day in the context of a training event.

It has been demonstrated in other blast-related and injury-related fields of research that the resistance of structures, including the human body, is generally a function of loading magnitude and duration of application. Although still limited, there is recent evidence suggesting that blast cumulative impulse may be a correlate for the risk of acute neurobehavioural/neurocognitive impairment. A cumulative impulse threshold of 31.7 psi\*ms (219 kPa\*ms) (50% risk level) over a day of exposure to low-level blast may be used with caution, and in conjunction with other proposed exposure thresholds, to minimise the risk of negative brain health and performance effects.

It is important to note that the analysis yielding the proposed threshold was not designed to accommodate other exposure parameters, such as time duration between exposure events, which are assumed to have relevance to outcomes of interest. This method was designed to be usable in the near term, using primary quantifications of blast exposure, and will likely evolve over time as further evidence is gathered in emerging blast exposure monitoring programs.

### Conclusions

The use of a repetitive exposure guideline of 31.7 psi\*ms (219 kPa\*ms) on-body cumulative impulse over a single day is a useful first step to begin helping military personnel reduce their risk of reaction time decrements over a day of training. While factors such as time between exposures, effect of multi-day training, and linkage to long-term neurocognitive deficits have not yet been evaluated, adopting this guideline will reduce risks for the warfighter, including potential safety concerns with neurocognitive deficits during a training exercise.

### 3.2.3 Lifetime History of Blast Exposure (Blast Exposure Threshold Survey and Generalized Blast Exposure Value)

#### Method

The Blast Exposure Threshold Survey (BETS) is a self-report tool with two components and designed to be completed in 5 – 10 minutes. The first component is a blast exposure estimator that queries the number of exposures across five categories of weapon systems. These categories include:

- 1) Small arms,
- 2) Large arms (including shoulder-fired),
- 3) Artillery (or large weapons carried by vehicle),
- 4) Small explosives, and
- 5) Large explosives.

Respondents are asked to estimate the number and frequency of exposures within each category. The second part of the BETS is a cursory symptom estimator. A truncated form of the Neurobehavioral Symptom Inventory (NSI) is used, along with questions related to post-traumatic stress (PTSD) symptoms. The BETS generates a total Blast Exposure Count (BEC) for each of the five categories of weapons systems. The Generalized Blast Exposure Value (GBEV) is a single index value that may be calculated from the BETS survey. This value was derived from an algorithm that was formulated from the initial study sample of 984 respondents [25]. The GBEV is calculated by applying weighting factors to each of the categorical BEC values derived from the BETS through the following formula:

$$GBEV = 0.976(1BEC) + 288(2BEC) + 41(3BEC) + 77(4BEC)(4freq) + 75(5BEC)(5freq)$$

The weighting factors for the GBEV were defined from the original BETS study by determining the individual contributions of the blast counts within each weapons system category to dose–response thresholds identified by examining the NSI and PTSD outcome data derived from the second component of the BETS [25]. Weapons and explosives that produce higher-intensity blast overpressures contribute disproportionately to the overall GBEV score. 1BEC, relating to the small arms category, is minimally weighted, whereas 4BEC and 5BEC, relating to small and large explosives, respectively, each have very high weights. The *freq* weightings that are applied to 4BEC and 5BEC describe the percentage of exposures that occurred two days in a row and are expressed as the decimal equivalent of that percentage + 1.

#### Threshold Value

The initial publication describing the BETS/GBEV identified a GBEV threshold value of 200k for self-report symptoms related to ringing in the ears and forgetfulness and 400k for self-report symptoms hearing loss

and changes in taste/smell [25]. Since the initial work, additional studies have been performed that have helped to refine this value using advanced imaging and other highly sensitive measures in specific military populations, such as those exposed to artillery rounds. Specifically, changes in neuroimaging structure and function are seen across multiple principal components clusters at 3BEC values of 12,600 and above. Studies are planned or underway to define comprehensive dose–response thresholds for cumulative blast exposure for the other weapons system categories within the BETS (1BEC, 2BEC, 4BEC, and 5BEC).

### **Level of Evidence**

The BETS was developed and initially administered through an anonymous online survey of 984 respondents across the US DoD [25]. Significant changes at the 200 – 400k threshold levels were observed in hearing loss, ringing in the ears, changes in taste/smell, and forgetfulness in this study. The GBEV was developed from the contributions of individual weapons systems categories to the thresholds associated with these self-report symptoms.

### **Applicability for Short- and/or Long-Term Brain Health Effects**

The BETS/GBEV is a self-report tool that estimates a career history of blast exposure. Studies conducted to date have demonstrated association with longer-term symptoms and objective brain health measures [14], [26]. As such, the tool has been used primarily to understand risk associated with long-term brain health effects. The tool has also been discussed as a potential measure to stratify risk for experiencing acute brain health effects based on prior blast exposure.

### **Usability**

The BETS is a self-report tool that can be completed in approximately 5 – 10 minutes. As such, it is a low-cost, readily deployable solution with a high level of usability.

### **Discussion**

The BETS is a useful tool that allows for the efficient collection of information related to prior exposures to repeated blast over a career. The tool collects information across five different weapons system categories, from small arms to large explosives. Based on the answers to the provided questions, total number of exposures for each weapon system is calculated over a career. Additionally, information on overall proportion of exposures two days in a row or more are also collected to determine a frequency factor for each weapon system. The GBEV is a single number that represents a lifetime history of blast exposure. That number is calculated based on the formula described above. Since the initial BETS study, the BETS/GBEV tool has been employed by a number of research programs that have conducted studies acquiring brain health outcome measures alongside the BETS/GBEV that extend well beyond the original BETS study. These measures include neuropsychological assessments, extended symptom inventories, fluid biomarkers, neuroimaging, and functional assessments. The number of warfighters assessed across these programs are now beyond 16,000 and counting. In addition to being employed as a key measure for research, the BETS/GBEV is being administered as a part of the USSOCOM Comprehensive Assessment Symptom History (CASH) screening program [27].

The BETS/GBEV was incorporated into a study exploring neuroinflammation in special operators recruited from US Special Operations Command (USSOCOM)<sup>7</sup>. Significant correlations were seen between prior blast exposure, as reflected by the GBEV and multiple brain health outcome measures, including changes in cortical thickness and volume, functional connectivity, neuroimaging of neuroinflammation, and brain-derived extracellular vesicle concentrations of Glial Fibrillary Acidic Protein (GFAP) and Neurofilament Light Chain (NfL) derived from serum. The study employed Principal Components Analysis (PCA)-based approaches

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to define the critical thresholds methodology that is being used in subsequent studies to define comprehensive dose–response thresholds for cumulative blast exposure.

BETS/GBEV was incorporated into the Experienced Artillery Study [28], where, using the critical thresholds approach, preliminary analyses demonstrate positive correlations with multiple neuroimaging measures of cortical thickness, alterations in white matter, and changes in cerebral blood flow, along with self-report inventories reflective of symptoms associated with concussion and psychological health. These analyses have identified changes in neuroimaging structural and function at BEC3 values of 12,600 and above.

With respect to the overall validity of the BETS/GBEV approach as a tool for defining lifetime exposures and thresholds for cumulative blast exposure, a recent psychometric study conducted by the US Defense Health Agency’s Traumatic Brain Injury Center of Excellence (TBICoE) assessed the convergent and discriminative ability of the BETS/GBEV [29]. For this study, the GBEV was calculated from BETS data, along with modified GBEV indices, which incorporated BEC2-5, BEC3-5, and BEC4-5 data. GBEV was not significantly correlated with any of the three non-blast-related variables that were incorporated in the study. In contrast, the GBEV was significantly correlated with all blast-related variables, which included the number of prior combat deployments, variables associated with low-level blast exposure, combat exposure, number of combat deployments, and high blast risk Military Occupational Specialty (MOS). A stronger association was seen between the modified GBEV indices that incorporated higher-intensity weapon systems.

A separate study demonstrated that high lifetime blast exposure, as indicated by the BETS/GBEV, was associated with worse warfighter brain health following mild traumatic brain injury [30]. Specifically, 103 warfighters and veterans with a medically documented diagnosis of mild TBI were recruited and subdivided into high vs. low blast exposure based on the BETS/GBEV. In the absence of clinically meaningful PTSD symptoms, participants with high lifetime blast exposure had worse scores on the majority of neurobehavioural measures. Additionally, the high lifetime blast exposure sub-group consistently had a greater number of elevated scores compared with the low lifetime blast exposure group.

### Conclusion

The BETS/GBEV is a self-report tool to estimate career history of blast exposure. The tool is efficient, readily deployable, and demonstrates high convergent and discriminative validity. It has enabled research to identify cumulative dose–response curves in blast-exposed military personnel. Additionally, it has seen initial use in operational populations within the US as a screening tool. A GBEV threshold value of 200k – 400k is proposed to mitigate risk for long-term neurocognitive deficits from cumulative blast exposure.

### 3.3 RISK ASSESSMENT

The risk assessment framework is a means to assess and document risk. It combines Hazard Severity (HS) and hazard probability in a Risk Assessment Matrix through which a risk assessment code can be derived. This type of structure has been widely utilised for occupational health and safety programs. In the US, a framework similar to this has been utilised to establish an allowable number of rounds for each weapon system/munition for hearing preservation, following US Technical Guide 351, ‘Health Hazard Assessor’s Guide’ [31].

Current methods to predict and assess the HS and HP associated with exposure to blast are focused primarily on the lung, other air-containing organs, and the ears as the most vulnerable to injury [31]. However, the observed response to blast for tissues such as the lung result from exposures several scales of magnitude greater than is typical for repeated low-level blast exposure measured during Tier 1 weapon use [32]. In the US,

assessment processes assign HS and HP in accordance with US Military Standard (MIL-STD) 882E and require health hazard exposure thresholds to be clearly defined [33]. The dose–response relationships between blast exposure (dose) and adverse brain health outcomes (response) are not yet fully understood. The intent of this section is to outline the framework for risk assessment and how it might be implemented as our knowledge of dose–response evolves. Implementation of this framework is currently being explored by the US DoD as an Interim Brain Health Protection Criteria (HPC).

The HS represents the magnitude of the adverse health outcome to a system user that will occur from exposure to a hazard during normal use of the system and the HP represents the degree of likelihood that exposure to that hazard will produce an adverse health outcome [34]. Table 3-1 and Table 3-2, adapted from MIL-STD-882E, display potential descriptions of the HS categories and HP levels. These HS categories and HP levels were defined for other types of injuries and level of exposures; alternate definitions may be more appropriate to describe adverse brain health effects. For some body parts, such as the ears, not all categories are used. The standard categories and levels may not match with the eventual categories and levels that can be used for adverse brain health effects.

**Table 3-1: Hazard Severity Description.**

| Hazard Severity* |          |                                                                                                                     |
|------------------|----------|---------------------------------------------------------------------------------------------------------------------|
| Description      | Category | Result Criteria                                                                                                     |
| Catastrophic     | 1        | Could result in death or permanent total disability.                                                                |
| Critical         | 2        | Could result in permanent partial disability, injuries, or occupational illness that may result in hospitalisation. |
| Marginal         | 3        | Could result in injury or occupational illness resulting in one or more lost workdays.                              |
| Negligible       | 4        | Could result in injury or occupational illness not resulting in a lost workday.                                     |

\*Source: US Army Regulation 40-10, adapted from MIL-STD-882E.

**Table 3-2: Hazard Probability Description.**

| Hazard Probability* |       |                                                                                                        |
|---------------------|-------|--------------------------------------------------------------------------------------------------------|
| Description         | Level | Likelihood of Occurrence                                                                               |
| Frequent            | A     | Likely to occur often.                                                                                 |
| Probable            | B     | Will occur several times.                                                                              |
| Occasional          | C     | Likely to occur sometime.                                                                              |
| Remote              | D     | Unlikely but possible to occur.                                                                        |
| Improbable          | E     | So unlikely it can be assumed occurrence may not be experienced.                                       |
| Eliminated          | F     | Incapable of occurring. This level is used when potential hazards are identified and later eliminated. |

\*Source: US Army Regulation 40-10, adapted from MIL-STD-882E.

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Ultimately, the identified health risk is characterised by a Risk Assessment Code (RAC), which represents the intersection of the HS category and the HP level in the Risk Assessment Matrix, and corresponds to a risk level (Figure 3-2).

| SEVERITY<br>PROBABILITY | Catastrophic (1) | Critical (2) | Marginal (3) | Negligible (4) |
|-------------------------|------------------|--------------|--------------|----------------|
| Frequent (A)            | High             | High         | Serious      | Medium         |
| Probable (B)            | High             | High         | Serious      | Medium         |
| Occasional (C)          | High             | Serious      | Medium       | Low            |
| Remote (D)              | Serious          | Medium       | Medium       | Low            |
| Improbable (E)          | Medium           | Medium       | Medium       | Low            |
| Eliminated (F)          |                  |              |              |                |

Source: MIL-STD-882E.

**Figure 3-2: Risk Assessment Matrix. (Source: MIL-STD-882E).**

A unique combination of Hazard Severity and Hazard Probability alphanumeric values (e.g., 1A, 2B, 3B) describe risk and corresponding risk level identified within the risk matrix (e.g., High, Serious, Medium, Low). The use of RACs is a standard way of portraying risk by the two individual HS and HP components rather than by a single risk level. Because a single risk level may be correlated with several different RACs, expressing risk in terms of an alphanumeric combination provides more information about the nature of the risk [34].

This method should be interpreted as a framework that can be adapted to incorporate applicable thresholds as they become available. To apply this framework, cutoffs and conditions to differentiate between the different HS categories and HP levels must be determined based on appropriate thresholds and dose-response information. In the context of adverse brain health effects due to blast exposure, there is currently no widely accepted Occupational Exposure Limit (OEL) for blast exposures to the brain.

### Conclusion

When the HS categories and HP levels are defined, the risk assessment framework may help to prevent adverse brain health outcomes associated with military personnel use of weapon systems. It can be continually updated as new and relevant information is learned and be expanded to consider additional important metrics such as blast characteristics, individual exposure history, or individual susceptibilities to injury from blast exposure. It aims to output actionable risk levels and risk mitigation recommendations in language that is generally familiar to military personnel. Ultimately, such framework can be used in conjunction with existing assessment capabilities based on risk of lung injury and hearing loss due to BOP exposure. The ability to assess the risk of adverse brain health outcomes associated with exposure to heavy weapons and breaching charges will provide commanders and risk acceptance decision-makers with the information they need to better protect brain health.

### 3.4 CONCLUSION

RTG HFM-338 has reviewed published and emerging research on blast exposure and associated adverse brain health effects. Three methods were identified by expert opinion due to their relative maturity in the field and applicability as a threshold method. These three methods may be used as thresholds to reduce the risk of adverse brain health effects from blast exposure. A risk assessment framework was introduced to assess risk linked to severity and will be useful as more data is collected on blast dose–response.

As the current state of science, RTG HFM-338 found the 28 kPa (4 psi) peak on-body overpressure for a single exposure, a cumulative impulse of 219 kPa\*ms (31.7 psi\*ms) over a single day, and a cumulative GBEV of 200k – 400k as thresholds for blast exposure to limit the risk of adverse brain health effects. The peak on-body overpressure method provides a direct limit for any single blast exposure. The cumulative impulse provides a daily limit for blast exposures in specific scenarios. The GBEV provides a threshold for multiple blast exposures over multiple years. Applying the three types of thresholds provides limits for single exposures as well as multiple exposures. The three methods can be applied separately, and health assessments can be taken when any of the thresholds are passed.

These identified methods are deemed to provide the most suitable threshold at the time of writing. However, they are still limited in evidence of mitigating adverse brain health effects. Proven injury criteria do not exist yet for this type of injury and it is recommended these be developed. Meanwhile, the proposed methods are interim thresholds, which may be used to start limiting blast exposures and associated brain health risk while the scientific community works on refinement of these criteria.

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## INTERIM EXPOSURE GUIDELINES

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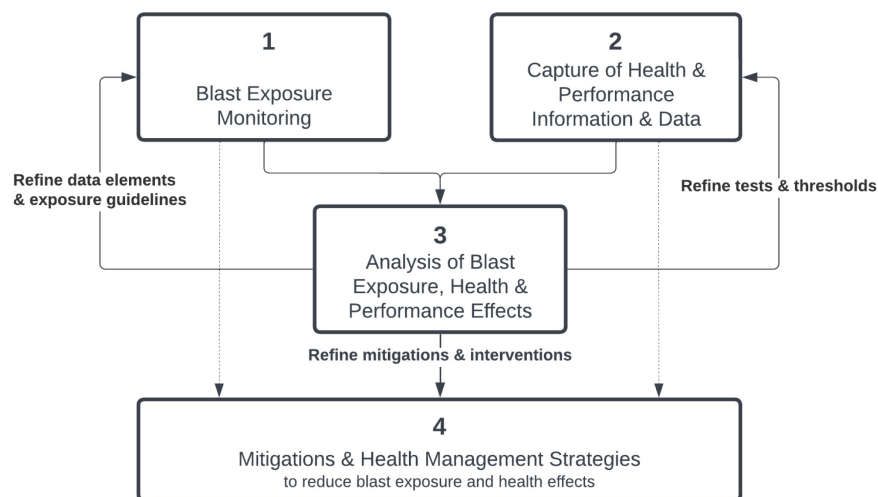
## Chapter 4 – OPERATIONAL GUIDELINES

### 4.1 INTRODUCTION

This chapter describes practical guidelines based on the current knowledge and experience of the experts present in the HFM-338 group. These guidelines are designed to be applicable for all NATO members and allied countries and will contribute to force health protection, long-term readiness, and the requirements and demands of the military leadership to address their responsibility as employers. The operational guidelines describe what measures countries can take to reduce blast exposure and its health effects.

The operational guidelines are structured in four separate capabilities which countries can develop to start (or to continue) mitigating military occupational brain health risks from repetitive blast exposure. Implementing these is going to take a multidisciplinary approach from occupational health and safety professionals, engineers, policy makers, IT-support, and military staff members responsible for safety.

The four capabilities and their connections are pictured in Figure 4-1 and will individually be described in more detail in Sections 4.3 and 4.4. Starting with *Blast Exposure Monitoring* (Capability 1) and *Capture of Health & Performance Information & Data* (Capability 2) is important to enable future risk assessments as more guidance emerges on blast exposure safety thresholds. While *Blast Exposure Monitoring* and *Capture of Health & Performance Information & Data* may be performed independently, there are significant advantages to *Analysis of Blast Exposure* (Capability 3) being done alongside *Blast Exposure Monitoring* and *Capture of Health & Performance Information & Data* to incrementally refine data elements for monitoring and associated exposure guidelines, and to refine the health and performance tests and associated thresholds. Over time, dose-response relationships can be refined for both acute and cumulative exposures. *Mitigations and Health Management* (Capability 4) work together to reduce blast exposures and the associated health effects. Moreover, even without knowing the ‘safe’ exposure levels, a country can introduce *Mitigations and Health Management* strategies to reduce blast exposures and the resulting health effects.



**Figure 4-1: The Four Capabilities along which Countries Can Develop a Program to Mitigate Military Occupational Brain Health Risks from Repetitive Blast Exposure.**

## 4.2 GUIDELINES STRUCTURE

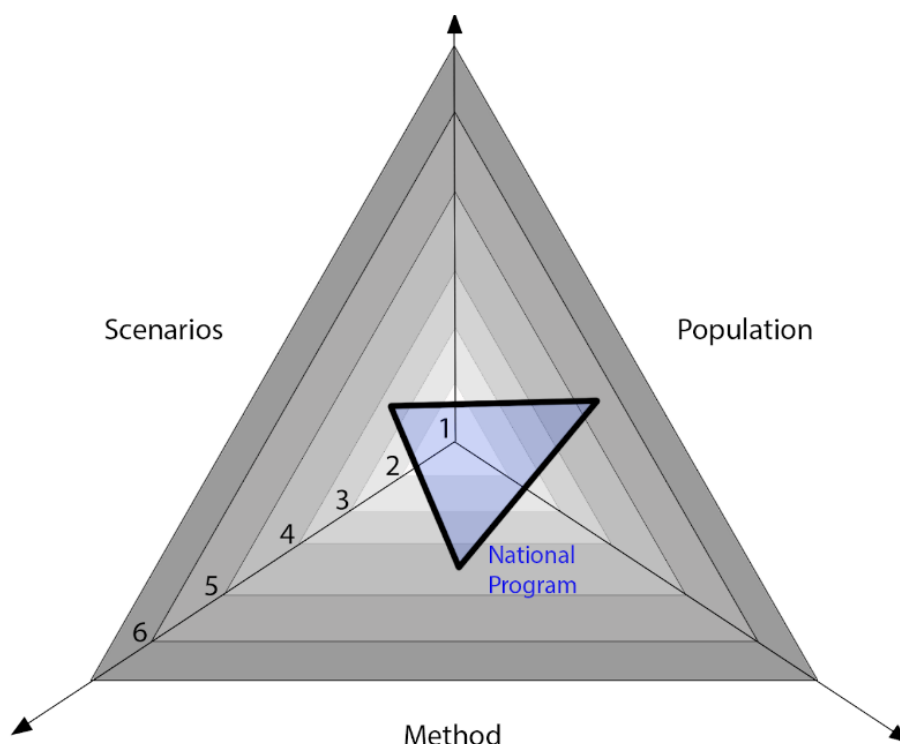
The operational guidelines consist of capabilities, sub-capabilities, and levels. Capabilities are the functional components of the operational guidelines and are further divided into sub-capabilities. For every sub-capability, six levels are described, which indicate advancement of guideline implementation. The different structural components of the operational guidelines are outlined in more detail below:

### 4.2.1 Capabilities

The capabilities describe the four functional components of the operational guidelines (Figure 4-1). When all capabilities are implemented, they form a comprehensive program aimed at monitoring and mitigating the health effects associated with brain health risks from repetitive blast exposure. Individual capabilities are suitable for functioning independently, but when combined, they complement and refine each other.

