Blast Overpressure (BOP) Tool for protection of Service members from blast exposure during training with heavy weapons and breaching explosives

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Abstract

Military service members face repeated exposure to low-level blast waves during heavy weapons training and explosive operations, raising concerns about potential neurological effects. While wearable sensors provide valuable data, they only capture exposure data at their mounted location and do not capture the full spatial extent of blast environments, nor offer information to support protection from exposure, necessitating comprehensive computational tools. The Blast Overpressure (BOP) Tool was developed to provide 360-degree prediction of blast exposure, complementing sensor data with whole-body and organ-specific dose calculations. The tool integrates databases of breaching explosive and weapon muzzle blast characteristics, virtual training scenes, and three-dimensional service member models. An interactive graphical user interface (GUI) enables simulations by adjusting personnel positions and postures to minimize blast exposure from single or repeated events. The BOP Tool comprises two modules: BOP SCENE for individual virtual service member overpressure predictions that account for position and posture, and BOP SITE for displaying blast overpressure around weapon systems. The tool calculates blast loads to the whole body and injury-sensitive regions including head, face, and chest. Validation was conducted using experimental data collected by pencil probes for different weapon classes. The BOP Tool provides essential capabilities for estimating blast exposure and developing safer protocols for repeated heavy weapon training. This systematic computational approach, includes sixteen weapon system models, enabling reliable overpressure prediction and supports evidence-based training adjustments to minimize unnecessary service member exposure while maintaining operational effectiveness.

Introduction

The past decade has brought increased awareness of the potential for neurological effects following repetitive exposure [1], [2] to blast waves generated by breaching explosives and military heavy weapons during training and combat operations [3], [4]. As the number of service member reports increased, so did the congressional interest in the use of heavy weapons during training, ultimately leading to the establishment of National Defense Authorization Act (NDAA) Section 734 for FY 2018 (Public Law 115–91) which required the Secretary of Defense to conduct a longitudinal medical study on blast pressure exposure of members of the Armed Forces during combat and training.

In response to these growing concerns, the Assistant Secretary of Defense for Health Affairs designed the Section 734 Blast Overpressure Study Program to improve understanding of blast pressure exposure effects on service members' brain health and inform critical policy decisions regarding risk mitigation, unit readiness, and health care delivery. The DoD Blast Injury Research Coordinating Office (BIRCO) was designated as the Office of Primary Responsibility for the Weapon System Line of Inquiry, with key responsibilities including (1) coordinate, collate, and analyze information on blast pressure resulting from heavy weapons and blast events, and (2) to inform strategies to account for emerging research on the effects of blast pressure exposure on health and performance.

While wearable sensors provide useful data for monitoring individual exposure, they are inherently limited to discrete measurement points, and a not prediction of blast overpressures in different training environments, which can be used to prevent excessive exposures. Wearable sensors only capture exposure data at their mounted location and lack the ability to capture the full spatial extent of complex blast environments, particularly when the sensors are shielded or not fully exposed to local blast conditions, leading to measurements that are not representative of the surrounding environment [5], [6]. Additionally, wearable blast-pressure sensors have been shown to misestimate exposure, often overestimating peak overpressure and impulse due to averaging methods and orientation effects that occur with changes in soldier posture, which can lead to inaccurate assessment of blast dosage [6]. Computational modeling tools offer an alternative approach to address some of these measurement limitations. More importantly, whereas wearable sensors provide information after the exposure whereas using these tools to predict exposure prior to events enables range managers and service members to take simple precautions that can meaningfully reduce their exposure. Changes in position and posture are simple steps that can have significant influence on blast overpressure exposure [7].

Leveraging information collected in support of the Sec 734 Blast Overpressure Study Program, the team developed the Blast Overpressure (BOP) Tool module to enhance DoD planning capabilities and improve understanding and determine expected service member BOP exposure during training with heavy weapons [8]. This tool development represents a critical response to documented deficiencies in current blast exposure management capabilities, particularly addressing the urgent need for enhanced service member and leadership awareness of blast exposures while providing actionable information to support evidence-based risk mitigation decisions. This BOP Tool is a software application, available for use on Windows laptops or desktops, that provides a computational model guided by placement of weapons and personnel for range safety planning. The tool provides estimated exposures based on the weapon, munition type, location, and posture of the individual. The current study presents a comprehensive status update on the BOP tool development [9], [10]. This work contributes directly to blast injury prevention and mitigation efforts by bridging the critical gap between evolving scientific understanding and operational protective measures in military training environments. This paper will introduce the BOP Tool and its enhancements, detail the various weapon systems currently included in the BOP Tool, and demonstrate the tool's capabilities through a 120mm mortar firing scenario. The discussion section will explore several applications of the tool and discuss potential future improvements to the tool.

Materials and Methods

BOP Tool Background

The prototype BOP Tool, presented in our prior publication [10], constitutes a computational framework designed to determine expected service member blast exposure in military heavy weapon training scenarios. The system employs the CoBi (Computational Biology; developed by CFD Research Corporation, Huntsville, AL, USA) human body model generator tools to reconstruct multiple training scenes involving virtual service members, in different postures and orientations, and various weapon systems. Additionally, it utilizes CoBi-Blast tools (developed by CFD Research Corporation, Huntsville, AL, USA) to develop weapon BOP models [11] and estimate blast overpressure exposure on a spatially and temporally resolved basis on the entire human body, and specific anatomical regions susceptible to blast loads, such as the head, face, and lungs. The CoBi-Blast tools were independently assessed in a prior effort [9]. This fast-running computational framework offers significant advantages, including simplified model setup, reduced simulation times (5-10 minutes on personal computers compared to hours on high-performance systems for traditional CFD models), and the capability to conduct rapid analyses for determining exposure based on various input parameters such as crew positioning, postures, and weapon orientations.

