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Physiological Signatures in Blast Overpressure: Implications for Wearable Monitoring

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ABSTRACT

Blast overpressure (BOP) has been associated with injury in Service Members for more than a century, with early accounts dating to World War I descriptions of "shell shock." While some effects are immediately visible, many are neurological, physiological, or functional and may present as delayed or cumulative "invisible injuries," complicating detection and monitoring in training and operational environments involving repeated low-level exposure. Although physiological measures may reflect blast-related effects, no widely fielded wearable system currently integrates biosignals with BOP exposure data. This review examines physiological, neurological, and functional biosignals associated with blast exposure, with emphasis on signals sensitive to early performance or physiological degradation rather than clinical diagnosis. Human studies identify several biosignal domains with demonstrated sensitivity, including cardiovascular and respiratory measures, oculomotor activity, gait and balance, and behavioral performance. Eye tracking detects changes in oculomotor features associated with cumulative exposure, while body-worn accelerometry captures changes in gait and balance following exposure periods. Multimodal approaches that integrate eye movement and body-based measures demonstrate improved sensitivity compared to single-modality approaches. Overall, findings indicate that different biosignal domains capture complementary aspects of blast-related effects and support the use of multimodal approaches for detection. Future work may focus on real-time monitoring strategies to support earlier identification of performance and physiological changes in populations with occupational blast exposure.

Keywords: Blast overpressure, Traumatic brain injury, Biosignal monitoring, Multimodal fusion, Real-time detection, Military health, Eye tracking, Gait and balance, Wearable sensors, Cardiovascular, Respiratory

INTRODUCTION

Blast overpressure (BOP) exposure in Service Members has been studied for more than a century, with early experimental work documenting blast-related lung injury and wartime accounts describing "shell shock" during World War I (Zuckerman, 1940; Taber et al., 2006; Sayer, 2012). BOP can produce a wide range of physiological, neurological, and functional effects, many of which are not immediately visible and instead present as "invisible injuries." These effects can emerge acutely or develop over time, particularly

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in the context of repeated low-level blast exposure common in training environments such as breaching and weapons training (Belding et al., 2021; Martindale et al., 2025).

Although prior work has focused on traumatic brain injury (TBI), increasing evidence demonstrates that BOP exposure affects multiple systems, including autonomic, respiratory, vestibular, and sensorimotor pathways (Taber et al., 2006; Sandlin et al., 2018). Notably, these disruptions can occur even without detectable structural injury on conventional imaging, complicating diagnosis and attribution (Mac Donald et al., 2011; Hoge et al., 2008). In response, blast overpressure has been formally prioritized across the Department of Defense as part of broader brain health initiatives (Department of Defense, 2022, 2023).

Accordingly, the literature reflects growing interest in identifying biosignals sensitive to BOP, particularly those capable of detecting early physiological or functional degradation prior to clinical diagnosis. This review synthesizes evidence across human and animal studies to identify candidate biosignals sensitive to BOP, with a focus on cardiovascular and respiratory measures, eye tracking, gait and balance, and behavioral performance.

Real-Time Multimodal Monitoring

These findings point to the need for approaches that capture physiological responses more closely aligned in time with blast exposure. Much of the foundational work on BOP effects has been conducted in controlled animal models, where continuous and high-resolution monitoring is feasible (Sandlin et al., 2018). In contrast, most human studies rely on post-exposure assessments or exposure-period aggregation, limiting the ability to attribute physiological responses to individual blast events (Williamson et al., 2022). Building on this work, these findings indicate a need to link acute physiological responses with longer-term effects to support earlier detection of performance and readiness deficits. Real-time biosignal monitoring is not intended to provide a definitive diagnosis, but rather to serve as an early indicator of impairment that may warrant intervention, rest, or further assessment. This approach may help address the limitations of delayed symptom reporting and clinical presentation (Hoge et al., 2008; Mac Donald et al., 2011).

Emerging research has focused on repeated low-level blast exposure and its cumulative effects. A growing body of evidence suggests that repeated low-level blast exposure is associated with cumulative physiological and functional effects over time, even in the absence of clinically diagnosed traumatic brain injury or overt structural abnormalities on conventional imaging (Hoge et al., 2008; Taber et al., 2006; Belding et al., 2021).

Breacher populations provide a clear example of this pattern. Studies suggest that cumulative exposure, rather than single high-magnitude events, is associated with subtle but measurable physiological, neurological, and biological changes (Rao et al., 2023; Liu et al., 2024; Williamson et al., 2022). However, because much of this work focuses on specific training or occupational groups, its applicability to broader military contexts may be limited.