### 4.2.2 Sub-Capabilities

Every capability is divided into multiple sub-capabilities that each describe a different aspect of the capability. A graphical representation of the different levels for the capability blast exposure monitoring (Section 4.3.1), and its three sub-capabilities (Scenarios, Population, and Method) is presented in Figure 4-2 as an example of implementation at different levels for each sub-capability.



**Figure 4-2: Conceptual Representation of a Possible National Program Across the Three Sub-Capabilities of Blast Exposure Monitoring. Numbers 1 – 6 indicate the different levels that the National Program has achieved for each sub-capability.**

## 4.2.3 Levels

Levels suggest an approach to developing the sub-capabilities and thereby provide a guide to expand the operational guidelines. From Level 1, no (or limited) policy on the topic, up to Level 6, maximum effort toward achievable stretch goals, they specify a logical progression to create comprehensive operational guidelines. Higher levels include the capabilities described for lower levels. A country may operate at different levels across capabilities and sub-capabilities as they evolve their country-specific operational guidelines.

## 4.2.4 How to Use this Chapter

The operational guidelines are described in three principal sections: 4.3 Guidelines, 4.4 Detailing the Operational Guidelines, and 4.5 Examples. *Guidelines* provide a concise itemized overview of the topics addressed in capabilities, sub-capabilities, and levels. *Detailing the Operational Guidelines* provides a more detailed narrative description of each item in *Guidelines*. Lastly, *Examples* provides several examples that show how the capabilities, sub-capabilities, and levels function in practice, and how the different capabilities are connected. From these sections the reader can select a section with the level of detail and practicality that is most appropriate for their situation.

## 4.3 OPERATIONAL GUIDELINES OVERVIEW

This section summarises the operational guidelines in tables with separate tables for each capability.

### 4.3.1 Blast Exposure Monitoring

One of the key enablers available to leaders today is the ability to better understand actual blast exposures on each at-risk individual, and there are several approaches that grow in complexity and the value of the data provided. This growth occurs across three primary axes: Scenarios (‘**Where** do I monitor?’), Population (‘**Who** do I monitor?’), and Methods (‘**How** do I monitor?’). See Table 4-1.

**Table 4-1: Capability: Blast Exposure Monitoring.**

| Sub-Capability | Level* | Description                                                                                                                                                |
|----------------|--------|------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Scenarios      | 1      | No specific scenario. Generally unaware that blast exposure is a problem.                                                                                  |
|                | 2      | Subset of training scenarios based on desk analysis of data gathered from other sources.                                                                   |
|                | 3      | Subset of training scenarios based on characterisation or controlled experiments that quantified the range of blast exposure occurring in given scenarios. |
|                | 4      | Monitoring of a broad range of training scenarios involving a high risk of blast overpressure + high-risk combat operations.                               |
|                | 5      | Monitoring of all training scenarios involving blast overpressure + high-risk combat operations.                                                           |
|                | 6      | Monitoring of all training and operational scenarios involving blast overpressure.                                                                         |
| Population     | 1      | Incidental through existing population surveillance (e.g., self-reporting).                                                                                |

## OPERATIONAL GUIDELINES

| Sub-Capability | Level* | Description                                                                                                                                                                                                                  |
|----------------|--------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                | 2      | Symptomatic individuals or those who request blast exposure monitoring.                                                                                                                                                      |
|                | 3      | Small targeted high-risk populations receiving blast exposure in the normal conduct of their job.                                                                                                                            |
|                | 4      | Large targeted sub-groups such as multiple infantry and/or artillery companies.                                                                                                                                              |
|                | 5      | All personnel with high risk of blast exposure.                                                                                                                                                                              |
|                | 6      | All personnel with any risk of blast exposure.                                                                                                                                                                               |
| Methods        | 1      | None or incidental through existing occupational hygiene surveys but without focus specific to blast exposure.                                                                                                               |
|                | 2      | Reporting a posteriori, through focus surveys or questionnaires estimating type and number/frequency of exposures.                                                                                                           |
|                | 3      | Documenting exposure events in structured logs with relevant contextual details. In addition, characterisation of blast exposure within the environment conducted (use of blast sensors within the training environment).    |
|                | 4      | Characterisation of individual exposure using wearable blast sensors OR experimental characterisation of exposure scenario, capturing period of firing (timing between exposures), intensity, and total number of exposures. |
|                | 5      | Higher fidelity characterisation of individual exposure through advanced processing of sensor data with an extended modelling strategy (e.g., combining simulation estimations with actual exposures from the field).        |
|                | 6      | High fidelity characterisation of individual exposure coupled with other wearable sensors providing more accurate contextual information (medical, environmental, etc.).                                                     |

*\*Previous levels are included in the current level.*

### 4.3.2 Capture of Health and Performance Information and Data

Capturing the health and performance information and data is crucial for mitigating military occupational brain health risks from repetitive blast exposure. This involves evaluating the downstream consequences of blast interactions with the brain. This capability is organised into three sub-capabilities: Health Domains (**what** health data to capture), Assessment Regimen (**when** to capture data), and Data Techniques for Information Capture (**where** to capture data). See Table 4-2.

**Table 4-2: Capability: Capture of Health and Performance Information and Data.**

| Sub-Capability                          | Level* | Description                                                                                                                                   |
|-----------------------------------------|--------|-----------------------------------------------------------------------------------------------------------------------------------------------|
| Health Domains                          | 1      | No current health domains assessed.                                                                                                           |
|                                         | 2      | Self-declared symptoms for possible blast-related brain health effects in any environment.                                                    |
|                                         | 3      | Active screening program for basic symptoms utilising standardised tools.                                                                     |
|                                         | 4      | Active screening program to include structured cognitive/affective standardised tools and evaluation (sleep, mood, cognition).                |
|                                         | 5      | Adding sensory systems assessments (auditory, vestibular, proprioception, oculomotor) to active screening program.                            |
|                                         | 6      | Adding fluid and/or tissue biomarkers, neuroimaging, electrophysiological measures.                                                           |
| Assessment Regimen                      | 1      | Blast-related brain health effects are not routinely assessed.                                                                                |
|                                         | 2      | Use of one time point of care measures to assess brain health effects.                                                                        |
|                                         | 3      | Use of one time point of care measures with detailed history to assess brain health effects.                                                  |
|                                         | 4      | Use of prospective, acute longitudinal measures (empiric or symptom-based) to assess brain health effects. Baseline measures may be included. |
|                                         | 5      | Use of prospective, subacute longitudinal measures (empiric or symptom-based) to assess brain health effects.                                 |
|                                         | 6      | Use of prospective, long-term (career-based) longitudinal measures to assess brain health effects and conduct periodic health monitoring.     |
| Data Techniques for Information Capture | 1      | No documentation obtained.                                                                                                                    |
|                                         | 2      | Military treatment facility/clinic record of medical encounter.                                                                               |
|                                         | 3      | Capture of symptom information documented at the unit level.                                                                                  |
|                                         | 4      | Infrastructure exists to obtain, maintain and store records of blast-related brain health effects assessments at the organisational level.    |
|                                         | 5      | Infrastructure exists to obtain, maintain, and store records of blast-related brain health effects assessments at the national level.         |
|                                         | 6      | AI/ML capability for capture and storage of multiple data points of brain health effects at any level (unit, organisational, nation).         |

*\*Previous levels are included in the current level.*

### 4.3.3 Analysis of Blast Exposure, Health and Performance Effects

The exploitation of monitoring data relies on efficiently assessing and analysing collected blast exposure data as well as health and performance information and data. This can be done independently to identify mitigation

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opportunities, or through combined and integrated analysis for supporting clinical diagnostics and reinforcing the causal link between blast exposure and adverse health effects (i.e., dose-response). This capability builds towards identifying safe blast exposure limits. The Analysis of Blast Exposure, Health, and Performance Effects capability is divided into three sub-capabilities: Health and Performance data analysis, Exposure data analysis, and Data Integration. See Table 4-3. The sophistication of these sub-capabilities can also grow in terms of handling, managing, and pooling collected data for analysis.

**Table 4-3: Capability: Analysis of Blast Exposure, Health, and Performance Effects.**

| Sub-Capability                  | Level* | Description                                                                                                                                                                                                                                                                                       |
|---------------------------------|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Health and Performance Analysis | 1      | No analyses performed as no health domains are assessed specific to blast-related effects.                                                                                                                                                                                                        |
|                                 | 2      | Clinician assessment of subjective self-declared symptoms with analysis driven by individual self-report.                                                                                                                                                                                         |
|                                 | 3      | Clinician assessment of objective data collected through a standardised clinical assessment conducted as part of an active screening program.                                                                                                                                                     |
|                                 | 4      | Comparison of quantitative clinical metrics to standard norms with incorporation of cognitive/cognition data.                                                                                                                                                                                     |
|                                 | 5      | Non-AI-based data integration approaches to include clinical symptoms, cognition, and sensory systems assessments.                                                                                                                                                                                |
|                                 | 6      | AI-based integrative health analysis platforms to include clinical symptoms, cognition, sensory systems assessments, sample biomarkers, neuroimaging, and electrophysiology.                                                                                                                      |
| Exposure Analysis               | 1      | No analysis of exposure monitoring data or no exposure data to work with.                                                                                                                                                                                                                         |
|                                 | 2      | Analysis is limited, reactive, and qualitative. It relies on self-reported exposure history and a basic understanding of low-level blast environments.                                                                                                                                            |
|                                 | 3      | Quantitative analysis of structured self-reported history or personal logs in conjunction with basic characterisation data from exposure sources.                                                                                                                                                 |
|                                 | 4      | Quantitative and direct analysis of individual-specific exposure data (e.g., peak pressure data, peak impulse data, etc.). Identify individuals with higher levels of exposure as compared to peers performing the same activity.                                                                 |
|                                 | 5      | Detailed analysis involving more complex exposure/injury metrics (e.g., cumulative session/career/recovery exposure). Higher accuracy in estimation of specific loads derived and post-processed from individual exposure data + significant automation of the data recovery and post-processing. |
|                                 | 6      | Advanced, state-of-the-art analysis (e.g., CFD/brain simulation using recorded exposure data as input) of exposure data to obtain the best possible estimation of brain stress/strain, combined with robust data management for AI application.                                                   |

| Sub-Capability   | Level* | Description                                                                                                                                                                                                                                                                                             |
|------------------|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Data Integration | 1      | No integration, exposure and/or health data is unavailable or used in isolation.                                                                                                                                                                                                                        |
|                  | 2      | Case studies relating an exposure dosage to a health response, without development of a risk function or extrapolation to other similar exposure scenarios.                                                                                                                                             |
|                  | 3      | Exposure and health data pooled from multiple collections/sources to retrospectively perform a risk analysis on scenarios.                                                                                                                                                                              |
|                  | 4      | Exposure dosage and health response data are pulled together for preliminary development of an injury risk function using simplified cumulative metrics.                                                                                                                                                |
|                  | 5      | Analysis of full blast wave forms and integrated health metrics used to generate advanced injury risk functions associated with repetitive exposure and subject specific factors.                                                                                                                       |
|                  | 6      | Development of risks associated with dose response using brain health surveillance information. Analysis to include subject specificity, accounting for the temporal aspect of exposure (i.e., recovery; moving from pure cumulative injury risk function to an exposure profile injury risk function). |

*\*Previous levels are included in the current level.*

#### 4.3.4 Mitigation and Health Management Strategies

At each mitigation sub-capability level, the operational guidelines are structured within the context of the Three Es (Education, Engineering, Enforcement). See Table 4-4. These mitigations are designed to reduce blast exposure, while health management strategies are designed to reduce the health effects of blast exposure.

**Table 4-4: Capability: Mitigations and Health Management.**

| Sub-Capability        | Level* | Description                                                                                                                                                                                                                                                                     |
|-----------------------|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Education Mitigations | 1      | There is no formal education or policy regarding blast exposure risk.                                                                                                                                                                                                           |
|                       | 2      | Inform the force and increase awareness on the risks and symptoms associated with blast exposure and implications to brain health and operational readiness. Introduce the As Low As Reasonably Achievable (ALARA) principle.                                                   |
|                       | 3      | Educate support personnel (e.g., range safety officer, instructor) and individual operators on exposure guidelines and general strategies to mitigate blast exposure risk based on the exposure environment and informed by blast measurement or physics knowledge.             |
|                       | 4      | Educate support personnel on exposure guidelines and training modifications based on collected exposure data (history of days/weeks), which includes individual dosage and identification of individuals with higher levels of exposures (outliers) as compared to their peers. |
|                       | 5      | Educate support personnel on exposure guidelines and how to continuously modify training based on real-time individual exposure data.                                                                                                                                           |

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| Sub-Capability          | Level* | Description                                                                                                                                                                                                                                                                                                                                                          |
|-------------------------|--------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                         | 6      | Educate individual operators on interpreting their personal exposure history to proactively follow exposure guidelines and to understand their individual risk.                                                                                                                                                                                                      |
| Engineering Mitigations | 1      | Determine minimum standoff distance from weapon systems and breaching charges for safe operation (e.g., Minimum Safety Distance (MSD) calculations and generation of look up tables).                                                                                                                                                                                |
|                         | 2      | Define basic guidelines for training range design to minimise blast overpressure exposure.                                                                                                                                                                                                                                                                           |
|                         | 3      | Map environment with pressure sensors and/or numerical models to estimate incident overpressure profile at the head in free-field environments or partially enclosed spaces. Explore the effect of changes from the environment. Characterise new and existing weapon systems.                                                                                       |
|                         | 4      | Include human surrogates (manikins) equipped with pressure sensors; refine and enhance the numerical models. Include more complex environments including reflective surfaces (i.e., vehicles, walls, obstacles). Characterisation should reflect true training conditions and geometry.                                                                              |
|                         | 5      | Perform physical testing of protective equipment with sensors to rank and compare PPE; support physical test results with computational modelling to evaluate variants of PPE or different exposure scenarios. Use computational models to design advanced test environments (e.g., new ranges) that reduce exposure risk. Use state-of-the-art evaluation criteria. |
|                         | 6      | Permanent/continuous programs for evaluation and adjustments of the entire operational environment (load cases, metrology, equipment, weapon systems, recovery times, nutrition, health monitoring). All systems verified and validated (not just comparative studies). Pulls in all risk factors and sources.                                                       |
| Enforcement Mitigations | 1      | Use existing protective equipment, procedures and general safety regulations during activities where blast exposure may occur (e.g., weapon systems, breaching, EOD). Provide guidelines and look up table/MSD calculations for recommended standoff distances.                                                                                                      |
|                         | 2      | Ensure training range design adheres to latest guidelines based on knowledge of blast physics.                                                                                                                                                                                                                                                                       |
|                         | 3      | Provide limits on number of exposures based on weapon system, position, and environment based on exposure count, exposure history, and health assessments.                                                                                                                                                                                                           |
|                         | 4      | Develop protocol for site visits/inspections to ensure training ranges adhere to the latest brain health safety criteria. Develop protocol to correct positioning errors or environmental factors leading to excessive outlier exposures.                                                                                                                            |
|                         | 5      | Standardise updates to training procedures at the unit level and require any modifications to be based on injury exposure assessments of the blast environment.                                                                                                                                                                                                      |

| Sub-Capability    | Level* | Description                                                                                                                                                                                                                                                                                       |
|-------------------|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                   | 6      | Standardise training and operational modifications at the organisation level, including employing personalised injury models that incorporate historic blast exposure, health assessments, and anticipated exposures. Incorporate blast mitigation requirements into the PPE acquisition process. |
| Health Management | 1      | No specific healthcare management capabilities related to blast exposure.                                                                                                                                                                                                                         |
|                   | 2      | Availability of primary care services to address health effects from blast exposure.                                                                                                                                                                                                              |
|                   | 3      | Primary care services addressing health effects from blast exposure in line with specific central policy.                                                                                                                                                                                         |
|                   | 4      | Availability of specialty referral services with expertise in health effects from blast exposure.                                                                                                                                                                                                 |
|                   | 5      | Multidisciplinary rehabilitative care for the comprehensive management of service members with repetitive blast overpressure exposure, available to select individuals.                                                                                                                           |
|                   | 6      | Multidisciplinary rehabilitative care for the comprehensive management of service members with repetitive blast overpressure exposure, available to all individuals with need across the enterprise.                                                                                              |

*\*Previous levels are included in the current level.*

## 4.4 DETAILING THE OPERATIONAL GUIDELINES

This section provides more in-depth details of the operational guidelines. It provides a description of the capabilities and sub-capabilities and describes each level at a greater level of detail.

### 4.4.1 Blast Exposure Monitoring Capability

The monitoring of blast exposure is essential to the quantification and understanding of the level of risk associated with a given individual exposure history. The general logical progression of this capability is an evolution from small-scale subjective monitoring (i.e., self-reported) to broad objective monitoring (e.g., wearable blast sensors). To progress towards such comprehensive monitoring capability, there are three key sub-capabilities that a policy should grow along:

- A) **Scenarios ('Where do I monitor?'):** Blast exposure monitoring may take place in various circumstances and risk environments, which combine to create scenarios of exposure. Scenarios of interest may be identified in different ways. A desk analysis based on previously documented scenarios involving training with similar types of explosive or weapon systems is a simple method of identification requiring minimal resources. Scenarios may be identified from any training activity involving a weapon system that is part of an agreed upon list of previously characterised weapon systems, or those of high concern. Scenarios of interest may even comprise of any activities (military education, training, exercises, and combat) that carry a reasonable risk of blast exposure, such as small arms ranges, areas of concussion grenade use, or a tank firing range.

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- B) **Population ('Who do I monitor?')**: Blast exposure monitoring can take place across various populations, from only those who had previously self-reported exposure or symptoms up to any warfighter at risk of exposure to a blast.
- C) **Methods ('How do I monitor?')**: Blast exposure monitoring may employ various methods and technology to achieve a given level of exposure quantification. The self-reporting of exposure history using a logbook is a simple way to collect information of number and frequency of exposure but relies only on rough estimates or notional levels of overpressure. Alternatively, individually worn blast overpressure sensors that automatically record and log all blast exposures experienced by each warfighter offer the potential for a characterisation of high resolution and accuracy.

### 4.4.1.1 Scenarios

**Level 1:** The military organisation has not identified specific training or operational scenarios which it wishes to monitor in any way. At this level, decision-makers are generally unaware that occupational blast exposure poses a health risk to its population.

**Level 2:** The selection of exposure scenarios to monitor is informed by external sources of information on blast exposures and typically consist of a small subset of exposure scenarios at the higher end of the expected exposure range. These external sources of information may comprise scientific articles (see Kamimori et al. [1]) and CONQUER weapons summary [2], [3], [4], from the open literature and foreign defence department policies, like the US Tier 1 weapons list (shoulder mounted, 50 cal. weapons, indirect fire systems, and breaching charges). At this level, the scenarios to monitor are selected because they are deemed likely scenarios for which relative or quantitative characterisation data was available, and for which the level of exposure is deemed significant. The main shortcoming of this type of desk analysis is that blast exposures in a live environment can be highly variable and affected by small changes in the scenario details. As such, individual exposures in one country can be significantly more or less than that reported by another study or country. For example, there is potential risk in assuming that the use of a given weapon system by a defence force will generate the same individual exposures as the use of the same system by another user group. Finally, this approach to scenario selection may not consider the likelihood of unplanned events that could cause spikes in exposure during the use of certain weapon systems or explosive charges.

**Level 3:** At this level the strategy towards the selection of scenarios to be monitored resembles that of the previous level, but it is now informed by characterisation data obtained through controlled experiments that are specific to the defence organisation's operating procedure. Controlled experiments may consist in the recreation of real blast exposures while deploying a small quantity of pressure sensors (e.g., pencil probes, etc.) in select locations to measure the range of blast exposures involved in that scenario. This approach alleviates the risk involved with assuming that for seemingly similar scenarios, externally obtained exposure characterisation data is representative of the domestic exposures. Scenarios may be selected based on a specific overpressure threshold of interest or based on a relative ranking of exposure severity. At this level, scenarios of interest are typically still limited to a subset of blast exposures representing the higher end of the exposure spectrum.

One of the advantages of a decision based on controlled experiments is that they can be implemented in the process of weapon system procurement or (ammunition) testing. The main shortcoming of this approach is that it still does not account for crew variations around the weapon system or explosive charge and, similar to the previous level, the likelihood of unplanned events causing spikes in exposure are not necessarily considered. This method also assumes access to blast experts and the capability to conduct full scale blast experiments.

**Level 4:** Relative to the previous level, a significant increase in the amount of training scenarios selected for monitoring is expected, as well as the monitoring of certain specific operational scenarios. The identification of scenarios to be monitored may still be based on controlled experiments, but may now also be informed by more advanced individual exposure characterisation methods such as personal blast sensors, computer modelling, etc. Because the number of scenarios to be monitored is increased, it is expected that factors other than the range of recorded overpressure are considered, such as frequency (i.e., how often is the scenario occurring) and likelihood of unplanned increased exposure. The selection of scenarios should nevertheless be focused on what is deemed to be significant blast exposure.

**Level 5:** At this level the strategies for the selection of relevant operational scenarios may remain the same as for the previous level, but the scenarios to be monitored now include any training scenarios involving blast exposure.

**Level 6:** At this level the scenarios to be monitored now include all training and operational scenarios involving blast exposure. Note that because of the unpredictable and uncontrolled nature of operational exposures, the choice of monitoring all operational scenarios does imply access to methods of monitoring that can capture the occurrence of an exposure along with critical contextual information, at a minimum.

#### 4.4.1.2 Population

**Level 1:** At the first level, the monitored population is not defined or homogenous in terms of roles and group affiliation. The monitored population is mostly incidental and a product of other existing health care monitoring programs without a focus on the effects of blast exposure.