BOP Tool Enhancements

Building upon the foundational capabilities of the prototype BOP Tool presented before [9], [10], we implemented several enhancements to improve accuracy, expand functionality, and enhance user experience. These improvements address limitations identified during initial demonstration, to operational communities, and incorporated feedback from multiple stake holders. The enhanced BOP Tool maintains the core architecture the tool while introducing refined algorithms and expanded weapon system support. These improvements represent iterative development based on operational requirements and feedback across various training environments. Each enhancement was designed to increase the tool's usability in predicting blast overpressure exposure while maintaining the rapid processing capabilities essential for real-time training scenario planning and post-event analysis. A detailed description of the status of the BOP Tool is included in the following sections.

Weapon Systems in the BOP Tool

As part of the enhancements to the BOP Tool, additional weapon systems were incorporated into the BOP Tool library, summarized in Table 1.

Table 1. Weapon systems included in the current version of the BOP Tool. Systems shaded in blue represent data collected by collaborators at WRAIR, while those shaded in green represent data from collaborators in the CONQUER study.

Small Arms (.50 Caliber)	**Shoulder Mounted**	**Mortars**	**Howitzers**	**Breaching Explosives (Net Explosive Weight)**
M107 Special Application Sniper Rifle (SASR)	AT4/M136 84mm (Carl Gustaf)	M120 120mm	M777 A2	Open Space (0.2 lb. or 3.5 lb. Det. Cord)
M2A1 machine gun	M72 LAW	M1 81mm	M109 A6	Door (0.11 lb. Water Breacher)
GAU-21 machine gun	M3 MAAWS	M224 60mm	M119 A3	Exterior Wall (6.75 lb. Fracture, 8.44 lb. GBuster, 10.4 lb. Satellite)
MK-15 sniper rifle				Door (2 lb detonation cord)

Data Collection for BOP Tool

The development and validation of the weapon BOP tool library was based on experimental data from the above weapon systems (shown in Table 1), provided by the Combat and Training Queryable Exposure/Event Repository (CONQUER) operational static monitoring program [12] at the Uniformed Services University of the Health Sciences and by research teams at the Walter Reed Army Institute of Research (WRAIR). This data encompass: (a) pencil probe pressure measurements, (b) sensor schematics, including the arrangement of pencil probes around the weapon, the distance of the sensors from the weapon, and their orientation relative to the weapon, (c) photographic images of the arrangement, and (d) videos. The data collected by WRAIR include the M107 Special Application Sniper Rifle (SASR), AT4/M136 Shoulder Mounted Assault Weapon

(SMAW), M120 120mm mortar, and a 0.3 lb. door breaching detonation cord. The rest of the data were obtained from the CONQUER program.

Data Integration, and Validation:

The conceptual framework for the blast overpressure assessment tool was initially explored in our prior publication in Military Medicine [10]. The tool development methodology follows a systematic data-driven approach that transforms empirical measurements into validated computational parameters for operational use. The process begins with segregation of collected pencil probe data into two distinct datasets: calibration and validation subsets. The calibration dataset serves as the foundation for developing weapon-specific blast overpressure input parameters through statistical analysis and parameter optimization techniques. These derived parameters are subsequently integrated into the physics-based blast propagation models that form the computational core of the modeling engine. Forward simulations using the calibrated parameters are then executed to generate predicted blast overpressure fields, which are compared against the validation dataset to assess parameter accuracy and model performance. This validation process ensures that the weapon BOP input parameters accurately reproduce observed blast characteristics with Pmax values at the sensors of a scene showing errors of less than 20% on average. Upon successful calibration and validation, the finalized weapon-specific parameters are permanently integrated into the comprehensive weapon database that supports the BOP Tool's operational functionality. This systematic approach ensures that each weapon system's blast characteristics are accurately represented in the tool's predictive capabilities, providing users with reliable blast overpressure assessments for training scenario planning and risk mitigation decision-making.

BOP Tool Structure

The desktop or laptop environment instance of the BOP Tool is composed of two key modules. The first module is the SCENE module, and the second module is the SITE module (Figure 1).

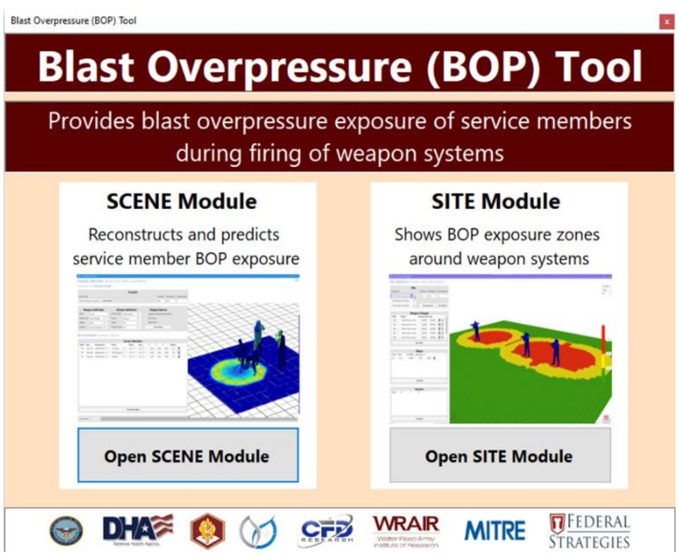

Figure 1. User interface of the BOP Tool showing the buttons to access the SCENE and SITE modules.