Cumulative Effects of Repeated Blast Exposure

Evidence indicates that repeated low-level blast exposure is associated with cumulative physiological and functional effects, even in the absence of clinically diagnosed TBI (Hoge et al., 2008; Taber et al., 2006). Studies of military training populations demonstrate that these effects may manifest as gradual performance degradation rather than discrete injury events, including changes in reaction time, cognitive performance, and other neurobehavioral measures (Carr et al., 2016; Belding et al., 2021; Rao et al., 2023; Williamson et al., 2022).

Longitudinal studies of Veterans further suggest that blast-related symptoms may persist or worsen over time, affecting cognitive, emotional, and physical functioning (Mac Donald et al., 2017; Martindale et al., 2025). These findings underscore the importance of biosignals capable of detecting subtle, cumulative changes associated with repeated exposure, which may call for early clinical intervention to mitigate symptoms.

Temporal Characteristics of Biosignals

A key distinction across biosignal domains is timing relative to blast exposure. Cardiovascular and respiratory responses have been successfully measured concurrently with blast exposure in controlled animal models (Sandlin et al., 2018). In contrast, most human studies rely on post-exposure assessments or exposure-period aggregation (Williamson et al., 2022; Skotak et al., 2019).

METHODS

A literature review was conducted using PubMed, IEEE Xplore, and Google Scholar to identify studies examining physiological and functional responses to blast overpressure exposure. Search terms included combinations of the following: “blast overpressure”, “blast exposure”, “biosignals”, “physiological monitoring”, “eye tracking”, “gait”, “balance”, “wearables”, and “heart rate variability”.

Studies were included if they:

- Examined physiological or functional responses to blast exposure
- Included human or animal models
- Reported objective biosignal or performance-based measures

Studies were excluded if they:

- Lacked physiological outcomes
- Focused solely on modeling or structural injury
- Examined only long-term clinical outcomes without biosignal measurement

21 studies were reviewed, with emphasis on biosignal sensitivity, temporal characteristics, and operational relevance. Biosignals were grouped into domains to enable comparison across measurement approaches. Based on these selection criteria, this review was not conducted as a formal systematic review but instead provides a synthesis of key findings across relevant studies.

No strict publication date limitation was applied. Studies were selected based on relevance with inclusion of foundational studies to provide context alongside more recent work.

REVIEWS OF BIOSIGNALS IN BLAST EXPOSURE RESEARCH

Key characteristics of leading biosignals in BOP studies are summarized in Table 1, including sensitivity to low-level BOP, measurement timing, and operational feasibility across domains. Variability in blast exposure characterization across studies complicates direct comparison and interpretation of findings. Sensitivity refers to a biosignal's ability to detect physiological or functional change following blast exposure, particularly at low-level ranges relevant to training environments, and wearability reflects feasibility based on sensor maturity, portability, and suitability for operational use. These ratings are qualitative and reflect general trends across reviewed human studies rather than precise thresholds.

Table 1: Biosignal domains sensitive to blast overpressure in humans and their measurement characteristics and wearable feasibility.

Biosignal Domain	Example Measures	Sensitivity to Low-Level BOP	Measurement Timing	Observed Effects	Wearability
Cardiovascular	Heart Rate (HR), Heart Rate Variability (HRV)	Moderate	Concurrent (animal); post-exposure (human)	Transient autonomic changes (HR/ Blood Pressure (BP), reduced HRV)	High (mature)
Respiratory	Respiratory rate, apnea	Low	Concurrent (animal); post-exposure (human)	Respiratory pattern changes	High (mature)
Oculomotor	Blink rate, saccades, pupil response	Moderate	Near concurrent, often requires post-analysis	Changes in blink rate, saccades, coordination	Moderate (head-mounted)
Gait & Balance	Postural sway, gait stability	Moderate	Post-exposure	Changes in stability and balance	High (IMU-based)
Behavioral Performance	Reaction time, cognitive tasks	Moderate-High	Post/task-based	Changes in reaction time, attention, and cognition	Moderate (task-based)
Biochemical	Blood markers	Moderate	Delayed	Systemic responses (e.g., inflammation)	Low-Moderate (limited real-time use)