**Level 2:** At this level the monitored population is still not structured or homogenous in terms of group affiliation or belonging to a high-risk population. However, it now includes members presenting the common characteristics of being symptomatic (e.g., headache, cognitive complaints, oculomotor or eye problems, vestibular or balance difficulties, anxiety and mood changes, and sleep disturbances) or of having requested individual blast exposure monitoring. There is not a universal monitoring strategy at this level, as the selection of the population to monitor is more reactive than proactive.

**Level 3:** There is a coherent and more proactive approach towards the selection of the monitored population. The intent is to target a population that is still considered small relative to the country's fighting force but that represents a high-risk population when combining the aspects of exposure likelihood, levels, quantity, and frequency. Groups at high-risk may include warfighters, students, and instructors who operate and train with specific weapon systems and/or who conduct explosive entry. It may be groups exposed frequently to one system or groups exposed to multiple systems. It may be an infantry company responsible for explosive building entry and/or use of weapon systems associated with high levels of blast overpressure exposure (e.g., part of the US Tier 1 weapon systems).

**Level 4:** At this level the selection of the population to monitor is still based on the highest relative perceived risk, which is still a combination of exposure likelihood, magnitude, quantity, and frequency. However, the size of the selected population is expected to grow significantly compared to the previous level. Targeted sub-groups may now represent multiple infantry and/or artillery companies responsible for explosive building entry and/or use of weapon systems associated with high levels of blast overpressure exposure. The intent is to target a medium-sized at-risk population relative to the country's fighting force.

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**Level 5:** At this level any personnel at high risk of exposure to blast overpressure is targeted for monitoring. The definition of high risk is now more absolute as opposed to relative to other exposure schemes (i.e., high vs. highest). The intent at this level is to grow the monitoring program further to a large-sized at-risk population relative to the country's fighting force.

**Level 6:** At the last level, the population is intended to grow further, and the scope of the monitoring program now captures all personnel within the country's fighting force at-risk of being exposed to blast overpressure.

### 4.4.1.3 Methods

**Level 1:** There is no dedicated method for collecting exposure data. The collection of exposure data is incidental and a product of existing occupational hygiene surveys not focused specifically on blast exposure.

**Level 2:** At this level the collection of exposure data is performed a posteriori using focused surveys or questionnaires that allows for the estimation of the number and levels of blast overpressure exposures. Estimates of number of exposures are typically self-reported but may be supplemented by documents such as training schedules of unstructured logs capturing relevant training events with likely blast exposure. Levels of exposures are only grossly estimated from calculations based on the amount of propellant/explosive used or binned into severity categories. In addition to the low resolution of the exposure level estimate, a limitation of this method is that it does not consider variability in the exposure levels due to changes in personnel position, posture, equipment, environment, etc. The method assumes an approximate level of exposure for a given source of blast overpressure, regardless of the finer details of the exposure scenario.

**Level 3:** The collection of exposure data is done through the maintenance of structured exposure logs, which capture important contextual details at the group and individual level, and which enables a higher resolution description of the exposure scenario. Levels of exposure are estimated from documented overpressure signatures for similar weapon systems or explosive charges in similar scenarios. This method is used to assess an individual's exposure or to evaluate the exposure to Similar Exposure Groups by an occupational hygienist. This method still has the limitation of not considering variability in the exposure levels due to individual position, posture, and equipment. It also still assumes a specific level of exposure for a given blast overpressure source but may account for some specificity of the scenario, depending on the data available.

**Level 4:** The collection of exposure data now relies on higher fidelity measurements, specific to the scenario of interest, which may be done in real-time using wearable blast sensors or through static characterisation of the exposure scenario. The wearable blast sensor method has the advantage of capturing real-time data, which really capture each unique exposure instance, considering the effect of any subtle variations in environment, body posture, and position for a given scenario. A limitation of such sensors is that the measurement location on the body may have a great effect on the recorded pressure magnitude and may not always accurately represent true exposure of the head of the service member, though an algorithmic approach called FAST-CT has been offered to correctly apply the body-measured values to incident estimation to convert to head loading [5]. Static characterisation involves recreating the exposure scenario to measure the source of the blast. These measurements may be recorded by qualified technicians using state-of-the-art overpressure sensors and/or physical models deployed around the firing position and at any other relevant positions (e.g., observer, loader, instructor), in accordance with the associated training tactics and procedure for the weapon or explosive under consideration. The method has the advantage of not being influenced by on-body placement, and recordings may be further analysed to estimate exposure at the head of the member, by interpolating the entire overpressure field, or modelling the environment in a suitable computer fluid dynamic tool. Conversely, it has the limitation of not accounting for variability in environment, person posture,

and position, plus significant overhead and expertise required. With both methods, this level is characterised using higher fidelity measurements to estimate individual exposure. Automation in the data collection and data processing workflow is not necessarily expected at that level, but the data collection process should be linked to personal logs.

**Level 5:** At this level the higher fidelity measurements described at the previous level are used in conjunction with advanced processing or modelling techniques to achieve a more accurate estimate of individual blast exposure of the head. Wearable blast sensors may be used in conjunction with algorithms and/or Computational Fluid Dynamics (CFD) that can process all sensor data from a set jointly to compute parameters that are better representative of true head loads or head loading conditions [5]. On the other hand, static characterisation data for given scenarios may be used in conjunction with advanced modelling tools (e.g., CFD codes capable of handling blast propagation) to estimate the full distribution of pressure on the head in various positions. To be able to interpret the measurement data correctly it is necessary to record important measurement conditions. At this level a certain level of automation in the data collection, data process, and exposure estimates are expected. In the case of the blast sensors, automated data pulling to an analytical platform may differ between training and combat environments due to digital military communication restrictions in the latter. Overall, the level is characterised by a greater level of fidelity and specificity of the exposure estimates, along with a certain level of automation.

**Level 6:** At the final level, the exposure monitoring method includes one of the methods detailed at the previous level but is now also coupled with real-time automation of data processing, real-time head exposure estimation, and data linkage with individual or group logs. Also at this level, the collection of contextual data on the scenario is now enabled by additional health sensors and/or wearable sensors that can help to interpret the exposure data (e.g., health, environmental, posture, navigation, body cam, etc.).

#### 4.4.2 Capture of Health and Performance Information and Data

Assessment of blast exposure, health, and performance effects is an important component of a program to mitigate military occupational brain health risks from repetitive blast exposure. These effects represent the downstream consequences of blast interactions with the brain otherwise known as the brain health effects. The Blast Exposure, Health, and Performance Effects capability is organised into three sub-capabilities. These include: a) Health Domains; b) Assessment Regimen; and c) Data Techniques for Information Capture.

The sub-capabilities below provide additional information on each of these considerations, and are organised by level, ranging from least (Level 1) to most complex (Level 6). These recommendations represent a synthesis of what is presently known based on the available evidence:

- A) **Health Domains ('What health data to capture'):** The objective of this sub-capability is to best describe what areas of health information need to be collected to evaluate for brain health effects from blast exposures. Some examples of health data that have been researched in the setting of blast exposure, specifically through the US NDAA FY 18 SEC 734 studies, include but are not limited to the following: symptom reporting, neurocognitive and neuropsychological, sleep, mental health, sensory, such as vestibular (balance), auditory, oculomotor (eye tracking), blood and fluid biomarkers, neuroimaging and endocrine function through the collection of hair. Note that these areas of health information may be quite sensitive and may reveal effects of exposure that do not represent consequences for military personnel performance. Still pending is the definition of criteria that differentiate the detection of an exposure effect from the detection of threshold an exposure effect that has meaningful bearing on military personnel performance and health.

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- B) **Assessment Regimen ('When to capture data')**: This part is dedicated to the infrastructures necessary to collect and monitor the data and considerations about the analysis plan of the data, starting from one time point measure, adding medical and blast exposure history, and moving toward prospective, longitudinal monitoring following acute exposure, and in higher levels subacute or career long exposure. Considerations about baseline testing to aid in the assessment regimen is also discussed.
- C) **Data Techniques for Information Capture ('Where to capture data')**: Data capture may employ various methods and technologies to collect high fidelic information. The levels increase in both sophistication of data collection and retrieval as well as applicability to guide individual and nation-level interventions. This section considers the data storage and retrieval system that could be used at the most basic military unit level up to nation and NATO level.

### 4.4.2.1 Health Domains

**Level 1:** At this level no specific health data is assessed. At this level there is not a single test or symptom specific for blast TBI. Considering the overlap with mild TBI symptoms and tests used for the management of such health problems it is likely that blast TBI cases are captured within the casualty system developed for different severities of TBI. Similarities in reported symptoms with conditions such as mild TBI may also be captured but without necessarily being noticed as blast TBI. Nonetheless, a well-developed TBI casualty system can be used for retrospective analysis of blast TBI events and resulting brain health effects.

**Level 2:** This level represents an initial level of self-reporting and recognition of symptoms in relation to repetitive blast exposure. Military personnel – upon recognising common symptoms after blast exposure, such as headache, mental fogging including memory problems, balance issues, sleep and mood challenges – may seek a health assessment. It should be noted that if acute or chronic symptoms raise to the level of self-report that engages the health care system, then it is safe to presume that they are serious enough to have interfered with the daily life activities and job performance of the military member. It is also possible that these symptoms exist at a lower level but are not sufficient to warrant the warfighter to engage the health care system or the member's leadership. In some instances, the warfighter may not report symptomology due to stigma or fear of change of duty.

Acute assessment within hours or days of repetitive blast exposure may have some resemblance to acute concussion symptoms, whereas assessment of symptoms with cumulative exposures over many months or years may represent a different array of symptoms more closely associated with post-concussive symptoms, such as depressed affect, anxiety, mood alterations, irritability, sleep disturbances, and lingering headaches.

**Level 3:** The hallmark criterion for this level is active engagement to ask about symptoms through a screening program, in contrast to self-declaration of symptoms, as found in Level 2. This level consists of the development of an organised surveillance program with standardised tools. There are multiple examples in the literature where warfighters have reported high incidence and severe symptoms following blast exposures [6], [7], [8]. These symptom complaints may mimic the symptoms reported by those who have sustained a concussion or mild TBI and may fall within the following main six symptom clusters:

- 1) Headache,
- 2) Cognitive complaints,
- 3) Oculomotor or eye problems,
- 4) Vestibular or balance difficulties,

- 5) Anxiety and mood changes, and
- 6) Sleep disturbances [9].

It is also critical that auditory or hearing-related complaints are assessed due to the dynamics of blast exposure affecting the ear and auditory apparatus. This is unique to blast exposure in contrast to other brain threats, such as impact type injuries, that occur during sporting or parachuting activities. There are various symptom questionnaires (standardised symptom inventory tools) that may be used to assess both the presence of the symptom and the intensity or frequency by which the symptom is occurring. Two examples of common symptom questionnaires in North American English and in the public domain are the Rivermead Post-Concussion Symptoms Questionnaire (RPQ) or the Neurobehavioral Symptom Inventory (NSI). Both questionnaires inquire about all six symptom clusters noted above.

Tools used should be standardised across NATO countries and should address all six clusters. There are benefits to using the same questionnaire so that data can be collected across NATO countries for larger epidemiological efforts.

**Level 4:** The main advancement for this level is the addition of cognitive and affective assessments. Neurocognitive and neuropsychological assessments can be helpful in evaluating the effects of low-level blast exposure on the brain and behaviour. It is important to note that neuropsychological and neurobehavioural assessments are only part of a comprehensive evaluation for blast exposure. Neurocognitive assessments typically involve a series of standardised tests that evaluate various cognitive functioning domains, such as attention, memory, executive function, processing speed, language, and visuomotor/spatial abilities. These domains of cognitive functioning are cited as components of performance measured by these batteries. These tests can provide insight into the extent of cognitive deficits that may have resulted from blast exposure. Examples of computerized tests include the Automated Neuropsychological Assessment Metrics (ANAM), the Defense Automated Neurobehavioral Assessment (DANA), and the non-computerized symptom inventory Neurobehavioral Symptom Inventory (NSI). Neuropsychological assessments can also include measures of mood and behaviour, such as depression, anxiety, irritability, and impulsivity. These measures can provide information about the emotional and behavioural changes that may have occurred following exposure to blast. It is important to note that neurocognitive and neuropsychological assessments are only part of a comprehensive evaluation for blast exposure.

**Level 5:** This level adds sensory system assessments, specifically evaluating auditory (hearing), vestibular (balance) and proprioception (awareness of the body in space), and oculomotor (vision and eye tracking). Supervised sensory system assessments have been more strongly correlated with blast exposure magnitudes and other blast-associated effects than passive symptom reporting.

Auditory function assessment may include assessment of peripheral function (the outer, the middle, and the inner ear), central function (the cochlear nucleus to the primary auditory cortex), or both. Note that blast exposure-related hearing ability deficits have cascading consequences on effective interpersonal communications and other performance, and these effects have been observed even when appropriate personal protective equipment for hearing has been in place. Recent hearing ability assessments of this type have been made in field settings using a Wireless Automated Hearing-Test System (WAHTS) [10]) and further such assessments would be found in clinical settings.

Vestibular function and proprioceptive function assessments have been shown to account for performance variance not accounted for by other measures, suggesting that, when vestibular or proprioceptive deficits are present, they are less likely to be revealed through other assessments. There are a variety of vestibular function and proprioceptive function assessments suitable for field administration, including those that require no equipment as well as some that do require specialised equipment. Examples of assessments in common use

that require no equipment are the Romberg [11] and the Balance Error Scoring System [12]. An example of a device-based assessment is the Limits of Stability Test [13].

Oculomotor assessments following blast exposure, based on correspondence with Dr. W. Carr<sup>1</sup>, have revealed effects that correspond to magnitude of blast exposure and to elevations of blood-based biomarkers associated with neurotrauma. Assessments of eye motion include tracking smoothly moving stimuli, converging and diverging as stimuli move nearer or farther, eye gaze stability following stimuli disappearance, and pupil response to light flash. An example of an assessment in common use that requires no equipment is the Vestibular Ocular Motor Screening (VOMS) [14]. There are various examples of device-based assessment that directly measure and assess oculomotor function with camera technology.

**Level 6:** This level adds biosample biomarkers [15], [16], neuroimaging [17], [18], [19], and electrophysiological measures [20]. Biosample biomarkers are inclusive of fluids or tissue derived from individuals that may be reflective of changes associated with repetitive blast exposure. Most biosample biomarkers assessed to date have focused on the use of blood samples, with some of the most successful of these focusing on exosomes or small packets of protein and small molecules derived directly from the brain and released into the bloodstream. Several studies have examined saliva and hair. Assessed molecules reflect alterations in a variety of systems, including those involved with inflammation, blood brain barrier integrity, and a variety of structural proteins. Neuroimaging studies have focused primarily upon Magnetic Resonance Imaging (MRI) and Positron Emission Tomography (PET). These studies have shown changes in grey matter, white matter, blood flow, and functional connectivity between brain regions. Additionally, PET studies have demonstrated increased neuroinflammation in military personnel exposed to repetitive blast. In terms of electrophysiological measures, tools such as Electroencephalography (EEG) [20] and Magnetoencephalography (MEG) [21] exist and may be useful. Of note, several of the techniques at this level are difficult to assess in isolation at an individual warfighter level and may require a baseline and/or assessment as a cohort to understand and mitigate effects of repetitive blast exposure. Because this is an area that is rapidly evolving, it is anticipated that these measurements will become more utilised.

#### 4.4.2.2 Assessment Regimen

**Level 1:** Blast-related brain health effects are not routinely assessed; however, military health and casualty trauma systems may be aligned to capture blast TBI-related assessments.

**Level 2:** Blast-related brain health effects are captured in one point of care time frame. The assessment regimen is highly dependent upon how the warfighter self-reports symptoms. An example of a clinical tool that could be used to assess a warfighter after exposure to repetitive blasts that results in self-reported symptoms is the Military Acute Concussion Evaluation 2 (MACE 2) [22]. The results of the assessment will be communicated to the warfighter's unit and would be documented in their Electronic Health Record (EHR). Assessment of long-term, non-acute symptoms and their association with prior blast exposure could be accomplished through retrospective survey instruments, such as the Blast Exposure Threshold Survey (BETS), among others.

**Level 3:** The assessment regimen is further refined to use one time point of care measures but adds a detailed history, which will enhance the information obtained. Active surveillance and monitoring of symptoms and history can occur after an acute training exercise or an acute adversarial event. Providing a unit with a standardised symptom and history questionnaire to fill out after these blast events can serve as both

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<sup>1</sup> Dr. Carr is affiliated with the Walter Reed Army Institute of Research (WRAIR), Center for Military Psychiatry and Neuroscience (CMPN), Blast Induced Neurotrauma Branch (BINT).

a baseline for future symptom monitoring, as well as to triage for opportunities to be screened for blast-related brain injury. An example of a detailed history tool is the US Special Operations Comprehensive Assessment Symptom History, or the CASH. The CASH is used to document a detailed history and symptom reporting to support treatment or mitigation interventions [23].

**Level 4:** The assessment regimen is further evolved to include prospective, acute longitudinal assessments, which may be symptom and empirically based, to assess for brain health effects. Baseline assessments may also be utilised to help provide context for acute brain health changes and to add power to the analysis to support treatment and mitigation solutions. Neurocognitive and neuropsychological assessments are used to evaluate cognitive and psychological functioning in individuals who have experienced low-level blast exposure. These assessments typically involve a combination of standardised tests, questionnaires, and interviews to gather information about an individual's cognitive abilities, emotional functioning, and behaviour. Common examples of assessments that may be used in the evaluation of low-level blast exposure include the Trail Making Test [24], the Digit Span Test [25], the Wisconsin Card Sorting Test [26], the N-back Continuous Performance Test [27], the Stroop Test [28], and Automated Neuropsychological Assessment Metrics (ANAM) battery [29]. Additional measures may include self-report questionnaires to assess mood and behaviour, such as the Beck Depression Inventory [30] and the Behavior Rating Inventory of Executive Function [31].

**Level 5:** The assessment regimen is further enhanced by including prospective, subacute longitudinal assessments that also incorporates sensory system assessments. Pre-exposure baseline assessments can assist in evaluating changes post-repetitive blast exposure. The subacute assessment timepoints would serve to evaluate return to baseline or the presence of more long-lasting effects. An annual assessment regimen, maybe in conjunction with an existing assessment regimen (e.g., hearing conservation program), could serve to track change commensurate with chronically exposed populations, relative to populations without exposure.

**Level 6:** Level six incorporates prospective, long-term longitudinal assessments with health monitoring. This level is distinguished from the prior level as encompassing an entire military career of assessments. Like other occupational risks, such as radiation exposure, this level recognises that repetitive blast exposure is a risk throughout a career and should be captured as such. This would include capture of baseline information at the start of service.

#### 4.4.2.3 Data Techniques for Information Capture

**Level 1:** At this level no documentation specifically related to brain health effects from blast exposure is obtained. However, information already in the casualty management and trauma systems are ideally optimised for information capture of these conditions and could, with modifications, be optimised for capture of health data related to blast TBI. At this level blast overpressure and its brain health consequences are not treated as a specific medical entity.

**Level 2:** As a first line approach for repetitive blast exposure, symptom data assessment and capture is through an encounter with the military treatment facility. Some specialised units that are considered high risk for blast exposure or blast injury, such as Special Operations Forces (SOF) or Explosive Ordnance Disposal (EOD), may have advanced reporting infrastructure. Retrospective queries of these specialised unit databases and records may provide additional information.

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**Level 3:** Capture of data at this level resides within the military unit. Depending on the area of specialty, some units have infrastructure to support symptom-based questionnaires. However, another important aspect at the unit level is to assure that someone in the unit has access and can evaluate the symptom data as well as a detailed history profile. If the data is not available then opportunities for intervention, treatment, and/or mitigation are negated.

**Level 4:** Data techniques for information capture expands to the organisational level. Infrastructure exists to obtain, maintain, and store records of blast-related brain health assessments and measures at the organisational level. The data platform allows for analysis both at the individual warfighter level as well as the organisational level to evaluate trends and outliers. At this level there is more health-related assessment data which gives more power for the data analytics to yield actionable information.

**Level 5:** This level expands to include infrastructure to obtain, maintain, and store records of blast-related brain health assessments at the national level. Due to the size and magnitude of the brain health assessment data across a nation, these data merit a dedicated system or subsystem that affords the ability to compare assessment results over repeated administrations and long durations. Unstructured data in a general medical record system may preclude routine time-based comparisons and therefore obscure exposure-based effects while they are occurring. However, national-level data systems should support real-time analysis of blast-related brain health assessment information.

**Level 6:** This level is distinguished from the prior levels in that it addresses techniques for capture rather than the setting of information capture. These techniques may be applied to Levels 2 through 5 in this sub-capability. This level employs the use of Artificial Intelligence and Machine Learning (AI/ML) techniques for efficient and accurate information capture. These techniques may handle unstructured up to highly structured data, with ingestion of that data and translation into a uniform format. These approaches are well-suited for operational environments, where it is important that any assessment regimen is minimally disruptive and highly efficient. AI/ML techniques are used in this context for information capture and organisation alone. Use of these techniques for analysis are detailed in the *Analysis of Blast Exposure, Health & Performance Effects* section.

### 4.4.3 Analysis of Blast Exposure, Health and Performance Effects

The exploitation of monitoring data mostly relies on the capability to efficiently assess and analyse the collected blast exposure and health and performance information. This information may be analysed independently to provide multiple direct opportunities for mitigation and interventions. For example, individual exposure data may be analysed relative to group average exposure to identify outliers to intervene on, or levels of specific biomarkers may be tied to measurable performance decrement to identify threshold values not to be exceeded. Nevertheless, the combined and integrated analysis of the exposure and health and performance information presents significant benefits. Not only can it provide supporting evidence to clinical diagnostics, but it can contribute to further reinforcing the causal link between blast exposure and adverse health and performance effects. Perhaps even more important, the integrated analysis of exposure and health and performance data is critical to progress towards the identification and refinement of safe blast exposure limits.