The SCENE module is designed to reconstruct and predict the blast overpressure exposure on servicemembers based on their position, posture, and orientation with respect to the weapon. The SITE module is designed to show the blast overpressure zones around the weapon system and provide metrics such as the span of the different overpressure zones at different heights from the ground.

SCENE Module:

As mentioned above, the SCENE module was developed to estimate blast exposure on individual service members during the weapon firing. The SCENE module enables the user to either create their own customized firing scene or select from the existing preconfigured scenes. This module comprises a database of virtual service member models in different postures (i.e., standing, kneeling, prone). Each weapon firing scene can be created by selecting and placing the weapon system, selecting and placing the virtual service member models with respect to the weapon, and adding any virtual sensors i.e., points in space where the incident or reflected pressures can be recorded. An example of a weapon firing scene is shown in Figure 2.

Currently, the tool has the preconfigured or saved scenes for all the weapon systems shown in Table 1. Scenes, like that shown in Figure 2, were created based on the image and video data collected during live weapon firing exercises using both manual and automated methods [13]. The tool can estimate the exposure on the different anatomical regions corresponding to the service members based on the posture and position of the service member in proximity to the weapon. The SCENE module also allows users to compute cumulative dose metrics based on the number of firings and the duration of a session. Currently, the tool's cumulative dose metrics are comprised of two key metrics i.e., impulse and intensity, which are automatically calculated from user inputs. *Impulse* is defined as the area under the pressure–time curve for the entire session, while *intensity* is defined as impulse divided by the total session duration, providing an equivalent measure of average pressure over the session. Other capabilities of the tool include: (a) personalization of scene models, such as assigning names to virtual service member representations; (b) the ability to add additional blast charges within the environment; (c) customizable contour scale limits; and (d) adjustable frame speeds, time steps, and output frequency for blast simulations.

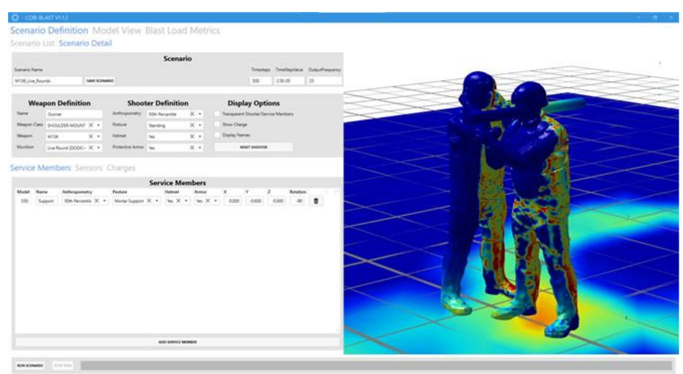

Figure 2. The BOP Tool SCENE module reconstructs and predicts service member exposure during a weapon-firing scenario. The color contours represent varying pressure levels.

SITE Module

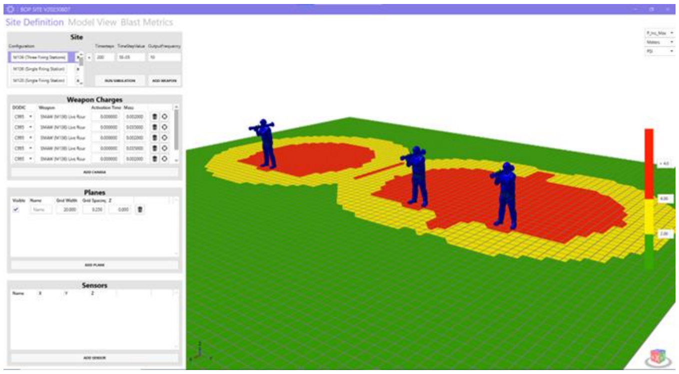

Figure 3. BOP Tool SITE module can show the blast overpressure zones around the weapon system at different heights from the ground.

The SITE module is developed to visualize blast overpressure zones around a weapon system (see Figure 3), drawing from the weapon BOP Tool library. It estimates the span of these zones, providing peak pressure values at varying distances. The zones are color-coded: red for exposures greater than 4 psi, yellow for exposures between 2 and 4 psi, and green for exposures less than 2 psi. Results can be displayed in either SI or non-SI units, selectable from a dropdown menu. When the unit system is changed, all previously entered data are automatically converted to the new units.

Validation for 120mm Mortar Weapon System

Experimental blast overpressure data for the 120 mm mortar weapon system, presented in this paper, was collected by the research team at Walter Reed Army Institute of Research. This data corresponds to a 120mm mortar weapon firing using charge 1. The measurement configuration is shown in Figure 4, which depicts both the field setup (left) and schematic layout (right). Three stakes, labeled 1–3, were arranged in a circular pattern 4 ft from the weapon muzzle. Stakes 1 and 2 each held two pencil probes at heights of 2 ft and 4 ft above ground, while Stake 3 contained a single probe at 2 ft. The probe annotated *"Red"* included two pressure-sensing elements. All probes were oriented parallel to the direction of wave propagation. The schematic uses color-coded annotations to map precise sensor locations, while the field photo shows their deployment around the mortar. This multi-height arrangement provided a three-dimensional measurement grid, enabling characterization of blast overpressure in both horizontal and vertical planes.

The collected pencil probe dataset was partitioned into development and validation sets. The development subset was used to develop weapon-specific BOP models for the 120mm mortar and munition combination. The remaining validation subset provided independent data for assessing model accuracy and reliability. Model validation was performed by comparing predicted blast overpressure values against the recorded measurements from the validation dataset, ensuring robust development of the weapon's blast BOP inputs.