Collectively, these patterns show that different biosignal domains capture complementary aspects of blast-related physiological and functional disruption, supporting integrated approaches for detection. Across domains, changes are often detectable following blast exposure but differ in temporal resolution, sensitivity, and feasibility for wearable implementation. At lower overpressure levels typical of training exposures (e.g., breacher and weapons training), performance-based measures often show the most consistent sensitivity in human studies. In contrast, autonomic signals reflect more subtle effects, and other domains are more reliably affected at higher or repeated exposures (Carr et al., 2016; Woodall et al., 2023; Kemmerer et al., 2026). These effects have been observed in low-level blast exposure environments, including sub-psi ranges reported during training (Kemmerer et al., 2026). Cardiovascular and respiratory signals reflect autonomic responses, while oculomotor, gait, and performance-based measures capture functional impairments relevant to operational tasks. Together, these differences reinforce the complementary nature of these domains and support integrated, multimodal sensing approaches for detecting blast-related effects. This approach is consistent with broader traumatic brain injury monitoring research, where multimodal passive sensing and sensor fusion have been explored to improve detection compared with single-signal approaches (Asani et al., 2023).

Cardiovascular and Respiratory Measures

Cardiovascular and respiratory biosignals are key indicators of autonomic nervous system disruption following blast exposure. In controlled animal models, blast exposure has been shown to produce transient decreases in heart rate and blood pressure, along with increases in respiratory rate and, at higher exposure levels, apnea and mortality (Sandlin et al., 2018). These responses are mediated in part through vagal pathways, as evidenced by mitigated physiological effects when the vagus nerve is severed (Sandlin et al., 2018). Findings from animal models provide insight into physiological mechanisms but may not fully translate to human operational contexts.

In human populations, cardiovascular responses are typically assessed using heart rate (HR) and heart rate variability (HRV), which reflect autonomic regulation. However, these measures are generally evaluated in post-exposure and interpreted alongside exposure history and self-reported symptoms rather than as event-level indicators (Hines et al., 2022; Therkorn et al., 2022). Respiratory outcomes are similarly assessed through pulmonary function testing or symptom reporting, which capture longer-term effects rather than acute responses (Hines et al., 2022).

In sum, cardiovascular biosignals are sensitive to blast exposure, while respiratory findings are more variable across studies. Together, these signals represent core indicators of autonomic disruption but remain limited by the lack of concurrent, event-level measurement in human studies.

Eye Tracking (Oculomotor Measures)

Eye tracking measures provide sensitive indicators of neurological and cognitive function, particularly in relation to attention, processing speed, and sensorimotor integration. Studies using electrooculography (EOG) in military training environments have demonstrated changes in blink rate, saccadic dynamics, and other oculomotor features associated with cumulative blast exposure (Rao et al., 2023).

These measures are notable in that they can be collected in close temporal proximity to blast exposure and reflect subtle neurological and functional changes not captured through conventional clinical assessments. Additional studies have reported changes in pupillary response, reaction time, and cognitive performance associated with repeated low-level blast exposure, further supporting oculomotor and performance-based measures as sensitive indicators of functional degradation (Woodall et al., 2023). Emerging work also shows that combined eye and head movement dynamics can distinguish individuals with blast-induced mild traumatic brain injury from controls, capturing disruptions in sensorimotor coordination (Popov et al., 2026). Overall, eye tracking represents a sensitive behavioral biosignal for detecting blast-related effects in the short-term, particularly in the context of repeated exposure.

Gait and Balance

Gait and balance measures reflect integrated function across vestibular, motor, and cognitive systems and are directly relevant to operational performance. Blast exposure has been associated with impairments in postural stability, gait coordination, and balance, consistent with disruption of vestibular and sensorimotor pathways (Taber et al., 2006; Sandlin et al., 2018).

Studies using body-worn accelerometry have demonstrated that gait and balance metrics can detect functional changes following periods of blast exposure, even in the absence of overt clinical injury (Williamson et al., 2022; Kemmerer et al., 2026). These changes are typically observed post-exposure, rather than during the blast event itself.

The sensitivity of gait and balance measures to blast-related effects highlights their value as functional indicators of performance decline. However, their reliance on post-exposure assessment limits their ability to capture acute physiological responses.

Behavioral and Performance Measures

Behavioral metrics, including reaction time and cognitive task performance, provide additional indicators of blast-related effects. Studies using task-based paradigms have demonstrated impairments in attention, processing speed, and cognitive performance following repeated low-level blast exposure (Kemmerer et al., 2026). Complementary evidence suggests that blast-related effects may occur even in the absence of clinically diagnosed TBI (Woodall et al., 2023).