The analysis capability are therefore divided into three sub-capabilities:

- A) **Health and Performance Analysis:** This sub-capability captures the level of sophistication of patient-reported and clinician assessment data. The intent is to develop a health and performance assessment suite to enable accurate derivation of subject baseline health and performance as well as detect deviation from this baseline.

- B) **Exposure Analysis:** The capture of blast overpressure exposure through increasingly detailed measurement and characterisation builds this sub-capability. Refinement of this sub-capability progresses towards a better estimation of on-body overpressure loads and translation of these loads to tissue stress/strain.
- C) **Data Integration:** This sub-capability is intended to describe the development of risks associated with dose response information. Specifically, the integration of health and performance data along with exposure data enable increasingly sophisticated injury risk assessment.

As with the previous capabilities, each sub-capability is articulated over six levels of refinement and complexity, ranging from a basic interpretation of the collected data to more advanced statistical analyses and up to AI-enabled analysis and interfacing with advanced modelling approaches. The analysis sub-capabilities can also grow in sophistication with regards to the methods of handling, managing, and pooling the collected data for analysis. For example, independent and distributed records of information may limit opportunities for analysis while automatic data aggregation from individual blast sensors into individual medical records may enable more options.

All six levels are further detailed below for each of the three sub-capabilities.

#### 4.4.3.1 Health and Performance Analysis

**Level 1:** At this level no health analyses are performed specific to blast exposures. Only regular health care assessment measures are considered when conducting health analyses.

**Level 2:** Clinician assessment of subjective self-declared symptoms related to blast exposure. The first line assessment of self-reported symptoms to a medical provider that could be medically trained assets embedded within an operational unit or a clinical encounter with a health professional at a health care facility. Clinical observations of the members self-reported symptoms would be recorded in the member's medical record.

**Level 3:** Clinician assessment of objective data collected through standardised clinical assessment. A second line clinical intervention with additional clinical assessment tools brought into the assessment through routine surveillance will enable more detailed analysis. The medical provider could be medically trained assets embedded within an operational unit or a clinical encounter at a health care facility. Clinical assessment would be a rudimentary neurological assessment, such as a mini mental status examination, together with other basic clinical workup measures that could include analysis of serum GFAP, a CT scan, and neuropsychological testing if warranted. Detailed clinical observations would be incorporated into the member's medical record.

**Level 4:** Many health-related tools generate information that is quantitative in nature. Integration of cognitive assessments or cognition data will enable more detailed analysis. Determination of whether a quantitative value reflects a 'normal' or 'abnormal' value may be accomplished by comparing that value to a reference standard. Such standards are defined by acquiring data from groups of normal individuals to establish a reference range. If a value acquired from an individual falls within that reference range, it is determined to be 'normal'. When compared to baseline levels, significant deviation, or if values fall outside of that reference range, it may be considered 'abnormal'.

**Level 5:** Health assessments may take the form of integrating multiple pieces of data to generate a scale or score that has diagnostic or prognostic value. A broad range of different types of tools follow this model, including physiological testing, cognitive tools, and testing of sensory systems. This level is defined by health assessments that employ this approach. Examples of these include the Glasgow Coma Scale (GCS) [32] or Glasgow

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Outcome Scale-Extended (GOS-E) [33] as well as the Rotterdam [34] and Marshall Scoring Systems [35]. This level is defined by the implementation of these types of approaches to integrate multiple data elements into a scale or scoring system to assist with operational decision making.

**Level 6:** Artificial Intelligence-based tools may serve as powerful approaches for performing adaptive assessments or revealing latent information within health data. These approaches may be employed to aid in ingesting large amounts of unstructured data in different forms, identifying key patterns that may assist with diagnosis, may help with outcome prediction, improve health-related workflows, and assist with decision support pipelines. Additional data streams incorporated into analysis may include – but are not limited to – the use of biosamples, biomarkers, neuroimaging, and electrophysiology. This level is defined by the capability to implement such approaches.

### 4.4.3.2 Exposure Analysis

**Level 1:** Monitoring data or an exposure log is generally non-existent and does not allow for any quantitative analysis.

**Level 2:** The available exposure data is generally in the form of self-reported exposure history, which may be complete, such as an estimation of exposure history over an entire career, or partial and focused on recent training events. This exposure history is generally not logged consistently or in a standardised format, which makes robust analysis over sub-groups or populations challenging. Analysis is limited by incomplete data and the low resolution and accuracy of the data available. Exposure may be described in nature or type but not typically quantified in magnitude other than in relative terms.

Clinicians and leaders may use self-reported exposure history along with generic quantification of the severity of the exposures, sourced externally for the weapon systems or explosives used, to estimate qualitatively the severity of the exposure to inform diagnostics and recommendation for treatment. For example, a clinician may use the self-reported exposure history of a member reporting certain symptoms and identify that the member has been recently exposed to a high number of low-level blasts of relevant magnitudes, therefore helping them choose the course of action, such as withdrawing a member from training involving blast exposure or weapon firing until symptoms subside.

This level of analysis is generally reactive to a warfighter reporting symptoms and not used as a mitigative measure.

**Level 3:** The available exposure data is structured and formatted in a way that enables a quantitative estimation of exposure numbers and levels. Estimation of levels may rely on collected data in real training events or on generic quantification from external sources but is generally specific to the scenarios monitored (weapon system or explosive). Metrics to better quantify the exposure history (e.g., lifetime exposure measurement tools, such as the BETS/GBEV and others) are used or developed to better enable injury risk analysis. Protocols for injury mitigation may rely on the review of personal logs, which may be done periodically or on demand. At this level the exposure data is not specific to the individual in the scenario and may come from static experiments where the blast signature of the weapon/explosive scenario was quantified using pressure sensors in the environment, or from averaged recordings from wearable blast sensors in a similar environment, but not necessarily in the same position/posture.

**Level 4:** Exposure data specific to individuals is now accessible through the deployment of personal blast sensors collecting all exposure events in the form of pressure–time recordings, or from an experimental/

modelling approach estimating individual exposure for someone performing the scenario being monitored in the same position/posture. At this level the collected or calculated pressure histories are typically analysed directly, with no further modification/post-processing aside from the standard signal processing done by the sensor unit or associated software, to remove artifacts, noise, or eliminate false positives. For estimation from an experimental/modelling approach, logged contextual data from the scenario is used to help estimate individual exposure data.

The analysis of the exposure data may be supported by software tools which enable efficient data recovery, scenario identification, logging, visualisation, and extraction of peak quantities, but it typically still involves significant manual intervention and querying. Quantities or metrics that are analysed mostly relate to total number of exposures in defined range of magnitudes, frequency of exposures, and single event peak overpressure or impulse (or averages, or any summation function).

For the case of wearable blast sensors, this level of analysis also provides near real-time opportunities for data exploitation, such as manual identification of abnormally high exposures (outliers), with the assistance of supporting staff to recover individual sensor data and monitor it frequently during a training event. It enables mitigation of exposures from rapid changes that can be applied in training (correct form/position change in environment, PPE).

In general, this level of analysis adds specificity to the exposure data by relying on more robust measurement and estimation of individual exposure using specialised sensors, either wearable blast sensors or deployed in a characterisation arena and coupled to blast simulations. It involves maintenance of logs with individual exposure data while still requiring significant manual intervention.

**Level 5:** At this level an even greater specificity of exposure is obtained through more complex analysis of the measured or estimated individual exposure data. Greater specificity implies added resolution of the exposure conditions, typically now evaluated at the head of the member. This type of data typically requires a combined approach, where personal-borne sensor data, collected on the member's body, is used in conjunction with modelling or AI-enabled systems to obtain head exposure for each event monitored.

A significant amount of automation is implemented for the recovery, download, and processing of the data from the sensors worn by everyone. Data is typically recovered without intervention from the user and minimum intervention from the staff in charge of the exposure monitoring program. For example, this may take the form of a wireless download, automatically or manually triggered, when being in proximity of a station or a mobile device. Basic anomaly and/or outlier detection can be done automatically following data recovery and offers opportunities for real-time exploitation of the data if desired. This may be done using algorithms that automatically detect when an exposure was abnormally high compared to other similar events, or to a reference event, and which sends a warning to safety and leadership personnel.

Additionally, the collected data includes full pressure waveforms from a sensor system that can enable the study of the blast flow field. Typically, data analysis goes beyond simple tracking of peak values and number of exposures and may include the calculation of more sophisticated waveform features and comparison to injury risk functions. Data analysis may also use simple classification algorithms to recognise activity types or classify exposures in various categories or bins.

The linking and logging of the data to personal exposure records and/or medical records are automated. There is typically a higher degree of data analysis being done on the exposure history, where metrics aiming at quantifying the cumulative exposure are automatically calculated and monitored. As with single event data,

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simple thresholds, anomaly, or outlier detection may be implemented over the entire exposure history, and warnings may be issued by the data management systems automatically.

In general, this level adds to the previous levels a degree of automation and a higher complexity of analysis of the single event and historical exposure data, thereby enabling robust dose–response studies. At this level one would have full exposure and waveforms and ability to look at the entire exposure history. This data would be, ideally, stored indefinitely.

**Level 6:** At this level the degree of analysis should be consistent with cutting-edge practices and should enable significant contribution to the advancement of knowledge in the field. Collected exposure data is now processed through a data pipeline combining state-of-the-art tools and technology (e.g., neural networks, advanced fast computing CFD modelling, etc.) and leveraging contextual data from various sources (logs, wearable sensors, etc.) to obtain a very high degree of specificity on the exposure.

A full description of the level of analysis is not possible as new methods and techniques may continue to emerge, but conceptually, these analyses should progress towards: generating a higher resolution and higher fidelity estimation of the individual's exposure, maintaining a data architecture that enables data science and AI applications, enabling the full automation of processes, and the integration of blast exposure monitoring processes to other types of exposure monitoring and health monitoring processes.

To achieve a higher resolution and higher fidelity on individual exposure data, the collected data may undergo significant manipulation. Sensor data may be used to reconstruct the whole blast of an event and/or obtain estimates of the local effects on the brain (i.e., brain strains), using validated advanced analytical, empirical, machine learning or numerical (i.e., CFD, FEA) models. The exploitation of these models may be part of the automated analysis pipeline.

Robust data architecture is critical at this level to enable deeper data analytics and AI applications. The data architecture should greatly facilitate the monitoring of an array of potential injury risk metrics. Considering the amount of collected and processed data generated at this stage, the architecture also serves the automation of the data analysis pipeline, which is also critical at this stage. While automation is desired throughout, maintaining the possibility of manual intervention and querying of the data is also important.

The data analysis pipeline is also integrated to other TBI monitoring programs of partner countries to enable the joint analysis of multiple types of exposure data. The data analysis is also optimised to facilitate the exploration of correlations between exposure history and health outcomes. At this stage the data analysis may be exploited in full prediction/mitigation mode, meaning that algorithms can be leveraged to predict the development of injury according to proposed activities or training schedule, or dictate future training schedule and exposure limits based on a known exposure history.

### 4.4.3.3 Data Integration

**Level 1:** At this level there is no integration of data. Health information and anecdotal exposure data may be used in isolation due to the collection of these data not being specific to the effects of blast overpressure exposure and/or measured on-body overpressure.

**Level 2:** Analysis may be used to for case study or series regional analysis to mitigate specific site exposures or use cases (i.e., integration of recorded brain health effects due to use of a specific weapon system with measured environmental blast overpressure of that weapon system to yield greater standoff distance for Range Safety Staff to mitigate the brain health effects of weapon system training). This data should be used with caution when applied outside of the scenarios in which the data was collected. The scope of these data are limited and do not allow for risk function development.

**Level 3:** Risk assessment and retrospective analysis are the primary intent at this level and may be used in some mitigation decisions through simple analyses of repetitive exposures. Again, this data should be used with caution when applied outside of the scenarios in which the data was collected. However, there is lower risk of extrapolation error due to the improved quantity and quality of the data used in the integrated regression analyses. These analyses may inform changes to testing environment (see Section 4.4.4.2) and protocol (see Section 4.4.4.3) with the effect of any changes assessed based on the variability of the pooled data. Health surveillance data and quantitative exposure data may be automated for basic dashboards. At this level analysis supports reactive decision-making and is not predictive in the outcome of changes as findings are only correlated to the current environment.

**Level 4:** Health and exposure surveillance data used with addition of cognitive function/performance screening data may be used for preliminary injury risk function development. At this level, the data used enables multifactor data analysis. In addition, basic computational modelling may be used to start formulating dose response using simplified metrics (i.e., peak overpressure, cumulative impulse, or lifetime history of blast exposure [GBEV]). The data includes multivariate risk outcomes (i.e., different functions related to different health outcomes) which may enable the preliminary assessment of subject specific factors (i.e., sex, morphology, exposure history, injury history) into more complex analyses.

**Level 5:** Data at this level is more robust and informed. The intent is to develop preliminary algorithms for analysis of risk associated with dose response using simplified metrics. Cumulative surveillance data with additional layers of routine screening data and sensory system data will support development of advanced injury risk function associated with repetitive exposure and subject specific factors. In addition, advanced computational modelling enabling waveform analysis using machine learning algorithms may be conducted to assess exposure and risk of brain health effects.

**Level 6:** At this level universal TBI monitoring and monitoring of available healthcare resources will be fully automated. Such automation will enable real-time analysis of risk associated with dose response using the full extent of the data with repetitive exposure and subject specific factors. In addition, the integration of available healthcare resources will facilitate the rapid deployment of healthcare resources to detect and/or predict risk of injury. A transition from the advanced injury risk function based purely on cumulative exposure will occur at this level such that an exposure profile injury risk function may be derived.

#### 4.4.4 Mitigation and Health Management Strategies

The following sub-chapters contain recommendations for strategies to mitigate blast exposure effects in training and operational scenarios, with health management based on analysis of the blast exposure and resulting health and performance effects. The contents are organised by capability level of recognising and counteracting the potential occupational risks, defined in Section 4.2.

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The operational guidelines for mitigations are structured along four sub-capabilities:

- A) **Education Mitigations:** The education leg of blast exposure safety is focused on influencing the behaviour of personnel (across multiple levels) through the transfer of knowledge on injury and exposure to blast overpressure. Personnel are trained on the risk factors associated with the blast environment so that they may be able to adapt to mitigate their exposure severity and, if possible, frequency, especially with training. Personnel are taught about the cumulative nature, short- and long-term health risks, and prognosis of blast exposure and are trained to monitor and recognise any adverse health effects so they can seek medical attention in a timely manner.
- B) **Engineering Mitigations:** The engineering aspect of blast exposure safety is focused on providing the methods, equipment, and environment necessary for quantifying and reducing the severity of exposure risk, and, where possible, mitigating the injury and improving the prognosis of the exposed personnel. Exposure risk is **mitigated** by changing the training procedures to reduce the threat, or by investing in new protective equipment technologies and design concepts evaluated against the quantified baseline. Analysis tools, validated by extensive testing and appropriate physical and biological models, facilitate exposure monitoring and health effects and provide better methods for assessing exposure risk and proposed mitigation and education strategies. Equipment testing programs with advanced manikins and computational models will evaluate the efficacy of the protective equipment.
- C) **Enforcement Mitigations:** The enforcement aspect of blast exposure safety is focused on establishing and monitoring organisational rules, protocols, procedures, and guidelines designed for mitigating injury and reducing exposure from blast overpressure exposure. Safety officers will provide oversight to ensure personnel are using the appropriate equipment and protocols for the **applicable** blast exposure environment, collation of exposure data, and reporting thereof. Protective equipment will be regulated and certified to ensure it meets the established technical specifications. Medical officers will be responsible to ensure that personnel comply with return-to-duty guidelines and medical readiness following exposure and/or injury.
- D) **Health Management:** The Health Management component of blast exposure safety is focused on establishing and developing organisational care systems designed for preventing, detecting, and managing injury and reducing subsequent health and biological effects of blast overpressure exposure. Personnel and medical force-specific care systems need to improve the health and resilience of the force for blast **exposure** and mitigate deleterious effects where possible. While member countries may possess certain capabilities related to the care of military personnel with concussion/mild TBI, the framework described below relates specifically to brain health issues related to blast exposure.

All sub-capabilities have an evolving scope of effort, with the comprehensiveness of the guidelines expanding with each increasing capability level. While blast exposure can lead to a multitude of physical and psychological injuries, the efforts defined herein are limited to mitigating effects of blast exposure on the brain, with risk defined as the risk for acute and cumulative, long-term brain injury. The goal is preserving warfighter brain health and operational readiness.

### 4.4.4.1 Education Mitigations

**Level 1:** At this level there is not a concentrated effort to educate operators and support personnel on the negative health effects of blast exposure and/or methods to identify risk or mitigation strategies. The training planning should cover known methods to estimate safe exposure limits, including look up tables and Minimum Safety Distance (MSD) calculations for breaching and EOD activities. Operators should be trained on existing protective equipment, procedures, and general safety regulations during activities where blast exposure may occur.

**Level 2:** Countries operating at this level are providing current state-of-science information to educate their general population of interest regarding matters related to blast effects. The information is disseminated broadly across the organisation via pamphlets/brochures, seminars, white papers, etc., at a level of detail appropriate for a broad audience. The information should raise awareness that repetitive overpressure exposures are cumulative in nature and have the potential to negatively affect brain health and operational readiness in the future. Further, the information should stress the importance of following all established guidelines and use of personal protective equipment and weapon-installed protective gear. Personnel should understand the symptoms associated with mild brain injury and the process to follow for health assessment as well as symptoms to monitor.

The basics of overpressure interaction with the environment should be integrated with the training to raise awareness of the effect of reflecting surfaces on potential exposures. Operators will be trained in the As Low As Reasonably Achievable (ALARA) principle for blast exposure. Actions to reduce risk of injury from blast exposure include:

- 1) Minimising the number of personnel in the vicinity of blast overpressure;
- 2) Increasing standoff distances from weapons and charges;
- 3) Minimising the duration of live-fire events;
- 4) Establishing a maximum allowable number of rounds that may be fired during each event or time period;
- 5) Ensuring application and appropriate use of personal protective gear and equipment; and
- 6) Training and education on blast overpressure hazards and risk management actions [36], [37].

**Level 3:** At this level countries are actively training their support personnel (e.g., range safety officers and instructors) on the current state-of-science of blast exposure risk, injury criteria, and mitigation strategies. The support personnel are trained to understand the basic physics of blast propagation within the blast environment in a limited capacity to determine if operators are at an elevated risk if positioned at certain locations within that environment. Specifics of this education for each training environment should include knowledge on blast propagation dynamics, the potential effect of operator positioning relative to weapon system, charge, and blast overpressure reflections, and structures in the environment. The training for mitigation strategies should address actions that can be taken for the specific unit to ensure the training exercise mitigates operator exposure (e.g., moving the operator(s) to a location with a lower risk of injury).

For weapon systems limits should be established on the allowable number of rounds which can be fired in a single session, a day, and on consecutive days. Training should emphasise the importance of following these guidelines, and detail how exposure counts are to be made based on distance from the weapon system, positioning, and environmental factors. Round counts should not only apply to the individual firing the weapon, but to all of those that are in the vicinity of the weapon, including the support personnel.

**Level 4:** At this level countries are enhancing the training of their support personnel (e.g., range safety officers and instructors) to include knowledge related to an individual's exposure history. Support personnel are trained on the risks associated with cumulative exposure and have the knowledge to take action to modify training protocols for individuals deemed at risk due to their blast exposure history, informed by the most recent injury risk functions (see Section 5.4.3.3 for discussion). Personnel should have a reasonably high confidence in their estimated/predicted exposure risk based on experiments carried out prior to having humans in the task. The risk to personnel should be minimised and the setup of the task should be proven to mitigate blast exposure risk yet still allow the operator to perform duties without hindrances. Personnel should be aware of exposure

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risks created by straying from the approved setup so they can make an informed decision. A database of proposed modifications and the modelled and tested results should be built and maintained for sharing and development of more advanced analysis tools at higher capability levels.

**Level 5:** At this level support personnel are trained to analyse blast monitoring data in real-time and make assessments on an individual's risk of injury during training based on their exposure history and known injury risk functions (see Section 5.4.3.3 for discussion). The support personnel have training to make immediate and continuous adjustments to the training procedures to mitigate the individual's exposure if they are at an elevated risk. Personnel understand the short and long-term, as well as cumulative effects, of blast overpressure injuries and understand the importance of continual monitoring before and after training/missions to secure their long-term health. Personnel understand how the data is used to ensure most effective use of their specific strengths and weaknesses and what they individually need to look out for and minimise to lower injury risk.

**Level 6:** Countries operating at this level are educating individual operators on the blast exposure guidelines and training them to be able to assess their exposure risk in real-time based on their history. The training would include several actions that the individual can take to mitigate their exposure risk (e.g., change position during training). Furthermore, the individual is trained to recognise when health intervention is required (e.g., awareness of relevant symptoms, high-risk exposure data). Personnel can review and understand system risk analysis output as applicable to him/her with a high level of confidence in the data presented. Understand and support continual monitoring both in terms of engineering and medical data and the long-term benefits.

### 4.4.4.2 Engineering Mitigations

**Level 1:** At this level countries use established standard safety procedures. There are no additional engineering controls in place to reduce blast exposure risk other than procedures to calculate Minimum Safety Distances (MSD) for events that produce blast exposure, such as training environments, weapon systems, and scenarios that produce blast exposure. The MSD calculations will correlate the size of the relevant blast source and inform personnel of locations with safer levels of blast exposure. The MSD will not be individualised but will apply to the standard operator, and no specific mapping of the environment will be involved; however, countries may utilise MSD calculations that are specific to a known environment (i.e., free-field vs. indoor). For frequent and repeatable/known scenarios these MSD calculations can be placed in a tabular format for easy and efficient use.