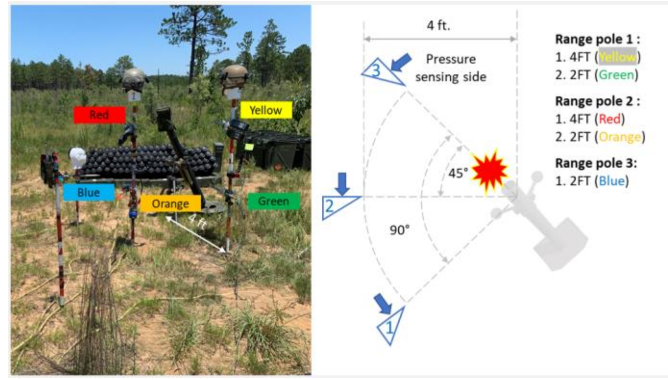

Figure 4. Pencil probe measurement setup for 120mm mortar weapon blast overpressure (BOP) determination and validation. Pencil probes positioned at various distances and angles around the weapon system collected data for BOP development and validation studies. This data was collected by the Walter Reed Army Institute of Research. The photograph (left) shows the field setup with probes mounted on stakes surrounding the mortar, while the schematic diagram (right) maps the precise sensor locations using color-coded annotations for each measurement position.

Results

Weapon BOP Development and Validation for 120mm Mortar System:

Figure 5 presents the comparison between predicted and measured blast overpressure time histories at the six sensor locations around the 120mm mortar system (shown in Figure 4). The model predictions (blue lines) demonstrate strong agreement with the experimental pencil probe data (red lines) across all measurement positions. Shaded band plots are included to illustrate the standard deviation around the experimental data, providing a visual measure of variability across different firings. The maximum peak overpressure (Pmax) values were well-captured by the model, with predicted magnitudes showing excellent correspondence to the experimental data at all sensor locations (the average peak pressure error is within 10%). The Red-Front and Red-Rear positions recorded the highest Pmax values of approximately 4 psi, while the remaining positions (Orange, Green, Yellow, and Blue) showed lower but consistent peak values ranging from 2-3 psi.

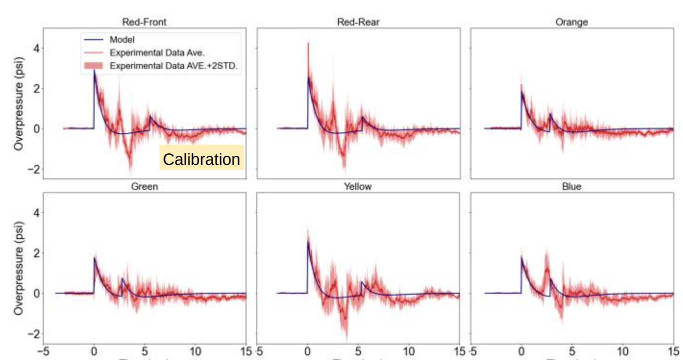

Figure 5. Plots comparing the model predicted pressure traces compared to the pencil probe recordings for the 120mm mortar

weapon system. The blue line shows the model prediction while the red line represents the experiment data.

This accurate prediction of Pmax demonstrates the model's ability to reliably estimate the most critical blast parameter for safety and design considerations. The temporal characteristics of the blast waves were also well-reproduced by the model, including the sharp pressure rise times and subsequent decay profiles. The positive pressure phase duration and the transition to negative pressure phases matched experimental observations across all sensor positions. The model did not capture the sinusoidal oscillation after the initial peak. These oscillations in the experimental data can be attributed to several physical phenomena, including Mach stem formation and interaction as the blast wave propagates and interacts with the ground, weapon system resonance where the mortar tube and mounting system act as acoustic resonators generating secondary pressure waves, atmospheric stratification effects causing blast wave refraction and focusing, multiple reflection paths from nearby structures or terrain features creating beating patterns, and sensor/mounting resonance where the pencil probes and stakes are excited at their natural frequencies by the blast. These secondary effects are not represented in the current model, which focuses on the primary blast wave propagation. Minor discrepancies between model and experimental data were also observed primarily in the later time periods (>10 ms), which may be related to these complex wave interaction phenomena not fully captured in the model. Importantly, these later-time discrepancies do not affect the accurate prediction of Pmax, which remains the primary validation metric for blast safety applications. The calibration process effectively aligned the model predictions with the experimental dataset, as evidenced by the close correspondence between the blue model lines and red experimental traces. This validation demonstrates the model's ability to accurately predict blast overpressure characteristics for the 120mm mortar weapon system across multiple spatial locations and azimuthal positions.

Example of BOP Tool SCENE Module output for the 120mm Mortar

The BOP Tool was used to conduct forward simulations for predicting blast dose on virtual service member body models using the SCENE module. *Figure 6* shows the blast wave interaction with a two-person mortar crew at different points in time. A total CPU time of approximately 5 minutes was required to run these simulations. This CPU run time generally depends on the complexity of the scene setup. For example, a scenario with two people will take less time to run compared to a scenario with three or four virtual service member body models.

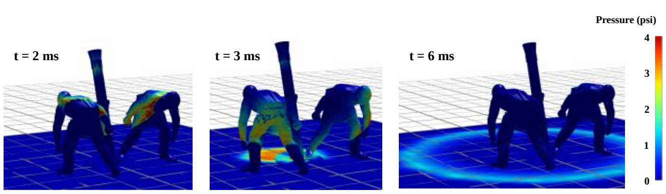

Figure 6. Simulation of blast wave interaction with a mortar crew at three different times: (a) t = 2 ms, initial blast wave impacting personnel; (b) t = 3 ms, peak overpressure propagating through the crew; (c) t = 6 ms, blast wave dissipating into the surrounding environment. The visualization is performed using the SCENE module visualization capabilities.