These signals reflect integrated neurological function and are highly sensitive to subclinical effects. However, they are typically task-based and collected post-exposure, limiting their applicability for continuous or event-level monitoring. As summarized in Table 1, biosignal sensitivity, measurement timing, and response patterns vary across domains, reinforcing the need for multimodal approaches.

Biochemical

Biochemical markers, including circulatory protein-based biomarkers, provide insight into systemic physiological responses to blast exposure, particularly those related to inflammation, blood–brain barrier disruption, and cellular injury processes (Liu et al., 2024). Preclinical animal models further demonstrate that repeated blast exposure induces neuroinflammatory and cellular injury responses associated with persistent neuropathological changes (Ravula et al., 2022). Together, these approaches capture underlying biological changes that may not be detectable through functional or performance-based assessments alone. Studies in military breacher populations have demonstrated blast-related alterations in microbiota and biomarker profiles, with samples collected pre-blast, one-hour post-blast, and sixteen hours post-blast alongside self-reported exposure histories and mTBI symptoms (Liu et al., 2024). These findings contribute to understanding systemic responses to repeated low-level blast exposure in operationally relevant settings.

However, biomarker-based assessments are typically collected at delayed time points and rely on retrospective exposure histories and symptom self-report in human studies. As a result, they are not suitable for real-time or wearable monitoring and have limited utility for immediate performance assessment in operational contexts.

These limitations highlight the need for approaches that integrate multimodal biosignals with blast exposure data to enable event-level, time-resolved interpretation of physiological responses.

A key distinction across biosignal domains is timing relative to blast exposure. Cardiovascular and respiratory responses have been successfully measured concurrently with blast exposure in controlled animal models (Sandlin et al., 2018). In contrast, most human studies rely on post-exposure assessments or aggregated exposure metrics, limiting the ability to attribute physiological responses to individual blast events (Rowland et al., 2024). This limitation reflects both ethical constraints and practical challenges in capturing precise, event-level data in operational environments. This gap represents a key barrier to measuring and interpreting time-resolved physiological responses in humans.

Limitations of Current Literature

Several limitations are consistently identified across the literature, including:

- Reliance on post-exposure measurements
- Limited event-level data in human studies

- Variability in blast exposure characterization
- Confounding factors inherent to training environments

These challenges complicate interpretation, limit the ability to establish consistent exposure-response relationships, and hinder comparisons across studies due to inconsistent exposure characterization (Rowland et al., 2024). These challenges complicate interpretation and hinder comparisons across studies due to inconsistent exposure characterization (Skotak et al., 2019; Belding et al., 2021; Williamson et al., 2022) and confounding factors inherent to training environments, including physical exertion and environmental conditions (Rowland et al., 2024; Skotak et al., 2019; Belding et al., 2021; Williamson et al., 2022) and confounding factors inherent to training environments, including physical exertion and environmental conditions (Williamson et al., 2022; Rao et al., 2023).

These limitations emphasize the need for standardized approaches that account for temporal alignment and cross-domain integration when interpreting biosignal data, particularly in training environments where measurement can be incorporated without introducing additional exposure risk. While individual biosignals demonstrate sensitivity to blast exposure, their utility depends on the ability to reliably relate observed responses to specific exposure events within operational environments.

CONCLUSION

The reviewed literature shows that blast overpressure affects physiological and functional systems, with measurable effects across cardiovascular, respiratory, oculomotor, and motor and cognitive domains. Cardiovascular and eye tracking measures demonstrate sensitivity to blast exposure, while gait, balance, and performance measures capture functionally relevant outcomes.

However, most human studies rely on delayed post-exposure assessments, limiting the ability to reliably relate physiological responses to specific blast events. Addressing this limitation will require improved temporal alignment between exposure and biosignal data, along with approaches that integrate multiple biosignal domains.

Overall, the evidence supports the identification of multisystem biosignature patterns associated with blast exposure and reinforces the need for integrated, multimodal wearable approaches to enable early identification of physiological and performance changes. Moving forward, efforts should focus on developing and evaluating systems that synchronize blast overpressure exposure data with physiological and functional biosignals in operational environments. Such approaches would enable time-resolved assessment of individual blast events, supporting earlier identification of performance degradation and informing decisions related to training, readiness, and recovery. Bridging blast exposure data with multimodal physiological sensing is a critical step toward improving early detection of blast-related performance and health effects in real-world environments.

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