**Level 2:** Countries operating at this level will have defined guidelines that improve training range design specifically to reduce blast overpressure exposure. Considerations should include optimised position planning for the operators based on MSD calculations, location and material of reflecting surfaces, facilities to optimise or enable safe cover, long-range warning signal transmission, optimised separation between adjacent teams on the training range, and defined locations of range safety personnel and spectators.

**Level 3:** For typical training scenarios where there is a high risk of significant blast overpressure exposure, the environment (surrounding area that observes increased overpressure) should be investigated to develop an understanding of the incident overpressure profile field at locations where operators are likely to be positioned. This investigation relies on overpressure mapping data or static characterisation data, obtained from numerical models or mapping experiments like those described in the exposure monitoring section (Section 4.4.1.3 Level 3 and 4). The same type of dataset may be used for exposure tracking and for informing mitigation strategies. Experimental mapping of the physical environment can also be used to inform, improve, and validate numerical models of the environment, or be compared against a numerical mapping simulation. Models can be used to explore the effect of changes in the environment such as weapon system, charge size, and operator

positioning. Validated models can be used reliably and complement mapping exercises conducted with pressure sensors and can provide additional insight into the propagation of the blast wave and resultant blast exposure. Numerical simulations also offer an increased number of monitoring locations as compared to the deployment of physical pressure sensors. Ultimately, the measurements and/or models provide an estimate of the pressure profile expected at the head for a given scenario, and this estimation is the metric to be minimised through mitigation strategies. During a material acquisition, the findings from mapping and evaluation exercises can be employed as a metric with a positive emphasis placed on material which produces low blast overpressure. Finally, the integrated exposure and health data (Section 4.4.3.3) may inform changes to the testing environment for specific site configurations analysed as case studies.

**Level 4:** This level includes reflected overpressure on the operators, complex reflection scenarios and the inclusion of physical bodies in the overpressure profile field. At this level the countries will utilise physical human surrogates and instrumentation and/or numerical models to quantify, model, verify, and assess risk and potential exposures. Numerical models will be refined based on correlation between numerical and empirical results. While subtleties in the environment and fine positioning can affect actual operator exposure, the models provide insight into factors influencing exposure and can guide operator placement to reduce exposures to the maximum extent possible. At this level the surrogates and models will be well characterised and fit for the purpose, and the analysts will have a thorough understanding of the intricacies of the model and surrogate. For example, the inclusion of physical bodies causes obstructions to the blast wave and must be included (numerically or physically) to obtain accurate blast behaviour; free-field simulations or mapping exercises must be enhanced to determine the true exposure. When estimating on-body pressure exposure, the placement of the gauge and its behaviour in relation to PPE must be well understood and accounted for (i.e., testing over or under PPE may provide drastically different responses and analysts must be aware of the physics and adapt testing procedures). Standard PPE without blast specific mitigation will be used.

Computer modelling is an efficient method that should be used to standardise training modifications and plan new scenarios. Quantitative exposure assessment and data collection should be conducted using manikins with pressure sensors in explosive environments to verify the computer model results. Prior to implementing new tactics or training exercises, employ experimental setups using manikins and/or perform modelling to assess the reduced exposure risk.

**Level 5:** At this level countries are engaged in physical testing of personal protective equipment to evaluate their efficacy for mitigating blast exposure risk. The evaluation program can be used to develop, test, and optimise new PPE designed to further reduce exposure to the operators, with appropriate exposure levels informed by the most recent injury risk functions (see Section 4.4.3.3). Performance of the physical testing of protective equipment should occur in the blast environment using instrumented dummies, and tests should utilise wearable blast sensor data collected during training for relative comparisons, when available. Equipment configurations can be ranked by performance based on the best available information regarding risk variables and injury criteria. Countries should also consider supporting physical testing with computational modelling to evaluate variants of protective equipment or different exposure scenarios.

This level will also rely on the use of computational models to design advanced test environments (e.g., new ranges) that reduce exposure risk, with appropriate exposure levels informed by the most recent injury risk functions (see Section 4.4.3.3).

**Level 6:** At this level a single comprehensive tool provides an online, real-time environment to analyse the required training and operational inputs and make recommendations for maximum loads and risks. It combines comprehensive system quantification and mapping data with verified and validated system

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and personnel models, injury criteria, and assessment tools. These are continuously updated with personnel operational and training engineering data and associated health data. This continuously improved system enables the minimisation of cumulative injury potential based on individual risk profiles. At this level, countries are engaged in a continuous evaluation program to optimise training ranges, scenarios, PPE, weapon systems, personnel sensors, and models to gain better insight into exposures and to reduce blast exposure As Low As Reasonably Achievable (ALARA). Exposure and engineering controls are individualised but executed homogeneously organisation-wide for all relevant military personnel.

### 4.4.4.3 Enforcement Mitigations

**Level 1:** Countries operating at this level will follow their existing guidelines for military personnel use of personal protective equipment such as helmets and body armour to help mitigate blast exposures that can lead to brain injury. Guidelines should be followed during both training and operations for activities with known typical overpressure profiles, including breaching, Explosive Ordnance Disposal (EOD), stun grenades, mortars, artillery, shoulder fired rockets, and large-calibre rifles (e.g., 50-calibre sniper rifle). Range safety personnel continually update safety instructions, look up tables, and MSD calculations for recommended standoff distances for specific explosives, weapon systems, and environments (e.g., breaching, EOD, flash bang, pyrotechnics, etc.), and following these guidelines.

**Level 2:** At this level countries are ensuring that their training range designs conform to the latest safety guidelines based on some knowledge of blast physics. The guidelines will include a blast exposure safety plan and assessment for training orders associated with the highest risk activities, as defined within each country. Countries will also enact procedures to continuously evaluate the design of training ranges to identify opportunities for improvements that reduce blast exposure risk (e.g., reflecting surfaces, defined positions for personnel and observers).

**Level 3:** Based on the latest safety information and guidance, countries shall place limits on the number of allowable exposures for each weapon system, operator position, and training environment, and form as part of the approved training plan/orders. Health assessments and recent history of blast exposure for everyone shall be considered when enforcing the exposure count, with SMEs providing guidance on recommended reduction in allowable exposure counts based on this information. Retrospective risk analysis from integration of exposure and health response data (Section 4.4.3.3) may inform changes to the training protocols for specific scenarios.

**Level 4:** Protocols should be developed by each country to define site visits and inspections for training ranges. These protocols should be updated as new insights emerge from assessment and analysis of blast exposure health and performance effects to ensure training ranges are adhering to the latest brain health safety criteria. Countries are not permitting deviations from established training protocols unless a risk assessment using models has been performed and the blast environment is sufficiently characterised, including an assessment of the realistic exposures to individuals. Evaluation of potential updates to the training standards are based on unit level modifications.

**Level 5:** Support personnel (range safety personnel, trainers) should review training plans using experimental or computational data and assessment tools and advise on training modifications based on the exposure data collected, including individual dosage. The training plan, including a specific blast overpressure risk assessment, should be updated and approved by the relevant/appointed personnel assigned to evaluate training risk. Countries should standardise training procedures at the unit level. Any modifications to these standards should be informed by assessments of the blast environment, its modification, and any changes in exposure risk based on the best available injury criteria.

**Level 6:** Standardise updates to training and operational standards at the broader organisational level. Specifically, training and/or operational planning shall be based on expected cumulative blast exposures, and everyone's personal risk, including historic exposures, brain injuries, or shifts from baseline medical tests. Up-to-date, adequate injury models for assessment of blast exposure health and performance effects will be utilised for everyone prior to mission approval.

#### 4.4.4.4 Health Management

**Level 1:** Countries operating at this level do not have specific healthcare management capabilities to support military personnel with adverse brain health effects resulting from blast exposure.

**Level 2:** At this level primary care is available to military personnel to address the health effects from blast exposure. These services are delivered by health care providers who are generalists with no specific training in the management of military personnel with a history of blast exposure. Specific care management would be anticipated to be largely symptom-based. No specialty services are available to military personnel for the specific management of adverse brain health outcomes resulting from exposure to blast.

**Level 3:** At this level primary care services are available to military personnel to address the health effects from blast exposure. These services are delivered by general healthcare providers with specific training and expertise in the management of military personnel with a history of blast exposure. Health care practitioners would base their care upon the latest guidelines for the management of military personnel with symptoms resulting from prior exposure to blast. Such guidelines may include symptom-based treatment, as well as rehabilitative strategies or other interventions, to minimise adverse brain health symptoms resulting from blast, as well as to optimize functional recovery and/or provide treatment for injury resulting from prior blast exposure. No specialty services are available to military personnel for the specific management of blast-related brain health issues.

**Level 4:** At this level specialty referral services are available to military personnel with a history of prior blast exposure. These special services may include practitioners with training in neurology, physical, and rehabilitative medicine, mental health, or other practitioners with other relevant skill sets. Specialty providers would provide focused support to aid with symptom control, rehabilitative strategies, and/or treatment for injury resulting from cumulative blast exposures.

**Level 5:** Countries at this level have established multidisciplinary care centres for the management of military personnel with a history of prior blast exposure. Such centres are staffed by health care practitioners from multiple specialties that are relevant to the care of military personnel with adverse brain health outcomes from prior blast exposure. At such centres, there is a team-based approach with effective communication amongst health care practitioners and the development of a multi-specialty care plan that is specific for the individual service member. Care teams base decisions on the latest guidelines for the management of military personnel with this condition. Additionally, multiple care management approaches are available, inclusive of pharmacological interventions as well as physical therapy, occupational therapy, and mental health support. At this level these centres are available to a select number of military personnel.

**Level 6:** At this level the multidisciplinary care model outlined in Level 5 is available to all military personnel with need across the enterprise. Centres are positioned geographically across a member country within specific areas to improve access and ensure that military personnel with a need are able to receive support.

## 4.5 EXAMPLES

**Example 1:** A country recognises that their dismounted 81 mm mortar causes significant blast exposure, especially when fired rapidly. Given the risk, leadership decides to monitor whenever training calls for rapid fire (**Blast Monitoring: Scenario 4**) but only focus on veteran 81 mm mortar crews (**Blast Monitoring: Population 3**). They plan to run a simulation of a common training site and issue wearable blast sensors to monitor the crews (**Blast Monitoring: Method 4**). Medics begin screening for early symptoms of blast exposure (**Health Management 3**). Data from wearable blast sensors and screenings are stored by the Regimental Surgeon (**Data Techniques 4**) for later comparison to symptoms (**Integration of Data 3**). Prior to training crews are taught about the risks of high exposures due to improper positioning (**Mitigation: Education 2**) and provided lower round count limits (**Mitigation: Enforcement 3**).

**Example 2:** The same country also funds its Defence Research Institute to equip manikins with laboratory-grade blast sensors around an 81 mm mortar in two of the commonly used dug-in firing positions to estimate exposures (**Mitigation: Engineering 4**). This team is also given access to the data coming in from the crews and performs an analysis comparing individual crewmembers' actual exposures against their recovery time (**Exposure Data Analysis 5**). Meanwhile, the Regimental Surgeon's Office performs assessments on crewmembers flagged during screenings from the medics (**Health Analysis 3**) and begins a program to check-in with crews weekly, asking about symptoms commonly associated with blast exposure, like headaches (**Health Domain 3**). They prescribe rest for one day as needed (**Assessment Regimen 2**).

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## Chapter 5 – RESEARCH AND DEVELOPMENT GUIDELINES

### 5.1 INTRODUCTION

The HFM-338 expert panel identified critical areas to further the development of knowledge for blast overpressure monitoring exposure to mitigate risks to brain health. This chapter outlines the Research and Development Guidelines aimed at addressing specific gaps in the current practices of monitoring and analyzing blast exposure data. These guidelines provide a multidisciplinary approach with complimentary input from the biomechanical, biomedical, and military occupational exposure and implementation domains. The target audience for these guidelines includes those responsible for implementing blast exposure monitoring capabilities, those who ensure the accurate and timely transfer of exposure data to medical records, as well as practitioners responsible for managing the health effects related to blast overpressure exposure. These guidelines include an overview of the Research Focus Areas, a description of the identified gaps, and a detailed discussion of the research approach and goals for addressing each gap. The guidelines discuss how this research can advance the field of blast overpressure exposure monitoring and identify possible progression factors.

### 5.2 GUIDELINES STRUCTURE

The Research and Development Guidelines consist of Research Focus Areas, which are further divided into specific research gaps relevant to each Research Focus Area. Research Focus Areas were developed by the expert panel who represented experience in multiple areas of research. The following Research Focus Areas are identified:

- 1) Blast Exposure Monitoring.
- 2) Load Mechanisms.
- 3) Injury Mechanisms.
- 4) Injury Risk Function and Thresholds.
- 5) Individual Specificity.
- 6) Detection of the Brain Health Correlates of Blast Effects.
- 7) Mitigation and Intervention Strategies.
- 8) Data Elements, Processing, and Analysis.

The intent of RTG HFM-338 was to identify emerging research objectives achievable within the next one to ten years. These guidelines are divided into two sections: Research and Development Guidelines Overview and Detailing the Research and Development Guidelines. The different structural components are outlined in detail below:

- **Research and Development Guidelines Overview:** Each Research Focus Area is presented with a brief description of relevant research gaps and details of the research goals associated with each research gap.
- **Detailing the Research and Development Guidelines:** The research gaps are described in detail with justification of their importance to further the field of blast overpressure exposure monitoring. Details include:

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- A description of the research, with inclusion of progression factors when appropriate;
- A brief overview of the current state of science;
- A proposed general approach to solving the research gap;
- Motivation and critical path for future research;
- The goals and outcomes of solving the research gap; and
- An explanation of how the goals and outcomes of the solved research gap may advance blast overpressure exposure monitoring guidelines and interface with other gaps and possible progression factors.

### 5.3 RESEARCH AND DEVELOPMENT GUIDELINES OVERVIEW

This section summarizes the Research and Development Guidelines in tables, with separate tables for each Research Focus Area.

#### 5.3.1 Blast Exposure Monitoring

The quantification of blast exposures through various methods of monitoring is a critical aspect of understanding the risk of negative health effects or injury. RTG HFM-338 recommends additional research to improve knowledge around what can and should be collected, automation where possible, and additions such as coupling with biological monitoring and exposure histories and biological monitoring. The gaps and research goals for this Research Focus Area are listed in Table 5-1.

**Table 5-1: Blast Exposure Monitoring: Research Gaps and Goals.**

| Gaps                                                                                  | Research Goals                                                                                                                            |
|---------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| Lack of understanding of what contextual information is needed from blast monitoring. | Define what contextual information is needed for more accurate risk of injury.                                                            |
| Need for automated collection of contextual information.                              | Determine what can be captured with wearable blast sensors and static blast sensors, as well as alternative automated methods.            |
| Lack of understanding of the level of accuracy required from blast monitoring.        | Determine what level of accuracy and specificity is needed for individual exposure data to estimate risk of adverse brain health effects. |
| Need for improved biological dosimetry.                                               | Develop new biological sensors or assays that monitor for the physiological effects of blast exposure.                                    |
| Need for improved methods to capture exposure history.                                | Determine the necessary data and/or platforms to elucidate individual career exposure history.                                            |

### 5.3.2 Load Mechanisms

Blast overpressure events exert various loading effects on the human body, which can be categorized into primary, secondary, tertiary, and quaternary effects, as described in more detail in Section 5.4.2. The following research gaps are focused on the primary load mechanism and its interaction with secondary, tertiary, and quaternary effects as they relate to blast-induced brain injury. The gaps and research goals for this Research Focus Area are listed in Table 5-2.

**Table 5-2: Load Mechanisms: Research Gaps and Goals.**

| Gaps                                                                                 | Research Goals                                                                                                       |
|--------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|
| Lack of understanding of the interaction of blast loading with other mechanisms.     | Determination of the interaction between blast exposure and the concomitant exposures associated with the explosion. |
| Lack of understanding of the sensitivity of the brain to blast loading on the body.  | Develop blast transfer function from on-body overpressure to the brain.                                              |
| Lack of predictive modeling of blast exposures to consider future combat operations. | Predictive modeling of future operations that may consider different loading conditions.                             |

### 5.3.3 Injury Mechanisms

We lack knowledge on the effect of blast on the human brain and other organs. It is complex, involving physiological, biomechanical, historical (cumulative), environmental aspects and individual specificity, such as age, gender, weight, fitness. Advancing understanding of injury mechanisms must be addressed through a combination of methods. These are applicable substantiated testing (physical models) and concomitant simulation modeling (virtual models) combined with monitoring and recording. It is important to improve the validity of the physical and computational models through use of the testing, and pathophysiological acute and cumulative and environmental effects, both recorded and directly observed. The gaps and research goals for this Research Focus Area are listed in Table 5-3.

**Table 5-3: Injury Mechanisms: Research Gaps and Goals.**

| Gaps                                                                                            | Research Goals                                                                                                                       |
|-------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|
| Biofidelic surrogates for blast brain injury risk analysis do not exist.                        | Develop physical and virtual models to predict human brain injury from blast loading.                                                |
| Need for preclinical/translational blast exposure models that scale more effectively to humans. | Identify blast exposure animal models that scale effectively to humans.                                                              |
| Lack of understanding for the pathophysiological mechanisms of acute blast exposure.            | Elucidate the physiological changes that occur with acute exposure to blast overpressure that leads to adverse brain health effects. |

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| Gaps                                                                                                            | Research Goals                                                                                                                                       |
|-----------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| Lack of an understanding of the pathophysiological mechanisms of repetitive blast exposure.                     | Elucidate the physiological changes that occur with repetitive exposure to blast overpressure that leads to cumulative adverse brain health effects. |
| Lack of understanding of how environmental factors influence the pathophysiological response to blast exposure. | Understand how physiological response to extreme environments relates to acute and long-term adverse brain health effects.                           |

### 5.3.4 Injury Risk Function and Thresholds

The mitigation of adverse health effects hinges on a detailed understanding of the relationship between blast exposure dosage and human physiological response. An injury risk function is a relationship that correlates a physical quantity describing the exposure dose, also called an injury criteria, to a risk of occurrence of a specific injury or negative health outcome. It is a type of dose–response relationship with a focus on a specific outcome. Injury thresholds may be derived from an injury risk function by identifying the minimum value of the injury criteria at which an injury or outcome is observed, or by selecting a level of acceptable risk and identifying the corresponding criteria value. Injury thresholds may represent values of the injury criteria for which acute or chronic health effects will occur.

There have been several studies attempting to establish correlation between such physical descriptors of the dose and an adverse acute health effect captured from specific neurocognitive assessment tools, physiological response tests, or biomarker levels. However, most of these studies still suffer from either a poor or low characterization of the dosage or from a lack of specificity in the measured response.

The lack of common data elements between studies and the multifaceted nature of the response, where different adverse effects may have different thresholds, renders difficult the definition of an injury risk function validated over multiple exposure scenarios. Also, this relationship is likely multivariate, as anatomical variability, individual sensitivities and pre-existing conditions may influence the risk associated with a given exposure profile. The gaps and research goals for this Research Focus Area are listed in Table 5-4.

**Table 5-4: Injury Risk Function and Injury Thresholds: Research Gaps and Goals.**

| Gaps                                                                                                                 | Research Goals                                                                                                                                                                                          |
|----------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Incomplete understanding of blast exposure brain injury criteria to establish risk.                                  | Develop comprehensive blast brain injury risk functions for single and repetitive blast exposures.                                                                                                      |
| Incomplete understanding of blast exposure thresholds for the <b>acute</b> brain health effects of blast exposure.   | Develop exposure injury thresholds to update safety limits for acute brain health effects of blast exposures, considering blast intensity, frequency, and weapon system.                                |
| Incomplete understanding of blast exposure thresholds for the <b>chronic</b> brain health effects of blast exposure. | Develop exposure injury thresholds to update safety limits for lifetime brain health effects of cumulative blast exposures, considering injury criteria, blast intensity, frequency, and weapon system. |

### 5.3.5 Individual Specificity

It can be assumed that individuals respond differently to the same load of blast exposure to the brain in a fashion similar to other forms of brain injury due to individual susceptibility based on age, sex, genetic predisposition, etc. Table 5-5.

**Table 5-5: Individual Specificity: Research Gaps and Goals.**

| Gaps                                                                                                  | Research Goals                                                                                                                           |
|-------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Lack of an understanding of individual susceptibility to blast exposure and its brain health effects. | Determine the role of individual risk factors on vulnerability of the brain to blast loading and its effect on lifetime exposure limits. |

### 5.3.6 Detection of the Brain Health Correlates of Blast Effects

Table 5-6 summarizes the identified research gaps in the detection of brain health correlates related to blast exposure. The main gaps identified are screening methods, clinical tools, effects on operational performance and long-term clinical data and outcome and their concomitant research goals are described.

**Table 5-6: Detection of the Brain Health Correlates of Blast Effects: Research Gaps and Goals.**

| Gaps                                                                                                                    | Research Goals                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|-------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Inadequate screening methods to detect the adverse acute and chronic brain health effects of repetitive blast exposure. | <ol style="list-style-type: none"> <li>1) Develop screening methods for the brain health effects of blast exposure that will: <ul style="list-style-type: none"> <li>• Discriminate between acute vs. chronic brain health effects of blast exposure.</li> <li>• Be field expedient and able to be administered without the oversight of trained professionals.</li> </ul> </li> <li>2) Determine optimal timing and scenario for the administration of screening tools.</li> <li>3) Determine screening program modifications needed to accommodate personal history and individual susceptibility to the adverse brain health effects of blast exposure.</li> </ol> |
| Inadequate clinical tools to identify the adverse acute and chronic brain health effects of repetitive blast exposure.  | <p>Determine optimal clinical tools for detecting adverse brain health effects including:</p> <ol style="list-style-type: none"> <li>1) Specific symptom profiles</li> <li>2) Neurosensory approaches</li> <li>3) Neuroimaging</li> <li>4) Physiological measures</li> <li>5) Cognitive/affective measures</li> <li>6) Biosample biomarkers</li> <li>7) Other novel modalities</li> </ol>                                                                                                                                                                                                                                                                             |

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| Gaps                                                                                        | Research Goals                                                                                                                                                   |
|---------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Incomplete understanding of the effects of blast exposure on operational performance.       | Determine the effects of blast exposure on warfighter tasks and operational readiness.                                                                           |
| Lack of longitudinal data that elucidate the long-term clinical outcomes of blast exposure. | Development and implementation of a longitudinal approach that can follow blast-exposed military personnel and controls during and after their military service. |

### 5.3.7 Mitigation and Intervention Strategies

Table 5-7 summarizes six gaps and concomitant research goals to reduce the effect of repetitive blast exposure on all exposed personnel in the short, medium, and long-term through mitigation and intervention strategies.