The graphical user interface (GUI) of the SCENE module provides high-resolution, time-resolved visualization of blast wave propagation on the service members. Users can examine the temporal evolution of pressure on specific anatomical regions, as illustrated in *Figure 6*. For instance, *Figure 6* presents the overpressure distribution associated with a 120 mm mortar firing scenario at three distinct time points (2, 3, and 6 ms). In addition, the SCENE module automatically generates tabulated total peak overpressure (Pmax) values for different anatomical regions and highlights those that exceed a user-defined threshold (Figure 7), thereby enabling rapid identification of body regions subjected to higher blast exposure. The module also incorporates personalization features, allowing operators to assign identifiers (e.g., “Joe” and “Jim”) to service members within the scene. In the example scenario, a Pmax of approximately 9 psi was observed on one of the service members. Currently, the module displays Pmax data for the head and chest regions while computing values across all anatomical regions. Future developments will enhance functionality by enabling users to export Pmax data for any anatomical region of interest.

Pressure Summary

Threshold (PSI) 4

NAME	DESCRIPTION	MAX PRESSURE (PSI)
Joe: Chest	Stand_BentOver Standing, bent over, with armor and helmet	7.701
Joe: Head	Stand_BentOver Standing, bent over, with armor and helmet	9.112
Jim: Chest	Stand_BentOver Standing, bent over, with armor and helmet	7.698
Jim: Head	Stand_BentOver Standing, bent over, with armor and helmet	5.043
PP1 02	User placed Sensor.	1.099
PP2 04	User placed Sensor.	0.507
PP3 05	User placed Sensor.	1.162
PP4 08	User placed Sensor.	1.418

Figure 7. SCENE module’s Pressure Summary section automatically displays maximum blast pressures at body locations and user-placed sensors. Values exceeding the 4 PSI threshold are highlighted in red. The 4 PSI threshold can be edited or changed by the user for a custom threshold.

Additionally, the tool automatically and rapidly calculates preliminary cumulative dose metrics for each service members involved in the scene. Figure 8 shows a snapshot of this functionality. The cumulative metrics include impulse and intensity, which are calculated using the number of firings and session duration information, as defined in the Materials and Methods section. Both the number of firings and total session duration are user-editable parameters, enabling real-time estimation of cumulative dose metrics based on user inputs.

Cumulative Dose Summary

Num of Firings 10

Total Duration (min) 60

NAME	CUMULATIVE METRIC	VALUE
Joe: Chest	Impulse (PSI-s)	1.69E-01
Joe: Chest	Intensity (PSI)	4.70E-05
Joe: Head	Impulse (PSI-s)	1.67E-01
Joe: Head	Intensity (PSI)	4.64E-05
Jim: Chest	Impulse (PSI-s)	1.71E-01
Jim: Chest	Intensity (PSI)	4.74E-05
Jim: Head	Impulse (PSI-s)	9.75E-02
Jim: Head	Intensity (PSI)	2.71E-05

Figure 8. Cumulative Dose subtab for a 120 mm blast scenario with 10 firings over 60 minutes. The table displays cumulative impulse

and intensity values at various body locations and user-placed sensors.

Lastly, the tool provides functionality for plotting temporal exposure profiles of multiple service members within a training scenario. For example, Figure 9 shows the pressure-time histories for the head and chest of the one service member ("Jim") during this mortar firing scenario. This feature enables direct comparison of anatomical region-specific responses across individuals exposed to the same blast event, thereby offering insight into localized risk distributions and differential exposure patterns.

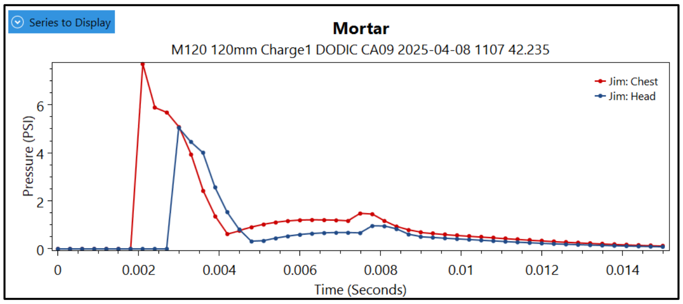

Figure 9. Time-history plotting feature for a 120 mm mortar blast (Charge 1), showing overpressure at a virtual service member's chest and head. Data series can be interactively selected from the dropdown menu.

BOP Tool SITE Module for the 120mm Mortar

As mentioned above, the BOP Tool SITE module is developed to show a bird's eye view of the blast overpressure zones generated by weapon systems, with the 120 mm mortar serving as a representative example. The module calculates incident pressures at user-defined heights above the ground and presents the results as color-coded overpressure zones to facilitate rapid interpretation. While the module includes service member models positioned around the weapon system, these are used exclusively for visual purposes and do not contribute to exposure or dose estimations. This design choice emphasizes that the focus of the SITE module is on the characterization of overpressure fields rather than individual personnel risk assessment.

Simulation runtimes, in the SITE module, typically range from 5 seconds to 1 minute, with computational efficiency dependent on factors such as training grid resolution, the number of grids employed (see an example of a simulation using 3 grids at different heights in Figure 10), and the overall complexity of the site configuration. By providing a rapid and flexible means of assessing peak overpressure distributions, the SITE module supports training, planning, and evaluation of blast effects in operational contexts.

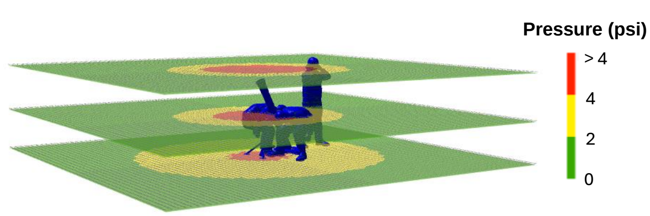

Figure 10. 120 mm mortar blast (Charge 1), showing overpressure at the ground and a virtual service member's chest and head.

The overpressure zones, for the 120mm mortar weapon system, vary with the height of assessment above the ground (**Error! Not a valid bookmark self-reference.**). At head height for the average service member (1.7 m), overpressures exceeding 4 psi spanned the region within ~1.05 m of the weapon, while the 2–4 psi zone extended from 1.05 to 1.65 m, and pressures <2 psi are observed at distances greater than 1.65 m. At head height for a crouching service member (0.8 m head height), the >4 psi zone was limited to within 0.85 m, with the 2–4 psi region spanning 0.85–1.55 m, and pressures <2 psi occurring beyond 1.55 m. At ground level, the >4 psi zone was highly localized (<0.05–0.1 m), while the 2–4 psi region extended up to 1.55 m, and pressures <2 psi dominated the region. These results indicate that when 2 psi is applied as a threshold criterion, the corresponding zone consistently begins beyond 5.1 ft (1.55 m) from the weapon at all assessed heights. This demonstrates that overpressure effects greater than 2 psi are limited to regions within 5.1 ft, while pressures fall below this level beyond that boundary. Figure 10 depicts the incident overpressure fields (direct + ground-reflected components). It does not show reflected-overpressure factors at surfaces; thus, values represent the free-field incident pressure distribution influenced by ground reflection. The >4 psi zone is largest at the top plane because the charge is located near this elevation, where direct incident pressures dominate. At lower planes, the >4 psi footprint is smaller and more localized, as peak amplitudes attenuate with distance from the charge and are only partially reinforced by ground reflection.

Table 1. Blast overpressure zone spans determined by the BOP Tool SITE module for the 120mm mortar weapon system.

Height of the SITE from the ground	Overpressure Zone Span		
	> 4 psi	**2 – 4 psi**	**< 2 psi**
1.7 m (standing head height)	< ~ 1.05 m (3.4 ft)	1.05 – 1.65m (3.4 – 5.4 ft)	> 1.65 m (5.4 ft)
0.8 m (crouching head height)	< ~0.85 m (2.8 ft)	0.85 – 1.55 m (2.8 to 5.1 ft)	> 1.55 m (5.1 ft)
0.0 m (ground)	< ~ 0.05 – 0.1 m (0.1 – 0.3 ft)	0.1 – 1.55m (0.2 – 5.1 ft)	> 1.55m (5.1 ft)

The SITE module also enables simulation of multiple firing stations in a single scenario. In simulations involving multiple crews or firing stations, the SITE module can effectively identify overpressure hotspots. Figure 11 illustrates the distribution and overlap of BOP from various firing stations. This analysis evaluated three distinct firing station positions with different separation distances, revealing that stations positioned 3 meters apart (left and middle positions) produced two separate overpressure hotspots in the intermediate zone, characterized by significantly elevated pressure values. In contrast, the crew located 6 meters from the middle station exhibited reduced interaction effects. These capabilities can be useful in determining optimal separation distances during range planning, design, or modernization. It is important to note that this assumes the simultaneous firing of weapons, which may not be realistic, but it provides conservative estimates for determining safe separation distances during range planning.

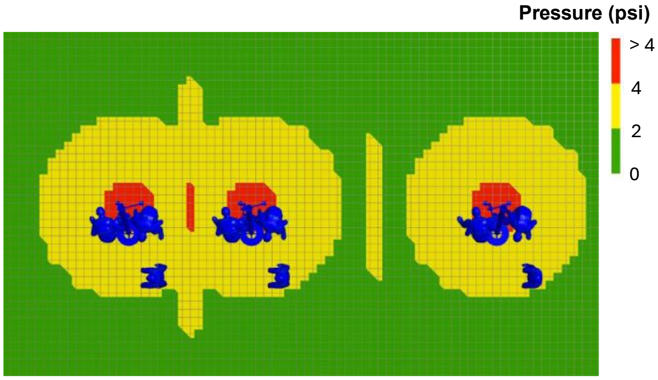

Figure 11. Distribution of BOP for a scenario with multiple 120 mm mortar crews (Charge 1).

Discussion

In summary, this paper introduces the enhanced BOP Tool architecture and its constituent modules, integrating weapon systems from various classes. The BOP Tool can run simulations significantly faster than traditional computational fluid dynamics (CFD) simulations. For instance, run times of simulations in the SCENE module typically require 5-10 minutes, depending on the complexity, whereas SITE simulations demonstrate a runtime of seconds. The tool features interactive and user-friendly interfaces. This paper addresses the weapon BOP model development and validation methodology, demonstrated using the 120mm mortar weapon system. Comprehensive weapon BOP development and validation results for the remaining weapon systems will be detailed in forthcoming publications, offering a complete assessment of the tool's predictive capabilities across all weapon platforms. As previously mentioned, only pencil probe data was utilized for the development and validation of the weapon BOP models. Due to the ambiguities associated with wearable sensors [5], [6], and the fact that pencil probes are considered the gold standard for pressure measurements.