**Table 5-7: Mitigation and Intervention Strategies: Research Gaps and Goals.**

| Gaps                                                                                                                      | Research Goals                                                                                                                                                                                                                                                                                                                                                                 |
|---------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Lack of blast specific design criteria for personal protective equipment to mitigate the effects of blast exposure.       | Define blast specific design and associated test criteria and methods to ensure personal protective equipment minimizes blast loading on the brain to the maximum extent possible.                                                                                                                                                                                             |
| Lack of adequate specifications for the assessment and design of the training environment to reduce brain health effects. | Determine the influence of infrastructure and equipment on personnel blast loading to: <ol style="list-style-type: none"> <li>1) Define criteria for training environment design and use;</li> <li>2) Design specifications for assessment of the training environment;</li> <li>3) Develop methods for implementation.</li> </ol>                                             |
| Inadequate testing standards to quantify weapon system blast load on the brain.                                           | Standardize methods for characterizing the blast load on the brain from each weapon system and develop safety standards for weapon procurement and use.                                                                                                                                                                                                                        |
| Lack of objective data to inform techniques that best reduce blast exposure.                                              | Identify opportunities to implement changes in training that reduce exposures without reducing training effectiveness.                                                                                                                                                                                                                                                         |
| Inadequate health-related mitigation approaches pre-exposure.                                                             | Investigate pre-exposure factors that can reduce adverse brain health effects of blast exposure.                                                                                                                                                                                                                                                                               |
| Inadequate health-related intervention approaches post-exposure.                                                          | Develop therapeutic approaches to treat and/or mitigate adverse brain health effects following blast exposure. Investigate modifications of standard treatments to consider other co-occurring conditions. Investigate rehabilitative strategies for reducing and adjusting to long-term symptoms of blast exposure. Determine optimum recovery time before returning to duty. |

### 5.3.8 Data Elements, Processing, and Analysis

We identify development of common data tools, data processing, and analysis to be critical for the progression of the blast TBI research. Table 5-8 describes the major research gaps and goals of this field.

**Table 5-8: Data Elements, Processing, and Analysis: Research Gaps and Goals.**

| Gaps                                                                                                                     | Research Goals                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |
|--------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Inadequate methods for transmission of common data elements to exposure and medical records within authorized databases. | <p>Develop approaches for transmission of exposure and health effects data to medical records and authorized databases.</p> <p>Optimize approaches for making de-identified blast exposure and health effects data available for research.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |
| Lack of adequate data science tools for understanding and managing adverse brain health effects of blast exposure.       | <ol style="list-style-type: none"> <li>1) Development and refinement of large language model type approaches for the acquisition of unstructured data.</li> <li>2) Data dimensionality reduction techniques to overcome false discovery problems inherent in broad and diverse datasets.</li> <li>3) Empiric tools for multimodal data integration to examine dose–response, sensitivity, and specificity questions related to techniques for identifying blast exposure.</li> <li>4) Improved deep learning tools for the rapid and thorough analysis of datasets related to blast exposure.</li> <li>5) Develop AI/ML/big data techniques that improve the accuracy of the default test-based screening by integrating the history of exposure data and additional risk factors.</li> </ol> |

## 5.4 DETAILING THE RESEARCH AND DEVELOPMENT GUIDELINES

This section provides more in-depth details of the Research and Development Guidelines. For each research gap in the eight Research Focus Areas, the research gap, motivation, general approach, and outcome are described.

### 5.4.1 Research Focus Area: Blast Exposure Monitoring

The gaps in current understanding and methodologies related to blast monitoring and exposure management are multifaceted. Firstly, there is a notable absence of clear criteria regarding what contextual information is needed to improve blast overpressure monitoring. This includes factors like body position relative to the blast wave, environmental conditions, and individual physical characteristics, which may be important for accurately assessing health risks associated with blast exposure. Secondly, there is a critical need for automated systems capable of capturing such contextual data alongside basic blast wave characteristics, enabling scalable analysis across diverse populations. Thirdly, current wearable blast sensors, while effective in recording local overpressure, may not accurately reflect head loads due to localized effects influenced by body posture. Addressing this gap requires advanced processing techniques to align sensor data with actual exposure scenarios. Moreover, there is a gap in understanding the necessary accuracy levels for blast monitoring to effectively quantify exposure and its correlation with health outcomes. Finally, there is a pressing need to develop biological

dosimetry methods that can reliably assess the physiological effects of blast exposure, complementing direct measurements and facilitating longitudinal studies to establish exposure–response relationships. Establishing robust methods for recording individual blast exposure histories using wearable or static blast sensors is also crucial for mitigating adverse health effects and informing operational and health decision-making within military contexts.

### **5.4.1.1 Gap: Lack of Understanding of What Contextual Information is Needed from Blast Monitoring**

There is an absence of objective data informing what contextual information is required to best monitor blast overpressure exposure. Potentially relevant contextual information may include body position relative to the blast wave, proximity to reflective surfaces, exposure environment (open air, enclosed, confined spaces, etc.), and body morphology. Additional contextual information will better inform how explosive blast overpressure affects the body and may be used to more accurately relate blast overpressure exposure to health risk when monitoring this exposure.

Objective contextual data may be overlayed onto dose response analyses to assess the relationship to health risk. A multivariate approach may be required as the addition of contextual information may lead to complex relationships. This will provide leadership, health professionals, and researchers with a better understanding of the factors that contribute to increased health risk associated with blast overpressure exposure. At the unit level, troops will improve their ability to operate safely and remain under blast exposure guidelines while maintaining, or improving, the efficacy of their training and operations. Such information will be critical to an effective monitoring program.

### **5.4.1.2 Gap: Need for Automated Collection of Contextual Information**

Current blast exposure monitoring sensors typically capture relatively basic characteristics of the blast overpressure waveform. Determining what additional contextual data can be captured with wearable, environmental, and static sensors (e.g., could be environmental sensors, cameras, etc.) through automated methods is required. Automated collection of this contextual information is critical to appropriately scale data analyses to the populations of interest.

Identification of the data that can be captured through automated methods will guide the implementation of exposure monitoring, ensuring practical and achievable methods.

Accessible monitoring solutions that do not impede the user will be developed with a focus on what is achievable based on an improved understanding of what contextual information is of value.

The goal is to establish what contextual information can be captured and to further develop the exposure monitoring framework within these limitations.

### **5.4.1.3 Gap: Lack of Understanding of the Level of Fidelity Required for Blast Monitoring**

The various existing strategies to estimate, predict, or measure blast loads on personnel do not yield the same level of fidelity. Estimates based on static characterization of the blast environment may not account for the effect of body posture and blast reflections. Wearable blast sensors can readily record local overpressure histories at the location where they are worn, but the collected data may not accurately represent the loading experienced at the head of the exposed personnel due to localized effects influenced by the posture of the body relative to the propagation of the blast wave. Predictions of head loads obtained through numerical simulations may also be limited to specific body postures.

In order to successfully quantify the relationship between blast exposure (dose) and brain health effects (response), an accurate characterization of the exposure is required.

Characterizing the relationship between estimates, numerical predictions, or wearable blast sensor measurements – and the actual loads on the head of exposed personnel in an array of different exposure scenarios – will help understand if additional transformation or processing is required to obtain a more accurate representation of blast exposure.

More accurate estimations of personal exposure histories in longitudinal studies will help to identify correlations between blast exposures and brain health effects, whereas imprecise characterization of exposures may hide subtle trends and hinder the identification of proper exposure limits and injury thresholds. For monitoring strategies, more accurate estimation of head loads following blast exposures will likely necessitate advanced processing techniques that can digest and transform large quantities of data rapidly with a lower computational cost.

#### **5.4.1.4 Gap: Need for Improved Biological Dosimetry**

New biological sensors or assays that monitor for the physiological effects of blast exposures need to be developed. Biological dosimetry for monitoring blast exposure means assessment of associated effects among exposed persons rather than direct measurement of blast overpressure during exposure events. At present, there has not been a clearly defined and demonstrated reliable relationship between blast exposure dose and biological response, although there has been research progress toward that end.

Having a clearly defined blast exposure dose and biological response relationship would provide a qualitatively different method for monitoring blast exposure, complementing and adding flexibility to direct measurement of exposure effects in field settings.

Developing biological dosimetry methods for blast exposure may be based on basic science with non-human models but implementation will depend on some studies and validation with human subjects, acknowledging that human subjects' studies will be with lower-level exposures that occur in routine military training to follow ethical standards for research. In these studies, both measurement of the exposure and degree of biological response will need to be employed concurrently so that dose–response associations can be demonstrated with evidence. It will be important to consider these associations as both a function of acute exposure (e.g., single day of training) and of chronic exposure (e.g., across a military career of several years).

A biological dosimetry program could range from portable non-invasive assessments in acute exposure environments (e.g., symptom reporting, behavioral performance evaluation, handheld biosample assay device) to more remote assessments available in clinical treatment settings (e.g., cerebrospinal fluid sampling, advanced neuroimaging). A corollary to a clinic-based biological dosimetry assessment program may be observed in typical hearing conservation program, in which those enrolled are periodically evaluated for hearing ability deficits instead of having their work environments quantitatively evaluated for noise level.

The type of approaches implemented for biological dosimetry in a blast monitoring program can be based on effectiveness of measurement as well as logistical and practical considerations. Biological dosimetry will be most informative and revealing when used in conjunction with direct measurement of exposure, but effective biological dosimetry could also be employed independently when complementary measures of exposure are not available or are too resource-intensive for implementation.

### 5.4.1.5 Gap: Need for Improved Methods to Capture Exposure History

There is a need/requirement to develop the methodology and infrastructure to document exposures to blast overpressure events for military personnel to enable approaches to mitigate adverse cognitive and mental health outcomes from blast exposures. This can be accomplished in several ways depending upon the institutional infrastructure to support. A straightforward method to capture, record, and memorialize individual blast exposures is with wearable blast sensors that permit recording of key blast exposure parameters that are then logged into a system available to the operational units and medical communities. In the absence of wearable blast sensors, the recording can be accomplished using static field sensors to characterize a group environment exposure or having military personnel estimate the number and intensity of exposures. This latter method is low-cost, readily deployable, and affords insight into cumulative exposures, but may pose limitations inherent with self-reporting and memory recall.

Strategies to mitigate adverse neurological outcomes from repetitive exposure to blast overpressure events associated with explosives and weapon systems necessarily depend upon accurate recording of exposure parameters and then subsequent memorializing in operational and medical records systems.

The parameters of blast overpressure exposures, such as intensity, duration, and frequency, are presumed to be of a fidelity to permit recording of essential elements of the blast exposure that can be linked to brain health effects. The common data elements required to provide a high-fidelity blast record remain to be determined. The approach of recording blast overpressure exposures in military personnel is not unlike the systems/infrastructure used to record specific parameters for military divers that include dive duration, depth, ascent rate from depth, water temperature, specifics around the diving equipment that is recorded and stored at the operational unit level and in a health safety center charged with recording occupational exposures for military personnel.

The goal of the military health system will be to institute a system to log blast exposures in a similar manner that is available to operational units, medical providers, and health system analysts. A system is envisioned to record blast exposures over the entirety of a service member's career.

The establishment of a database record of exposure to blast overpressure events will enable continual analysis of blast overpressure exposure guidelines to determine same thresholds and exposure conditions, including repetitive exposures contributing to cumulative effects.

### 5.4.2 Research Focus Area: Load Mechanisms

Blast overpressure events exert various loading effects on the human body, which can be categorized into primary, secondary, tertiary, and quaternary effects. Primary effects result directly from the initial shockwave affecting the body, leading to barotrauma and brain injuries. Secondary effects are caused by flying debris and fragments propelled by the blast, causing penetrating injuries, lacerations, amputations, and fractures. Tertiary effects occur when individuals are thrown or impacted by the blast wave, resulting in blunt trauma, concussions, and traumatic brain injuries. The load mechanisms, the phenomena, and the physical effects of the blast, effectuating the adverse effect on the human body, need further research to achieve a comprehensive and full understanding of the effects, their interaction, and potential superpositions. The two research gaps are described in detail in the following section, which focus only on single exposure events (which might comprise multiple, overlapping blast events) and not repetitive, cumulative exposures.

#### **5.4.2.1 Gap: Lack of Understanding of the Interaction of Blast Loading with Other Mechanisms**

Non-blast-related environmental and operational factors may have interactions on the blast load which are not well understood. Sources that may interact with the blast loads include local accelerative forces and momentums (tertiary blast, e.g., firing long-range rifles, shoulder launched rockets), changes in atmospheric conditions due to hot plumes, gasses and potentially toxic ingredients (quaternary blast), alterations of exposure due to body posture (standing, crouching, horizontal), blast reflections, and multiple blast origins. Next to that, it is assumed that, for example, the short-term dynamic compression of the upper body, the organs, and vessels located in this area can generate additional cerebral effects that may have potential for injury.

The investigation of these interactions and interfering effects is of high importance, as they may both increase or decrease the resulting load affecting the body. Further, understanding these effects will potentially enable optimization of PPE and range design, and refine SOPs. All these interactions should be considered in the holistic investigation of the injury risks for blast-related mTBI.

The general approach for the investigation of these interfering load mechanisms requires comprehensive experimental investigations with generic, common set-ups, and scenarios and a well-tuned parameter matrix. Various combinations of parameters should be studied to identify combinations that lead to worst-case exposures (maximum of loads). Numerical investigations should also accompany the experiments to extend the results beyond what is capable or feasible with experimental testing. The numerical models need to be efficient and validated for the range of parameters studied. Experimental studies to analyze the phenomena and the additional load mechanisms resulting from the load on the torso using animals, human cadavers, or other surrogates should be part of the scientific approach.

The goal of these research efforts is to have a deeper understanding of the phenomena and the physics related to the interactions of other mechanisms with the blast, next to the identification of reinforcing (worst-case) and mitigating effects and scenarios.

The research filling this gap will help optimize training procedures, improve monitoring tools and procedures, develop mitigation strategies with regards to range design (positions, structural layout, etc.), and weapon system development and characterization of relevant parameters of the overall exposure resulting from a weapon system. Further, cooperation with gaps related to injury mechanisms will help to identify consequences of the adjusted loads on the subsequent, resulting injury mechanisms and the effects on the brain.

#### **5.4.2.2 Gap: Lack of Understanding of the Sensitivity of the Brain to Blast Loading on the Body**

Monitoring tools for operators like wearable blast sensors are typically attached to the operator's equipment at tactically, operationally, and ergonomically appropriate positions, e.g., chest, shoulder, and back of the helmet, and tools like static sensors provide incident overpressure measurements at a limited number of locations. For practical reasons, comprehensive measurements of the overpressure field across the entire head of the operator are not collected, so the effective load on the head from a blast exposure must be inferred from the available sensor measurement points. However, a validated transfer function enabling estimation of the load on the brain based on sensor data (and knowledge of sensor positions, PPE worn, anthropometry, etc.) is lacking. The research and development of such a transfer function is of high importance to assure accurate estimations of brain exposure load, as significant under or overestimations of exposure will compromise exposure monitoring efforts and potentially lead to erroneous medical or training decisions regarding the exposure status of the operator.

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The general approach for the development of suitable transfer functions requires comprehensive experimental investigations with physical surrogates equipped with body and head-based pressure sensors, using blast set-ups and scenarios using a robust study design investigating various parameters related to the blast and the configuration of the surrogate operator. Numerical simulations and investigations should also accompany the experiments to extend the results beyond what is capable or feasible with experimental testing.

The expected outcome of this research is a validated, statistically confirmed transfer function with known limits and measuring faults. The set of empirical parameters should cover different, typical sensor positions, common body postures and orientations, and a broad spectrum of individual anthropometric parameters.

The existence of such a transfer function will facilitate the future application of monitoring tools for the operators and increase the quality of the data gained during the monitoring. This research will also enable solution providers to optimize the specified attachment and positioning of the monitoring tools only under tactical and operational aspects without unnecessary decline in data and monitoring quality, resulting in less constraints for the operators. Interfaces exist with all research gaps described in Section 5.4.1 (Blast Exposure Monitoring Capability), especially with the gap covering the level of accuracy required for blast monitoring.

### 5.4.2.3 Gap: Lack of Predictive Modeling of Blast Exposures to Consider Future Combat Operations

Predictive modeling will assist in exploring and understanding the blast overpressure risk to the service member with training and combat missions. Simulations can accommodate a wide range of blast threats and complex environments and any number of potential locations within the environment that the soldier could be positioned. This understanding enables planners and leadership to implement mitigating measures to reduce the blast overpressure exposure of soldiers. Predictive models need to be verified and validated, ensuring realistic, applicable results and a thorough understanding of the assumptions and limitations enabling sound interpretation of the results as applicable to the mission. Predictive simulation models can consider many different loading conditions.

Although there are a wide range of blast damage and injury simulation tools, simulating human body vulnerability and injury, both directly and indirectly within simple free-field and complex environments, these programs are mostly limited to acute injuries. They do not appear to address injuries related to low-level and/or repeated insults, especially from a wide range of threats such as muzzle and back blast from deployed weaponry. This weakness is partly due to limited understanding of repeated low-level insults to the soldier and related brain injury mechanisms, human tolerance, and acceptable injury risk limits. Although many gaps still exist, predictive simulation models can easily be updated, verified, and validated as understanding grows.

Modifying existing or building the required predictive blast exposure models requires parameterized threats and related overpressure source models, environmental models, and human models with appropriate material models, load coupling, and reflection (impedance) models. Each of these requires verification and validation separately and then as a complex combined unit using published standards where possible. Steps have already been made to ensure the quantification of new weapons systems providing core model and verification data. This should be expanded to cover legacy systems and, where possible, adversarial threats.

The quantified threat, material, and reflection model data are provided through tests using standardized methodologies and, where possible, common instrumentation, positioning, and data processing techniques used in accordance with relevant standards to ensure comparable data from a range of sources. The predictive models should be verified against provided test data and then validated when initially applied to a training range and/or missions (where possible). A key challenge of predictive models is to enable ease of use and interpretation by non-specialist modelers while not compromising computational accuracy and applicability.

Predictive exposure models should be updated as they are applied, and validation data becomes available and new data with related injury mechanisms, human models, and tolerance and criteria limit updates.

Easy-to-use verified and validated predictive blast exposure models placed at the appropriate structure level with training will enable planners and leadership to evaluate training and missions in terms of blast exposure risk. Predictive exposure modeling will enable appropriate mitigating measures to be applied to new training or operational deployments, reducing the risk to deployed soldiers and supporting continuous training and operational improvement in terms of health risk.

### **5.4.3 Research Focus Area: Injury Mechanisms**

The fundamental question of how blast waves cause brain tissue mechanics that lead to injury is not fully understood, highlighting the need for in-depth research to unravel the complexities of this phenomenon. Here, the term “injury mechanism” refers to phenomena of mechanopathology, where the mechanics of brain tissue caused by blast exposure will lead to dysfunction and pathology within that tissue. Injury mechanism is the fundamental process which drives the correlation between the characteristics of blast exposure (the dose) and adverse brain health effects (the response).

#### **5.4.3.1 Gap: Biofidelic Surrogates for Blast Brain Injury Risk Analysis Do Not Exist**

Currently, we lack the fundamental understanding of the relationship between the characteristics of blast exposure and the internal biomechanical response of human brain tissue that will lead to adverse brain health effects and injury risk. Observational studies involving human subjects are necessary for identifying correlations between blast exposure and health outcomes, but these studies cannot establish causal mechanisms associated with the outcome. As such, biofidelic surrogates are necessary to perform these studies. Biofidelic surrogates, in both physical (e.g., dummies) and computational forms (e.g., finite element models), can identify better correlates between the exposure and the health outcomes observed in these field studies, and can play a pivotal role in elucidating the underlying mechanisms of blast-induced brain effects. While basic surrogates exist, their biofidelity is insufficient to capture the intricacies of blast-induced brain responses. To enhance these models, a comprehensive approach involving additional biomechanical research into the properties and responses of brain tissue under blast loading is necessary. Complementary efforts, utilizing a synergy of preclinical animal models and their corresponding computational models to simulate blast response, are also needed to contribute to identifying the fundamental injury mechanisms that can be translated effectively to the biofidelic surrogates. Fundamental injury mechanisms that lead to abnormalities such as hemorrhage, axonal injuries, and contusion, can be defined using biomechanical models that provide injury risks from a given exposure. With the development of biofidelic physical and computational models of human heads and brains, we can study the tissue mechanics caused by blast exposure that eventually leads to neuropathology and dysfunction. These surrogates need to be validated with field study data to verify their predictive capability. Once the links between human surrogates, animal studies, and observational data are established and validated, these biofidelic surrogates become powerful predictive tools. They could enable researchers to assess brain effects under nearly limitless exposure conditions, providing valuable insights that are not feasible through observational studies alone. This predictive capability may open new avenues for studying a wide range of blast conditions and developing targeted interventions to mitigate the impact of blast-induced brain injuries.