There are several applications for the BOP Tool including: (a) informing unit personnel of predicted blast exposures by translating complex pressure calculations into predictions that enable commanders and range managers to make data-driven decisions about exercise configurations and evaluate trade-offs between training protocols and exposure minimization; (b) supporting weapon design research through exposure-conscious design principles that allows designers to evaluate implications during development and incorporate mitigation features such as advanced muzzle devices and blast deflectors; (c) quantifying exposure data for health and performance studies [14], [15] by providing researchers with standardized approaches for estimating retrospective exposures based on documented training parameters, replacing subjective estimates with physics-based calculations that strengthen statistical power of health outcome analyses; (d) informing range modernization decisions by providing data to support design optimization that minimizes unnecessary exposures while maintaining training effectiveness through strategic positioning of firing positions and observer locations; and (e) supporting clinical decisions by offering healthcare providers a mechanism for reconstructing probable exposure scenarios based on training records, enhancing clinical assessment through objective exposure estimates that inform diagnostic considerations, treatment planning, and patient education regarding future exposure risk reduction.

Beyond real-time applications, the BOP Tool serves as a powerful retrospective analysis platform for refining training methodologies. Following training exercises, based on a comparison between the wearable sensor recording vs predictions, investigators can reconstruct blast exposure environments to identify potential training and safety protocol improvements. This capability transforms incident analysis from reactive reporting to proactive protocol enhancement. By modeling actual training configurations that resulted in concerning exposure levels or safety incidents, training developers can systematically identify optimal firing positions, observer locations, and equipment arrangements. The tool's ability to rapidly test multiple configuration scenarios accelerates the iterative improvement of training protocols and contributes to evidence-based safety standard development.

The current underlying modeling engine to the BOP Tool utilizes a semi-empirical spherical blast propagation model to simulate exposure scenarios across various weapon systems. While this foundational approach offers reliable predictions for symmetric blast events and serves as the basis for current safety assessments and training protocols, several development opportunities exist to enhance the tool's capabilities and accessibility. The incorporation of directionality [16], [17], [18], [19] effects into overpressure models represents a critical advancement opportunity for future iterations. The current model assumes uniform blast propagation; however, real-world scenarios often involve directional charges, terrain interference, and structural reflections that can significantly alter exposure patterns. Developing these enhanced models necessitates improvements in the modeling engine and comprehensive controlled datasets that can reliably quantify directional blast characteristics across different weapon systems and environmental conditions.

Similarly, current BOP calculations treat personal protective equipment (PPE) and clothing as rigid structures with static protective values, but future iterations could incorporate dynamic modeling capabilities that account for variable protective effects of different armor configurations, clothing material properties and layering effects, and the integration of emerging protective technologies.

A platform-agnostic BOP mobile application is in development and represents a transformative advancement in making blast overpressure assessment accessible at the point of training. Traditional computational approaches have created significant barriers through their requirements for specialized software and technical expertise, limiting real-time decision-making capabilities. A mobile BOP Tool addresses these limitations by placing predictive capabilities directly in the hands of range safety officers, training commanders, and even individual service members through an intuitive interface that allows rapid scenario modeling, parameter adjustment, and visualization of exposure risks without extensive technical background requirements. This increased accessibility to the blast exposure prediction tools will enable more informed safety decisions across all levels of training operations.

The team has also recommended Department of Defense adoption of the BOP Tool for integration into the Range Manager Toolkit (RMTK) to support the planning of range exercises and minimize unnecessary blast overpressure exposure by allowing users to examine predicted exposure based on personnel locations and postures. The RMTK suite of tools is used by range safety officials and instructors to support the planning of safe range exercises and is designed to modernize range operations and safety tasks through automated, digitally implemented range policies and minimum standards. This integration would enhance planning capabilities, minimize unnecessary blast exposure by optimizing personnel positioning and equipment use, and support automated implementation of range policies and safety standards.

Future development could also explore real-time video integration capabilities for continuous blast overpressure monitoring. Leveraging existing capabilities, this advancement would enable live assessment of blast events during training exercises, provide immediate feedback on actual versus predicted exposure levels, enhance post-event analysis and model validation, and integrate with existing range monitoring infrastructure [20]. Successful implementation of these enhancements requires collaborative data collection efforts to support advanced modeling, user interface design that maintains accessibility while expanding functionality, integration protocols that ensure compatibility with existing Department of Defense systems, and validation studies to confirm enhanced model accuracy and reliability.

Summary/Conclusions

The BOP tool is a user-friendly, easy to access, interactive computer application for assessing and predicting blast overpressure exposure during firing events for different weapon systems. The tool provides overpressure exposure metrics, for different weapon systems to directly inform service members. The scenarios are customizable which can inform decisions related to range modernization, training protocols, and range safety based on documented parameters. Furthermore, the BOP Tool enables service members directly involved in blast-related events to be educated and informed about methods they can implement to reduce their blast dose and associated health risks. The tool can also assist in estimation of weapon-specific blast exposure to support post hoc analysis of associated pathophysiology and drive innovative strategies to improve overall health and performance. The BOP Tool narrows the gap between scientific understanding of blast events and operational protocols intended to protect service members in military training environments. The BOP Tool addresses documented deficiencies in current blast exposure management by providing service members and their leadership with a readily accessible, usable, and actionable guide that supports better awareness of overpressure exposure in blast situations.

References

[1] C. R. LaValle *et al.*, "Neurocognitive Performance Deficits Related to Immediate and Acute Blast Overpressure Exposure," *Front. Neurol.*, vol. 10, 2019, Accessed: Nov. 29, 2023. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fneur.2019.00949

[2] G. H. Kamimori, C. R. LaValle, S. E. Eonta, W. Carr, C. Tate, and K. K. W. Wang, "Longitudinal Investigation of Neurotrauma Serum Biomarkers, Behavioral Characterization, and Brain Imaging in Soldiers Following Repeated Low-Level Blast Exposure (New Zealand Breacher Study)," *Mil. Med.*, vol. 183, no. suppl_1, pp. 28–33, Mar. 2018, doi: 10.1093/milmed/usx186.