#### **5.4.3.2 Gap: Need for Preclinical/Translational Blast Exposure Models that Scale More Effectively to Humans**

In-vivo preclinical animal models are a necessity for studying the injury mechanisms associated with blast exposure, but most of the in-vivo animal models injury literature has focused on the use of rodent models to study the neuropathology and behavioral changes following a blast exposure. Of these studies, there are few (if any) that have been designed to evaluate injury outcome as a function of the exposure conditions (e.g., peak pressure, positive impulse, duration). Furthermore, there is a debate about the relevance of small rodent models and the blast conditions used in their study to the types of exposures expected with humans (either from training or on duty). Translating the exposure conditions and injury outcomes of preclinical models to equivalent human conditions is a biomechanical process known as scaling. For the relevance of the study, it is crucial that the preclinical model is exposed to loading conditions that are appropriately scaled to blast conditions experienced by operators. From a biophysical perspective, the closer the size of a species is to a human, the more effective the scaling process is in relating preclinical models to humans. Studies using medium- (e.g., ferret, rabbit) or large-sized animals (e.g., pig) have evaluated injury outcomes as a function of the blast parameters, but more research is needed in these models to translate into the robust scaling processes. The use of computational surrogates of animals and humans is also critical in identifying the scaling process to equate preclinical and operational loading conditions because they can account for the vast differences in anatomical structure, shape, and size of the heads, skulls, and brains of different species. Identifying better preclinical models of blast exposure and the related health effects, along with the knowledge of appropriate scaling processes, will ensure that preclinical studies, utilizing animals and appropriate loading conditions, are more likely to translate to human conditions. Low-cost rodent models may still be useful in a blast injury research program if the experiments are designed properly with relevant exposure conditions, and that they are used as a stepping-stone towards refining the study scope with larger animal testing. Coupling appropriately designed preclinical models with their corresponding computational models will contribute to identifying the fundamental injury mechanisms of blast brain injury and can elevate the capability of human surrogates for predicting brain health effects from blast exposure.

#### **5.4.3.3 Gap: Lack of Understanding of the Injury Mechanisms of Acute Blast Exposure**

There is a need to elucidate the physiological changes that occur with acute exposure to blast overpressure that contribute to adverse brain health effects with repetitive exposure. While there is a wealth of information on the acute effects of blast overpressure that result in overt trauma, much less is known about the acute physiological effects of lower-intensity blast overpressure exposures that contribute to long-term adverse cognitive and mental health outcomes. An understanding of the acute physiological manifestations resulting from blast exposure will contribute to a better understanding of these events and how they contribute to cumulative effects with repeated exposure over a military career.

A schema of blast exposure separates the characteristics of blast overpressure from primary to quinary injuries resulting from acute exposure to varying blast overpressure intensities. The principal concern around cumulative effects is understanding the acute manifestations of the blast wave with the focus then on the neurological effects of repetitive exposures that do not produce obvious acute effects but could result in subclinical injuries that may accumulate with subsequent exposures. The challenge is to determine the characteristics of the blast exposure, peak overpressure intensity and/or duration, and exposure frequency that contribute to these acute manifestations that can result in cumulative effects. Molecular and neuroimaging techniques for investigating military brain health/injury resulting from blast exposure have shown promising results in yielding potential biomarkers to inform exposures that lead to cumulative effects.

The goal of future research will be to elucidate thresholds for subclinical injury from blast exposure. What exposure parameters and physiological changes are considered “safe,” with minimal potential to contribute to cumulative effects? It is understood that exposures under 28 kPa (4 psi) may result in physiological changes that could be considered potentially injurious.

An increased understanding of the relatively “low-intensity” blast exposures that result in subclinical injury will inform recommendations for guidelines.

#### **5.4.3.4 Gap: Lack of Understanding of the Injury Mechanisms of Repetitive Blast Exposure**

There is a need to elucidate the physiological changes that occur with repetitive exposure to blast overpressure that leads to cumulative adverse brain health effects.

There is currently a lack of understanding regarding the injury mechanisms of repetitive exposure to low-intensity blast overpressure in military members. This gap in understanding hampers effective diagnosis, mitigation, and treatment strategies, and is hindered by the complexity of blast wave injury mechanisms and inadequate longitudinal studies. These mechanisms are particularly important in the context of subclinical injury following blast exposure. In this context, brain tissue damage with associated pathophysiological cascades may occur following blast exposure, which do not necessarily rise to the level of a clinical manifestation. Incompletely resolved subclinical injury may accumulate with subsequent exposures, resulting in long-term clinical manifestations. It is critical to understand the precise mechanisms by which injury occurs to better understand mitigation and treatment strategies for this condition.

Military members/Veterans with a history of repetitive head trauma – including, symptomatic concussions, mild traumatic brain injuries, or repeated subclinical injury attributable to low-intensity explosive blast waves – exhibit measurable performance decrements and adverse health outcomes. It is imperative to better understand, detect, monitor, and mitigate brain dysfunction to optimize health and performance, thereby preserving readiness and after-service life.

The injury mechanisms behind the brain dysfunction observed in those individuals exposed to repetitive blast overpressure and resulting chronic neurological disorders are still not well understood, especially in terms of persistent mental health consequences and risk of long-term neurodegenerative disorders. Promoting optimal brain health requires scientific evaluation of complex aspects of neurological function. The most promising avenues of investigation are in the neuroimaging and biomolecular domains. Molecular and neuroimaging techniques present distinct but complementary approaches for investigating military brain health/injury and have yielded potential biomarkers. Integration of these multimodal technologies employing data-driven Artificial Intelligence-enabled Machine Learning-based data analytics techniques could advance models of disease pathobiology, prognosis, ultimately improving precision care for subclinical and/or clinical neurotrauma. Future studies should strive to integrate multiple imaging modalities to further address outstanding neuroscientific problems.

Further investigation of the mechanisms of repetitive blast-related brain disorders/diseases may elucidate approaches for mitigation, treatment, and improved brain function. Brain imaging-based cognitive neuroscience and molecular tracers may unravel the underlying brain mechanism of cognitive dysfunction and/or progressive neurodegeneration and provide an avenue to develop a biological framework for precision biomarkers.

By elucidating the gaps in understanding the pathophysiological mechanisms of repetitive low-intensity blast exposure, advancements in guidelines can be made to enhance mitigation measures and optimize treatment

protocols for affected individuals. Furthermore, addressing these gaps can foster interdisciplinary collaboration and military interoperability, facilitate the integration of novel research methodologies, and stimulate further investigation into related fields, ultimately advancing our understanding of subconcussive neurotrauma/brain injury and related conditions.

### **5.4.3.5 Gap: Lack of Understanding of How Environmental Factors Influence the Injury Response to Blast Exposure**

Unlike the civilian population, the military is required by the mission to act in extreme environments. These extreme conditions may relate to external factors (temperature, hygrometry) or to internal factors (lack of sleep, high cognitive load, external stressors management, pain, intensive physical effort). In other conditions, such as PTSD and TBI, these factors are known to trigger negative coping/adaptation strategies which favor negative outcomes in the short- and long-term. Having control over the combined load of these factors, as well as understanding individual contributions, allows for short- and long-term protection of the warfighter brain, protecting the mission and operational effectiveness. It is therefore recommended to study the role of these factors in the brain health response to blast exposure and prioritize by level of importance. Additionally, it is recommended to quantify warfighter exposure to these factors to better understand risk to brain health in the setting of blast exposure. It is further recommended to study acute and long-term outcomes associated with these factors in the setting of blast exposure. Once the influence of environmental factors is known, counter measures may be developed and further studied.

### **5.4.4 Research Focus Area: Injury Risk Function and Thresholds**

The mitigation of adverse brain health effects hinges on a detailed understanding of the relationship between blast exposure dosage and human physiological response. Injury Risk Functions (IRFs, also called an injury criteria) are statistical relationships that link a quantity of exposure dose to the risk of occurrence of an injury or negative health outcome. It is a type of dose–response relationship with a focus on a specific metric (dose) and the risk of a specific outcome (response). An injury threshold may be derived from an IRF by identifying the dose value associated with a level of acceptable risk.

#### **5.4.4.1 Gap: Incomplete Understanding of Blast Exposure Brain Injury Criteria to Establish Risk**

There is limited evidence regarding the physical metric that best captures the aspects of blast exposure that are relevant to the risk of adverse brain health effects from repeated low-level exposures. Blast parameters such as peak overpressure or positive-phase impulse have been proposed as metrics for single exposure injury, which reflects the current state of science, but it is unclear if they are the best correlates for repetitive exposures. In addition, it is unclear if the best metrics for predicting acute effects from repetitive blast exposure during a short training period (up to a few days) are also the best for describing the risk of chronic effects from the accumulation of blast exposure over a career. Identifying the most relevant injury metric is crucial to develop adequate blast exposure monitoring strategies and select adequate monitoring technologies (i.e., the metric would need to be derived from quantities that are measurable or predictable). Addressing this gap is also on the critical path to the development of robust injury risk functions that will enable injury risk predictions and effective mitigation.

The general approach to solving this gap relies on robust study design and the establishment of common measurement and analysis techniques across multiple studies. Studies will need to include a characterization of blast exposure at the individual level, which will enable the calculation of multiple metrics from measured or predicted pressure histories. In parallel, relevant health data will need to be collected from those individuals and their effects documented. Statistical modeling of the most appropriate metrics should be made from a series

of options measured or calculated from blast exposure data in order to best correlate with quantified health effects. Generalizing an exposure metric will require multiple studies using different weapons systems, positions, and populations to gain more statistical power. The use of advanced computational models that can simulate blast exposure and predict the brain biomechanics that are leading to injury is likely to play a major role in identifying the best exposure metric and reduce the need for large experimental datasets.

The development of a reliable injury metric will pave the way for efficient monitoring strategies, focused on the blast parameters having an influence on risk. It will also enable changes in training, tactics, and procedures, by focusing on reducing these blast parameters of influence.

#### **5.4.4.2 Gap: Incomplete Understanding of Blast Exposure Thresholds for the Acute Brain Health Effects of Blast Exposure**

Evidence-based blast exposure thresholds for the occurrence of acute brain health effects are limited in validation. The characteristics and minimum quantity of blast exposures that may lead to acute effects remain tentative. Also, different exposure thresholds may be linked to different health effects. A more robust identification of blast exposure injury thresholds will enable updates to current safety limits to mitigate acute brain health effects of blast exposure. Solving this gap will require a statistical analysis to identify or estimate which metric of a cumulative exposure is associated with an onset of risk of acute effects. This process may focus on the identification of an acute threshold alone, or on the definition of a complete injury risk function, from which thresholds may be inferred or extracted.

Acute injury thresholds are critical to the development of exposure guidelines across all weapon systems or explosive scenarios, as it represents the limit that should not be exceeded to keep military personnel free of acute health effects and at peak operational readiness. It will enable decision-makers, responsible for members' safety and health, to understand the level of risk involved with certain frequencies of training on various weapon systems and with various explosive charges.

#### **5.4.4.3 Gap: Incomplete Understanding of Blast Exposure Thresholds for the Chronic Brain Health Effects of Blast Exposure**

The state of blast exposure thresholds linked to the occurrence of chronic brain health effects to provide reliable guidance on limiting the cumulative exposure history of military personnel is currently lacking. Similar to the injury thresholds linked to acute effects, the minimum quantity, intensity, and frequency of blast exposure that may lead to an onset of chronic effects are not well understood.

This information is critical to enable the mitigation of chronic effects through better management of individual blast exposure over longer periods of time, which may represent prolonged periods of use of a particular weapon system, or exposures of varying types over a career. Thresholds for chronic effects are potentially different from thresholds for acute effects, as chronic effects may emerge after multiple temporary instances of acute symptoms or with a minimal history of acute responses.

The definition of chronic effect thresholds relies on the identification of a cumulative metric that captures the important features of individual blast exposure history. A cumulative metric for chronic effects may not have the same resolution as those used in the context of acute effects. However, the approach toward defining a cumulative threshold will use similar statistical analysis to defining acute thresholds by correlating values of the cumulative metric to levels of risk of developing chronic effects. The approach to cumulative exposure analysis may require a combination of longitudinal data (full exposure history estimates), self-reported exposure

histories to specific weapon systems and explosive scenarios, and health and performance data from periodic monitoring. Chronic and cumulative thresholds could enable key personnel (e.g., decision-makers, doctors, career managers) to manage training and deployment schedules of military personnel to ensure that no individual reaches unacceptable levels of risk of developing chronic brain health effects due to their occupation and role during their service.

In modern medicine it is clear that individual biological variation (genetics, sex, age, previous or ongoing health disorders, etc.) does influence the outcome of health conditions and has an effect on its treatment. The field of blast TBI and the understanding of its medical background and treatment is in its infancy. Nonetheless, it can be foreseen that the outcome of a similar blast exposure will result in different outcomes in different individuals, similar to what is known about other forms of TBI. It is therefore important to address the knowledge gap regarding individual specificity and individual susceptibility in low-level blast TBI. Such knowledge will bring the diagnostics and treatment of blast TBI closer to what is referred to as precision or personalized medicine; the field of healthcare where decisions regarding disease mitigation, diagnosis, and treatment are customized to the individual patient based on the health prerequisites of that specific patient.

### 5.4.5 Research Focus Area: Individual Specificity

It can be assumed that individuals respond differently to the same load of blast exposure to the brain in a fashion similar to other forms of brain injury due to individual susceptibility based on age, sex, genetic predisposition, etc. This Research Focus Area examines the role of individual specificity in the brain health response to blast overpressure exposure.

#### 5.4.5.1 Gap: Lack of Understanding of Individual Susceptibility to Blast Exposure and its Brain Health Effects

Determine the role of individual risk factors on vulnerability of the brain to blast loading and its effect on short term to lifetime exposure limits.

It is possible that the brain response to blast exposure is dependent in part on individual factors. It is important to better understand if blast exposure response individual specificity exists and what the nature of this variable response may be. Even though individual responses to blast exposures are not well studied, some principal aspects can be described that will direct the research and could result in personalized or precision health approaches to the management of blast associated brain injury.

Individual specificity should be addressed in both clinical and experimental blast injury research by exploring:

- 1) **Prior blast exposures:** The potential that prior blast exposure may influence subsequent injury responses.
- 2) **Prior TBI:** The possibility that previous traumatic injuries to the brain of any type could result in individual responses to blast exposure.
- 3) **Other medical issues:** Exploring the possibility that other medical comorbidities (e.g., hypertension, atherosclerosis, diabetes, other neurological disorders) and/or mental health conditions may influence individual responses to blast exposure.
- 4) **Genetic factors:** e.g., differences in posttraumatic neuronal plasticity due to individual differences in growth factor function.

- 5) **Environmental factors:** Exposure to toxins, heat/cold, external stressors.
- 6) **Lifestyle factors:** e.g., sleep deprivation, physical activity, drug abuse, smoking.

The goal of more precisely being able to know the individual's specific response to blast exposure is to enable a tailored medical decision to an individual's genetic, environmental, and lifestyle profiles, allowing healthcare providers to make a more informed and effective choice about the patient's care.

Research advancements addressing this gap have the potential to move most, if not all, the other gaps forward when a deeper understanding of the individual responses and specific health findings can be moved into diagnostic tools, such as cognitive evaluation or biomarkers.

#### **5.4.6 Research Focus Area: Detection of the Brain Health Correlates of Blast Effects**

Reducing risk from blast overpressure is a critical objective to maximize operational readiness and effectiveness. Risk mitigation actions are predicated upon a comprehensive understanding of brain health effects from blast overpressure loads. An identified and prioritized Research Focus Area includes the development of screening and assessment tools that will facilitate a health evaluation should an individual have adverse health effects from repetitive blast exposures. Additionally, gaps remain in the area of translating adverse health effects that may present as symptoms to effects on operational performance. Adverse health effects may not rise to an injury level at present, so it is important to focus research investments and projects on correlating these effects on military relevant performance measures. Finally, there is a paucity of data that has examined the long-term outcomes from repetitive blast exposures. Focus on research in areas of screening, assessment, military performance tasks, and long-term outcomes describe the current research gaps. Findings from these areas are critical to develop further mitigation strategies and to counsel individuals on when and why to seek healthcare for blast-related adverse brain health effects. Early detection will provide the best opportunity for medical interventions that will optimize outcomes.

##### **5.4.6.1 Gap: Inadequate Screening Methods to Detect the Adverse Acute and Chronic Brain Health Effects of Repetitive Blast Exposure**

This gap addresses development of screening methods for the brain health effects of blast exposure that will:

- Discriminate between acute vs. chronic brain health effects of blast exposure.
- Be field expedient and able to be administered without the oversight of trained professionals.
- Determine optimal timing and scenario for the administration of screening tools.
- Determine screening program modifications needed to accommodate personal history and individual susceptibility to the adverse brain health effects of blast exposure.

Health screening is important for the identification of health conditions early in the process to allow for disease mitigation or treatment where indicated. An optimal screening method can be deployed at scale and yield results with high sensitivity allowing for selection of individuals for further workup. Current methods to screen for adverse brain health effects associated with repeated low-level blast exposure are inadequate and a need exists for the development of more optimal tools. Such screening tools would have the ability to be able to discriminate between acute and chronic brain health effects of blast exposure and could be administered without the oversight of trained professionals. The optimal timing and scenarios for the administration of such screening tools should be determined; consideration for any modifications needed to accommodate personal history and individual susceptibilities should be established as well. Development of a blast exposure

screening program would be reliant upon having a clear understanding of the brain health effects of acute and chronic exposures and the development of gold standard measures that are capable of clearly reflecting the nature of the condition in everyone. Screening tools under development would then need to be validated against these gold standards and should weight sensitivity over specificity to allow for referral for further medical workup. Achieving this research goal would significantly advance the field by ideally allowing for the identification of individuals with emerging deleterious effects of repeated low-level blast exposure prior to evolving toward a full manifestation of the condition. Early identification could allow for environmental optimization to alter the potential for future exposures as well as the connection with other health or rehabilitative resources.

### **5.4.6.2 Gap: Inadequate Clinical Tools to Identify the Adverse Acute and Chronic Brain Health Effects of Repetitive Blast Exposure**

There is a lack of effective clinical tools to identify the adverse acute and chronic brain health effects of repetitive low-level blast exposure. To address this gap, there is a critical need for developing optimal tools that encompass specific symptom profiles, neurosensory approaches, neuroimaging, physiological measures, cognitive/affective assessments, biosample biomarkers, and other innovative methods. These tools should enable healthcare professionals to accurately detect, monitor, and mitigate long-term neurological changes associated with military occupational exposure to low-level blast, enhancing early intervention and treatment strategies.

Further development and refinement of current clinical tools for identifying the adverse acute and chronic brain health effects of repetitive low-level blast exposure is crucial for clinicians and military healthcare providers to accurately diagnose and monitor neurological changes, enabling timely intervention and tailored treatment strategies based on specific symptom profiles, neurosensory assessments, neuroimaging findings, physiological measures, cognitive/affective evaluations, and fluid biomarker analysis.

Addressing the research gap in clinical tools for identifying the adverse effects of repetitive low-level blast exposure requires a multidisciplinary approach. This involves integrating findings from neurology, neuropsychiatry, radiology, and biomarker discovery to develop comprehensive assessment protocols. These protocols should incorporate specific symptom profiles (i.e., headaches, dizziness, memory problems, mood changes, and cognitive impairments that may indicate blast-related brain injury), neurosensory assessments (e.g., vision, hearing, balance, vestibular function, and proprioception to identify early signs of neurological damage), advanced neuroimaging techniques (such as MRI, DTI, fMRI, PET employed to visualize structural and functional alterations in the brain), physiological measures (i.e., EEG, MEG, TMS, HRV), cognitive/affective evaluations (including tests of memory, attention, executive function, and processing speed, along with affective measures to evaluate mood, anxiety, and psychosocial functioning), and molecular biomarker analyses (i.e., proteomic, genomic, metabolomic, and transcriptomic profiles) in blood, CSF, saliva, and other bodily fluids. This serves to provide objective indicators of blast-related brain injury/dysfunction to provide insights into neuroinflammation, neurodegeneration, synaptic dysfunction, and neuronal damage, offering valuable indicators of brain health status and injury severity for diagnostic and prognostic purposes. Overall, this will lead to a more holistic understanding of blast-related brain health effects and help guide personalized interventions and treatments.

Solving the research gap related to the lack of clinical tools for identifying adverse brain health effects from repetitive blast exposure will enhance the capability of both military and civilian care providers to accurately diagnose and manage blast-related injuries. The goal of solving this research gap related to the lack of validated tools is to develop comprehensive and integrated assessment strategies. By developing optimal tools that encompass specific symptom profiles, neurosensory approaches, neuroimaging, physiological measures,

cognitive assessments, and molecular biomarkers, healthcare providers can improve the early detection, personalized treatment, and mitigation of blast-related brain health effects, thereby improving outcomes and quality of life for affected individuals and ultimately enhancing overall military health and performance while benefiting civilian populations exposed to similar risks.

Developing clinically validated tools to identify adverse effects of repetitive blast exposure can advance military health and safety guidelines by informing military health policies, protective equipment design, and training strategies. Ultimately, this comprehensive approach will improve military personnel overall health and performance by mitigating the effect of blast-related injuries, enhancing resilience, and optimizing mission readiness across military operations.

### **5.4.6.3 Gap: Incomplete Understanding of the Effects of Blast Exposure on Operational Performance**

Determining the effects of blast exposure on warfighter tasks and operational readiness is the goal of this topic.

Associations between blast exposure and effects among exposed persons may be subclinical in nature and not diagnosable as injury, especially acute effects from low-level blast. Subclinical effects, particularly those that occur with repeated exposures, may be relevant to service member performance of warfighter tasks, and deficits may have consequences in safety or mission execution, which would be important for unit leader awareness.

A subclinical blast exposure-induced performance deficit that has consequences in safety or mission execution has a direct relevance that may be much more salient for unit leaders than a physiological effect or performance effect on a task designed for research purposes.