[3] M. Skotak, C. LaValle, A. Misistia, M. J. Egnoto, N. Chandra, and G. Kamimori, "Occupational Blast Wave Exposure During Multiday 0.50 Caliber Rifle Course," *Front. Neurol.*, vol. 10, 2019, Accessed: Nov. 28, 2023. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fneur.2019.00797

[4] G. H. Kamimori, L. A. Reilly, C. R. LaValle, and U. B. Olaghere Da Silva, "Occupational overpressure exposure of breachers and military personnel," *Shock Waves*, vol. 27, pp. 837–847, Nov. 2017, doi: 10.1007/s00193-017-0738-4.

[5] J.-P. Dionne, J. Levine, and A. Makris, "Blast injury model estimates from multiple overpressure measurement locations on a single person-borne device," *Shock Waves*, vol. 34, no. 4, pp. 339–356, Aug. 2024, doi: 10.1007/s00193-024-01166-5.

[6] A. Misistia, M. Skotak, A. Cardenas, E. Alay, N. Chandra, and G. H. Kamimori, "Sensor orientation and other factors which increase the blast overpressure reporting errors," *PLOS ONE*, vol. 15, no. 10, p. e0240262, Oct. 2020, doi: 10.1371/journal.pone.0240262.

[7] S. Wiri *et al.*, "Significant Mitigation of Blast Overpressure Exposure During Training by Adjustment of Body Position as Demonstrated With Field Data," *Mil. Med.*, vol. 189, 2024.

[8] R. K. Gupta *et al.*, "Blast Overpressure (BOP) Tool for monitoring blast exposure of Service members during training with heavy weapons," presented at the (2025) NATO Human Factors and Medicine (HFM)-371 Blast Exposure Monitoring in Military Training and Operations., Pending.

[9] R. Spencer *et al.*, "NDAA Sec 734 Line of Inquiry Weapon Systems: Overview and Blast Overpressure Tool - A Module for Human Body Blast Wave Exposure for Safer Weapons Training.", Accepted Military Medicine 2023," *Mil. Med.*, vol. Accepted, 2023.

[10] A. Przekwas *et al.*, "Fast-Running Tools for Personalized Monitoring of Blast Exposure in Military Training and Operations," *Mil. Med.*, vol. 186, no. Suppl 1, pp. 529–536, Jan. 2021, doi: 10.1093/milmed/usaa341.

[11] A. Przekwas *et al.*, "System and method for model-based calculation of blast exposure," US11145418B2, Oct. 12, 2021 Accessed: Feb. 02, 2025. [Online]. Available: https://patents.google.com/patent/US11145418B2/en

[12] S. Wiri *et al.*, "Dynamic monitoring of service members to quantify blast exposure levels during combat training using BlackBox Biometrics Blast Gauges: explosive breaching, shoulder-fired weapons, artillery, mortars, and 0.50 caliber guns," *Front. Neurol.*, vol. 14, p. 1175671, May 2023, doi: 10.3389/fneur.2023.1175671.

[13] H. T. Garimella *et al.*, "Generation of Warfighter Avatars from Weapon Training Scene Images for Blast Exposure Simulations," *J. Vis. Exp. JoVE*, no. 214, Dec. 2024, doi: 10.3791/66575.

[14] J. V. Rosenfeld, A. C. McFarlane, P. Bragge, R. A. Armonda, J. B. Grimes, and G. S. Ling, "Blast-related traumatic brain injury," *Lancet Neurol.*, vol. 12, no. 9, pp. 882–893, Sep. 2013, doi: 10.1016/S1474-4422(13)70161-3.

[15] G. A. Elder and A. Cristian, "Blast-related mild traumatic brain injury: mechanisms of injury and impact on clinical care," *Mt. Sinai J. Med. N. Y.*, vol. 76, no. 2, pp. 111–118, Apr. 2009, doi: 10.1002/msj.20098.

[16] R. A. Carson and O. Sahni, "Scaling Laws for the Peak Overpressure of a Cannon Blast," *J. Fluids Eng.*, vol. 139, no. 021204, Nov. 2016, doi: 10.1115/1.4034639.

[17] K. S. Fansler, "Description of Gun Muzzle Blast by Modified Ideal Scaling Models," Art. no. ARLTR1434, Sep. 1997, Accessed: Sep. 02, 2025. [Online]. Available: https://apps.dtic.mil/sti/html/tr/ADA330051/

[18] L. L. Pater and J. W. Shea, "Techniques for Reducing Gun Blast Noise Levels: An Experimental Study," Art. no. NSWCTR81120, Apr. 1981, Accessed: Sep. 02, 2025. [Online]. Available: https://apps.dtic.mil/sti/html/tr/ADA112290/

[19] K. S. Fansler, W. P. Thompson, J. S. Carnahan, and B. J. Patton, "A Parametric Investigation of Muzzle Blast," Art. no. ARLTR227, Accessed: Sep. 02, 2025. [Online]. Available: https://apps.dtic.mil/sti/html/tr/ADA270535/

[20] E. Brokaw *et al.*, "Evaluating computer vision and augmented reality guidance to optimize weapon training safety and performance.," presented at the Military Health System Research Symposium (MHSRS), Aug. 2025.

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Definitions/Abbreviations

BIRCO	Blast Injury Research Coordinating Office
BOP	Blast Overpressure
CoBi	Computational Biology
CONQUER	Combat and Training Queryable Exposure/Event Repository Project (Study)
DoD	Department of Defense
GUI	Graphical user interface
Pmax	Maximum Pressure
PPE	personal protective equipment
RMTK	Range Managers Toolkit
USAMRDC	US Army Medical Research and Development Command
WRAIR	Walter Reed Army Institute of Research
NDAA	National Defense Authorization Act