Developing an assessment directly related to operational performance is a cornerstone in the practice of Occupational Medicine and principles from that medical discipline can be used to identify methods to evaluate blast exposure effects on real-world behavioral performance. This approach may involve a different assessment for each occupation instead of a single assessment that generalizes across all. As an example, blast exposure-induced slowing of decision-making by a service member may be more important for some occupational specialties than others, and understanding such subclinical occupational effects can be helpful in relative risk management.

Unit leader decision-making can be supported when transient behavioral effects from acute exposure to blast are communicated in terminology of actual tasks required for training or mission execution effectiveness.

The direct relevance of blast exposure effects on activities already salient and important for unit leaders can promote application of blast monitoring guidelines. Consideration of blast exposure effects on operational performance is much more relevant to acute exposure and transient effects than to chronic exposure and effects associated with diagnosable injury.

### **5.4.6.4 Gap: Lack of Longitudinal Data that Elucidate the Long-Term Clinical Outcomes of Blast Exposure**

This gap addresses the development and implementation of a longitudinal approach that can follow blast-exposed military personnel and controls during and after their military service.

Currently, there exists inadequate longitudinal data describing the neurological effects of blast exposure in military personnel over their career. Much of the knowledge on the brain health effects of repeated low-level blast exposure to date has been learned from cross-sectional studies and retrospective medical chart reviews. While there is much that can be learned from those kinds of studies, and they do allow for the generation of actionable near-term knowledge, there is value in the availability of longitudinal data. A need exists for establishing support systems to generate longitudinal data in blast-exposed military personnel to help account for the influence of individual difference on the brain health effects of exposures over a career. Such approaches would need to be capable of spanning MoD/DoD and veteran systems. Longitudinal data collection could occur as a part of a prospective longitudinal study with a long-term commitment to the collection of key brain health and exposure data over a career. Such an approach would likely be supported by research teams and could involve the collection of research as well as clinical measures over a career. Conversely, an alternate or complementary approach could involve collection of data into a clinical registry that would allow for the structured collection and storage of information acquired as a part of the standard of care for a service member. The database of information collected through this registry could be queried to explore the brain health effects of blast exposure. Critical to any approach would be the incorporation of blast exposure measures to allow for an understanding of the exposure history of everyone over their career. The availability of such data could help inform a broad range of solutions for the optimization of brain health in military personnel exposed to blast over a career.

### **5.4.7 Research Focus Area: Mitigation and Intervention Strategies**

The purpose of this Research Focus Area is to effectively and efficiently direct research to provide the required inputs for personal protective equipment, specifications for test environment design, and exposure reduction both before and during service. Introduction of test standards, supported by research, that quantify blast effects will ensure the development and application of suitable test and evaluation methods that will drive the design of better equipment, training programs, and facilities as well as drive the design of weapons systems to reduce the effects of blast loading on the brain.

#### **5.6.7.1 Gap: Lack of Blast Specific Design Criteria for Personal Protective Equipment to Mitigate the Effects of Blast Exposure**

The design, development, and evaluation of personal protective equipment has primarily focused on non-blast threats, specifically to protect from ballistic trauma, and secondary blast injury (caused by fragments). This results in equipment that is not optimized and may not be effective in addressing blast loading mechanisms on the service member.

To drive the development of better equipment that results in greater protection of the warfighter from blast exposures in training and operational scenarios, design, and test standards for personal protective equipment that includes blast-related mitigation and protection assessment testing need to be developed. This research will provide personal protective equipment modified to reduce the effects of blast while retaining current ballistic protection. Generating loading data during research, development, and testing will increase understanding of how this equipment can be used to reduce or eliminate transmission of blast loading on the brain.

This research should provide an understanding of what criteria and methods are important and applicable to reduce blast loading on the brain and should thus be used to design and assess personal protective equipment. This can also influence doctrinal use of existing and new equipment to provide improved blast load reduction.

Data and understanding resulting from improved personal protective equipment development, standardized assessments combined with training, field applications, and user feedback will identify areas for operational guideline improvement and potential future standardization.

#### **5.4.7.2 Gap: Lack of Adequate Specifications for the Assessment and Design of the Training Environment to Reduce Brain Health Effects**

Current concepts for the construction and operation of training facilities (ranges, breacher houses, etc.) are mainly limited to the safety design and durability of the infrastructure as well as the functional realization of general military-relevant safety regulations. However, there are no existing guidelines for the design of the training environment that mitigate potential overpressure exposure. Next to that, the mitigating influence of different infrastructure (e.g., cover, enclosed environment geometry), other equipment on ranges and operational procedures (e.g., requirement to open selected windows/doors/relieve openings or to remove selected reflecting objects in the facility) to reduce exposures to all individuals present in the vicinity is not yet sufficiently quantified and available to improve range design.

The use of many tactical applications and weapon systems is associated with explosive energy releases. In unfavorable cases, the resulting effects can be amplified by the immediate surroundings (infrastructure) through reflection in general or adverse superposition of the peaks in a complex reflection geometry.

One approach could be to develop easy-to-use tools for carrying out analyses and assessments of training environments regarding the propagation of blast waves and the visualization of the overpressure color map throughout the environment. Functional steps may include 3D scanning of the environment, characterization and definition of the weapon system, simulation and visualization of the effects, and when necessary, supported by on-site measurements of the blast loads.

Users could thus reduce the amplified effects by temporarily modifying the exercise plans or making permanent infrastructural changes. The installation of monitoring tools/sensors on the training infrastructure, at predefined and suitable positions, to continuously monitor the blast load could support mitigation and monitoring approaches.

Prerequisites would be, for example, the availability of data (pressure development/propagation) of the respective weapon systems. This requires uniform test standards, as outlined in Section 5.4.7.3.

#### **5.4.7.3 Gap: Inadequate Testing Standards to Quantify Weapon System Blast Load on the Brain**

Weapon systems are a major contributor to blast overpressure exposure of military personnel. Qualification of these systems are not focused on minimizing the blast loading on users and nearby personnel, thus requiring post blast quantification to enable optimized training and operational use to minimize the blast overpressure exposure to the operators.

The implementation of standards that include testing of weapons systems will result in limiting the overpressure experienced by the operator and ensure that the brain health of the operator is considered during the development and employment of weapon systems. This will in turn allow for more frequent training, as the operator will not be as restricted to current training limitations due to excessive blast exposure.

Standardized procedures for capturing exposure data for weapon systems should be defined, with overpressure thresholds defined relative to preserving brain health to enable comparisons between different weapon systems and munitions. Development of generally applicable test procedures for the analysis of different weapon systems or

tactical applications provided to weapons manufacturers will ensure that a reduction in overpressure to the operator is a prime consideration in the development of new weapons, and in the refinement of existing weapons.

Providing adequate test standards for weapon systems will ultimately protect the warfighter, enable increased training frequency, and lead to the development of improved safety for the operators of these weapons. In addition, the use of weapons that result in high overpressure exposure that potentially the most injurious can be identified and phased out of service. Standards that are used in procurement will ultimately force weapon manufacturers to adhere to safety protocols and consider the operator and not just the on-target effects.

Developing a testing standard for each class of weapon will enable comparisons between weapon systems where operator brain health is a prominent evaluation criterion for the procurement of weapons.

#### **5.4.7.4 Gap: Lack of Objective Data to Inform Techniques that Best Reduce Blast Exposure**

In most of the military training taking place today, the absence of objective data informing opportunities for technique adjustments that reduce blast exposure hinders instructors' and trainees' ability to test and confirm hypotheses involving the best place to stand, best equipment to wear, best weapon firing posture, etc. The current state-of-the-art treatment for reducing brain health effects is mitigation, so any adjustments in training that can reduce exposures are critical.

More objective data from training, and subsequent information sharing, is needed. Troops must be given tools, like blast sensors, to measure their exposure, make changes, then remeasure to see the effect. If blast exposure is lower with the new method, and the efficacy of training is not reduced, then this learning must be communicated as widely as possible.

Troops must have the tools and education to adjust their tactics, techniques, and procedures that reduce blast exposure, promoting effectiveness in the field and long-term brain health for the force. This gap is core to any exposure guideline. As it is addressed, troops will increase their ability to operate safely and remain under blast exposure guidelines while maintaining, or improving, the efficacy of their training.

#### **5.4.7.5 Gap: Inadequate Pre-Exposure Health-Related Mitigation Approaches**

The effects of pre-exposure factors that can reduce adverse brain health effects of blast exposure are not well understood and require further study to mitigate health effects of repetitive blast exposure.

Scant evidence exists of pre-exposure prophylactic interventions against acute or chronic adverse health outcomes from blast exposure. Use of nutraceuticals or behavioral interventions, such as avoiding psychoactive substances and sleep deprivation, can possibly reduce the severity of brain health effects. Explorative research, such as basic research, preclinical studies, cross-sectional studies, or cohort studies, are needed to discover methods that are effective. Specifically, basic research and preclinical studies can help the discovery of mitigation strategies that target biological protective mechanisms rather than mitigating symptoms. High-quality randomized controlled trials are necessary to determine which approaches have a significant effect in (military) exposure scenarios. Additionally, research on mitigation strategies should differentiate between acute or chronic blast exposure, so strategies are developed for both types of exposure. If proven effective, these approaches can directly mitigate brain health consequences from blast exposure and mitigate use of ineffective substances or methods that cost time and resources while providing a false sense of security. Moreover, developments in this research area contribute to advancement of the capability "Mitigations and Medical Interventions" by providing improved options for protective measures.

#### **5.4.7.6 Gap: Inadequate Health-Related Mitigation Approaches Post-Exposure**

There is a need to develop therapeutic approaches to treat and/or mitigate adverse brain health effects following blast exposure. Rehabilitative strategies for reducing and adjusting to long-term symptoms of blast exposure need to be investigated, including determination of the optimum recovery time before return to duty and consideration of co-occurring conditions.

Preclinical studies show several possible avenues for mitigating adverse brain health consequences from blast exposure through post-exposure interventions, such as behavioral interventions, pharmaceuticals, or education and supportive interventions. There is a lack of high-quality studies of sufficient sample size investigating the effectiveness of these options. Explorative research is necessary to develop post-exposure interventions that enhance recovery from blast exposure or prevent escalation from acute to chronic injury states and cumulative injury. Time since exposure should be considered when assessing the effectiveness of interventions, to not only find methods that work directly after the exposure, but also during following time periods and chronic injury states. Similarly, as in Section 5.4.7.5, basic and preclinical research can contribute to finding interventions that target injury and recovery mechanisms rather than symptoms. Large-scale prospective clinical trials are needed to consolidate the results from exploratory research into evidence-based post-exposure prophylaxis methods, which can be used in Standard Operating Procedures (SOPs) that are applicable to specific (military) exposure scenarios. Furthermore, these interventions and SOPs may be integrated into the “blast exposure monitoring” and “health analysis” sub-capabilities outlined in this report to enable that when a certain exposure threshold is reached fast and effective healthcare measures will be provided.

#### **5.4.8 Research Focus Area: Data Elements, Processing, and Analysis**

##### **5.4.8.1 Gap: Inadequate Methods for Transmission of Common Data Elements to Exposure and Medical Records Within Authorized Databases**

To achieve a better understanding of blast exposure and its resulting health consequences, it is necessary to record and transfer exposure data to medical records and secured databases using standardized formats and/or common data elements. However, there is a current gap in the methods to transfer exposure data and adequate health data from in-field/training situations to relevant medical records and databases. Further, a lack of an established standardization of this data will inhibit the use of AI-driven data analysis and research across this high-dimensional data.

Development of approaches for transmission of exposure and health effects data to medical records and authorized databases is needed. The goal of this research is to enable better use of recorded data for research and development of future mitigation strategies but also for direct, in-training/deployed setting, feedback for optimal recovery/rehabilitation. Medical records should be standardized via common data elements between troops and member countries to enable collection and analysis of large datasets. Such data should be made available and useful for different end users: from documentation of service member exposures to use in short- and long-term clinical/public health-related matters as well as with industry partners. The collection of this kind of data will need to be automated as much as possible to minimize workload for soldiers and health care professionals in the collection of data. A fast, high through-put, high resolution data collection and storage of blast waveform and health data and transfer of such data with common datasets/technical platforms between different troops and different member countries MoD/DoD's and their affiliated health care system will contribute to virtually all other Research Focus Areas listed in this report.

#### 5.4.8.2 Gap: Lack of Adequate Data Science Tools for Understanding and Managing Adverse Brain Health Effects of Blast Exposure

Data science plays a critical role in addressing military occupational brain health risks associated with repetitive blast exposure. This interdisciplinary field contributes across multiple domains, including the acquisition, processing, and organization of information; the creation of advanced decision-support tools; and the identification of latent patterns in research data to facilitate new knowledge discovery. However, there is a pressing need for tailored data science tools to address the unique challenges posed by repeated blast exposures, which can have profound and long-lasting effects on service members' brain health.

**Data Acquisition and Organization:** The refinement of large language models and related technologies is essential for managing and organizing unstructured data generated in operational environments. This unstructured data can include reports, sensor readings, and environmental measurements. Automated processes should be developed to curate and store this information at both the individual level – tracking specific service members – and the group level, enabling analysis of broader patterns across units or the entire force. Furthermore, integrating advanced data techniques to combine exposure data with other known risk factors, such as pre-existing health conditions or environmental variables, could significantly enhance the precision of screening methods. These innovations would allow for more accurate, individualized risk assessments and broader insights into systemic vulnerabilities.

**Data Analysis and Integration:** To maximize the utility of acquired data, advanced analytical techniques must be developed and refined. Dimensionality reduction methods are particularly important to address the false discovery issues that arise when working with expansive and diverse datasets. Such techniques can help filter noise and highlight meaningful patterns, enabling more robust and reliable analysis. Additionally, there is an urgent need for improvements in multimodal data integration, creating a unified analytical space that can incorporate data from various sources – such as clinical records, operational reports, and sensor data – into a cohesive framework. This capability would allow for a more comprehensive understanding of how repetitive blast exposures interact with other factors to impact brain health.

Unsupervised machine learning approaches are another key area for development. These techniques can uncover hidden patterns within datasets, providing insights into relationships and trends that may not be immediately apparent. Applying these methods to blast exposure data could reveal previously unrecognized risk factors or pathways of injury, offering new directions for intervention and prevention.

**Closing the Gaps:** To address these challenges, the military and its research partners should prioritize the development and application of advanced data science tools. Leveraging existing datasets from operational, clinical, and research sources is a vital first step. These datasets, enriched with real-world insights from blast-exposed populations, can serve as a foundation for creating more effective analytical tools. Simultaneously, direct investment in cutting-edge technologies – such as machine learning, natural language processing, and high-dimensional data analysis – will enable the creation of solutions tailored to the military's unique needs. By aligning these efforts with broader advancements in the data sciences, the military can develop a comprehensive approach to mitigating the brain health risks associated with repetitive blast exposure.

Through these measures, data science can serve as a transformative force, driving innovation in prevention, diagnosis, and treatment strategies for military personnel affected by blast exposure.

## Chapter 6 – SUMMARY

### 6.1 INTRODUCTION

While injury from blast exposures has been an important topic of research historically, research has largely focused on combat or incident related injuries. This has resulted in the development of injury models for e.g., assessment of lethality due to lung injuries and eardrum ruptures. More recent missions of NATO members and allied countries in Iraq, Afghanistan, and Mali showed an increase in blast exposures during combat and increased concerns for brain related injuries. A US and Australian deployment of wearable blast sensors revealed significant exposures from firing heavy weapons in theatre, creating an awareness of the repetitive overpressure threat from weapon systems in the training environment [1]. Increased rates of traumatic brain injury triggered a response to expand screening and clinical care programs as well as research investments. This resulted in more attention to the total burden of blast exposures on military personnel. Some sentinel research conducted in the US began to explore the hypothesis that blast exposure could result in brain health changes similar to those seen with diagnosed mild TBIs (concussions). US Navy Special Warfare cohorts and specifically with the Carl Gustaf recoilless rifle, which showed transient neurocognitive changes, balance disturbances, and complaints of headaches after training exercises. A 2018 review of US Marines who fired an unusually high number of artillery rounds while deployed for six months found that these service members suffered a higher rate of traumatic brain injuries than the rest of the artillery community [2]. Interest and research expanded from combat blast-related TBIs to repetitive low level blast exposures occurring in the training environments. Concerns for both acute and chronic adverse brain health effects led to more research investigations to explore the relationship between blast exposures and acute and chronic brain health effects.

There are large differences in attention to the long-term brain health effects across NATO members and allied countries. While several NATO members and allied countries were performing multiple years of research in multiple fields, other countries were just getting started with this topic. Most of the research is still ongoing and the first practical solutions have started to form. At the beginning of RTG HFM-338 a shared NATO approach on how to address this current topic with a set of guidelines was missing.

As stated in the introduction, the strategy to cope with the risks of blast exposure and adverse brain health outcomes within a military setting is based on a three-stage development of guidelines (expert-based, knowledge-based, and experience-based) in the upcoming 15 – 25 years.

### 6.2 OUTCOMES OF HFM-338

RTG HFM-338 has defined a set of expert-based guidelines, reflecting the state of science, defined by the experts in the field who have biophysics, biomedical, and/or operational backgrounds. The countries contributing to the HFM-338 were Canada, France, Germany, Norway, South Africa, Sweden, The Netherlands, United Kingdom, and The United States.

The intent of the guidelines contained in this report are to be user-friendly, practical, and dynamic. It is expected that these guidelines are a starting point by which NATO members and allied nations may begin to address critical issues related to repetitive blast exposures, brain health effects, and impacts to operational readiness and performance. These guidelines attempt to provide ambitious but necessary goals to position NATO members and allied nations for the future fight.

## **SUMMARY**

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The Interim Exposure guidelines provided the state of science on blast exposure threshold values. These values may be used to mitigate the risk of adverse brain health effects due to blast exposure. Four different methods were identified, and recommendations were proposed on how these can be used in future assessments.

The Operational guidelines provide a wide range of practical recommendations, which will support prevention activities aimed at reducing adverse brain health effects. The four capabilities of (1) Blast Exposure Monitoring, (2) Capture of Health and Performance Information and Data, (3) Analysis of Blast Exposure, Health, and Performance Effects, and (4) Mitigation and Health Management Strategies set the structure of these guidelines. Each capability includes sub-capabilities further detailing the operational guidelines. Each sub-capability is presented in an ordinal fashion, starting with Level 1 through Level 6. Level 1 proposes basic activities and progresses through Level 6, which would represent a mature and comprehensive solution to the specific area discussed. The Operational guidelines were provided in a table format, providing a short overview of the guidelines as well as in a more detailed narrative, providing the details required to start implementing these guidelines. NATO members and allied countries are now armed with the state-of-the-science and available data to address and mitigate military occupational brain health risks from repetitive blast exposures. This report sets conditions to mitigate the effect of blast exposures today while positioning NATO members and allied countries to leverage additional research and mitigation capability development for tomorrow.

The Research and Development guidelines present eight targeted Research Focus Areas with accompanying gaps and goals. The guidelines provide insight into what research is necessary to make improvements in the Exposure and Operational guidelines. These guidelines will allow nations to direct their research to the most urgent topics.

## **6.3 RECOMMENDATIONS**

The operational guidelines were defined in four capabilities, thirteen different sub-capabilities each at six different levels. While a great level of detail is included in these guidelines, they are not specified up to NATO member or allied country requirements. Since each country will have differences in the organisation of military leadership, medical command, and the training environment, the Operational guidelines will need to be implemented and specified to each country's requirements accordingly. Only when this step has been taken, the Operational guidelines can be fully implemented and aid in limiting the adverse brain health outcomes from blast exposures.

The multiple nation collaboration in HFM-338 to formulate evidence-based guidelines provides insight into the sheer magnitude of effort of research needed to protect and mitigate from adverse brain health effects due to blast exposures. It shows a multiple nation research effort, and further alignment of research programs are required to ensure research results will be available as soon as possible to limit the amount of military personnel who develop adverse brain health effects. As such, it is vital to enable future collaborative research across countries, starting with topics like common data elements and data sharing.

The Research and Development guidelines have listed 29 research gaps and goals, which require further research. These may be used to select and direct future research in this field. While no prioritisation has been made for these research gaps, it is recommended that each country starts selecting the most opportune research goals and research on these gaps can be started.

This report is a critical step forward to address risks associated with blast exposures. NATO members and allied nations have and will benefit from more knowledge about identifying, monitoring, and mitigating brain health effects from blast exposure. These current guidelines have outlined blast exposure thresholds, medical evaluations, risk management actions, and exposure controls to better protect the brain health of military personnel. Deterring, competing, and winning in all operational environments means discovering how to maximise and sustain brain health while avoiding unnecessary blast exposures.

## **6.4 REFERENCES**

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## **SUMMARY**

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| REPORT DOCUMENTATION PAGE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                          |                           |                                        |
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| 14. Abstract<br>Blast overpressure exposure poses a significant occupational risk to military personnel and can cause negative effects to Force Health and Readiness. Most blast exposure occurs during training, where repeated low-level blast differs from single high-intensity blasts but may cumulatively harm brain health. Monitoring and documenting blast exposure is therefore essential to understanding long-term effects and protecting warfighters throughout and beyond their careers. The RTG HFM-338 developed a three-stage development of guidelines strategy to mitigate military occupational brain health risks from repetitive blast exposure. These three stages are expert-based (current), knowledge-based, and experience-based. The current report contains the expert-based guidelines. The group produced three products: 1) The Interim Exposure Guidelines define expert-based exposure thresholds, identifying limits for peak overpressure, cumulative impulse, and generalized blast exposure values. 2) The Operational Guidelines provide a structured framework for implementing a national blast exposure mitigation program, covering monitoring, health and performance data collection, analysis, and mitigation strategies, with multiple implementation levels. 3) The Research and Development Guidelines identify critical knowledge gaps across eight focus areas to advance understanding and long-term protection of brain health. These expert based guidelines can be adopted and implemented by NATO and allied partners to mitigate military occupational brain health risks. |                                          |                           |                                        |



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