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Auditory and Stress Effects of Long-Range Acoustic Devices in Hybrid Warfare: A Narrative Review

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Abstract

The Long-Range Acoustic Device (LRAD) is increasingly employed in hybrid warfare due to its unique capability to generate highly directional sound waves. The physiological effects of LRAD exposure raise significant concerns, as such exposure can result in acute hearing damage, disequilibrium, and pronounced psychological stress. Sound levels produced by LRAD systems may exceed 160 dB, posing a substantial risk to auditory function and often causing severe discomfort or pain. Prolonged exposure has been associated with an elevated incidence of Post-Traumatic Stress Disorder (PTSD), with affected individuals experiencing flashbacks and heightened auditory sensitivity. Furthermore, the sensory overload and disorientation induced by LRAD emissions can impair decision-making capacity and situational awareness, thereby complicating crisis response. In conclusion, although LRAD serves a critical tactical function in contemporary hybrid conflicts, the well-documented risks of both acute and long-term psychological and physiological harm to combatants and non-combatants necessitate the urgent development of comprehensive operational guidelines and robust ethical frameworks. Such measures are essential to ensure that its deployment aligns with human rights standards and minimizes long-term collateral harm.

Keywords: Long-Range Acoustic Device, Hybrid warfare, Physiological effects

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Introduction

Hybrid warfare constitutes an evolving paradigm of conflict that integrates conventional military operations with asymmetric and unconventional tactics to achieve strategic objectives. As advanced technologies become increasingly embedded within this multidimensional battlespace, innovative systems such as the Long-Range Acoustic Device (LRAD) have emerged as versatile tools capable of fulfilling both communicative and deterrent functions. Originally developed for maritime security and crowd control, LRAD systems are capable of projecting highly directional, high-intensity acoustic signals over distances exceeding one mile. This capability enables commanders to transmit warnings or instructions from a secure standoff distance while exerting a non-lethal influence on targeted individuals or groups (1).

Within hybrid warfare environments, where control over information and perception is often as decisive as kinetic force, LRAD offers distinct operational advantages. It facilitates real-time communication and enables the psychological modulation of adversaries or civilian crowds, particularly in situations where conventional communication channels are compromised

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or ineffective. This dual capacity to maintain operational distance while influencing behavior reflects a broader strategic principle, namely the reduction of direct physical engagement while preserving situational dominance (2).

Despite these advantages, exposure to LRAD presents considerable risks. High-decibel acoustic output, often exceeding established safety thresholds, can result in temporary or permanent hearing loss, tinnitus, and otalgia. Even sustained exposure at moderate intensities may damage cochlear hair cells, leading to irreversible auditory impairment (3). Moreover, intense acoustic stimulation can provoke a range of neurological responses, including migraines, vertigo, and, in susceptible individuals, seizure activity (4). The associated physiological stress response, characterized by elevated cortisol levels, may further contribute to long-term cognitive and emotional disturbances, including anxiety and memory impairment (5).

Beyond these physiological and neurological effects, the psychological consequences of LRAD exposure represent an equally critical concern. The abrupt and overwhelming nature of its acoustic emissions can induce panic, fear, and confusion, thereby disrupting cognitive processing, decision-making, and situational awareness. When deliberately employed to disorient or demoralize, LRAD functions not only as a tactical instrument but also as a mechanism of psychological dominance, a concept that is central to hybrid warfare strategies (6).

However, the deployment of LRAD systems at the intersection of military necessity and civilian exposure raises significant ethical and legal challenges. Reports of auditory discomfort and distress have intensified debates surrounding proportionality, accountability, and the permissible scope of use, particularly in non-combat settings (7). The convergence of technological capability, ethical responsibility, and human health considerations underscores LRAD's dual role as both a strategic enabler and a subject of ongoing humanitarian scrutiny.

Accordingly, this review examines the multifaceted role of LRAD in hybrid warfare, with particular emphasis on its operational applications, physiological and psychological effects, and the pressing need for regulatory frameworks to ensure its responsible and ethical use.

Search Strategy and Databases

A systematic literature search was conducted across several major electronic databases, including PubMed, Web of Science, Scopus, PsycINFO, and Google Scholar. Search queries were carefully constructed to capture key concepts related to LRADs, acoustic weaponry, stress physiology, neurobiology, psychoacoustics, PTSD, anxiety disorders, and hybrid warfare. Representative keyword combinations included, but were not limited to, "LRAD," "Long Range Acoustic Device," "acoustic weapon," "sound weapon," "stress," "HPA axis," "amygdala," "PTSD," "anxiety disorder," "neurobiological effects," "auditory effects," "cognitive deficits," and "hybrid warfare."

In addition, the reference lists of relevant primary studies and review articles were manually screened to identify further pertinent publications.

Eligible studies were those that directly addressed the physiological, psychological, neurological, or auditory effects of high-intensity acoustic exposure, as well as stress responses and neurobiological mechanisms associated with trauma and anxiety, particularly in contexts relevant to LRAD or analogous technologies. Only studies published between 2010 and September 2025 were included, ensuring the integration of both foundational and contemporary research.

Hybrid Warfare

Hybrid warfare represents a complex and continually evolving form of conflict that transcends the conventional boundaries of traditional warfare. It involves the coordinated integration of conventional military capabilities with a diverse array of unconventional tactics, including cyber operations, disinformation campaigns, economic coercion, and the strategic exploitation of social and political vulnerabilities (8). This approach enables actors to achieve strategic objectives while remaining below the threshold that would typically provoke a conventional military response, thereby complicating attribution and limiting the likelihood of direct retaliation (9).

The strategic rationale underpinning hybrid warfare is frequently asymmetric in nature. Less powerful actors leverage these methods to challenge stronger adversaries by exploiting systemic vulnerabilities while simultaneously avoiding direct military confrontation (10). The proliferation of non-state actors, coupled with rapid technological advancements, has further intensified the complexity of hybrid warfare, facilitating the dissemination of propaganda, manipulation of information ecosystems, and disruption of critical infrastructure (11).

Cyber capabilities occupy a central role in modern hybrid warfare, enabling espionage, sabotage, and influence operations to be conducted across national boundaries without the physical deployment of forces. This erosion of the distinction between peace and conflict diminishes the effectiveness of traditional deterrence models and necessitates more sophisticated, multidimensional approaches to security and defense (12). Furthermore, a nuanced understanding of cultural, social, and political narratives is essential for countering the information warfare dimension of hybrid conflict, as disinformation campaigns frequently exploit pre-existing societal divisions (13).

In addition, economic instruments, including sanctions, trade manipulation, and control over strategic resources, constitute a critical component of hybrid strategies. Such measures can destabilize a target state's economic foundations and erode social cohesion, thereby fostering internal unrest and vulnerability (14). Effective responses to hybrid warfare require a coordinated, whole-of-government approach that integrates defense, intelligence, law enforcement, economic policy, and diplomatic engagement. Given its inherent complexity and adaptability, hybrid warfare demands continuous strategic innovation and institutional learning (15). This review seeks to provide a comprehensive analysis of the multidimensional nature of hybrid warfare in order to inform more effective and resilient defense strategies.

Non-Lethal Acoustic Weapons

Non-lethal acoustic weapons, also referred to as sonic or acoustic hailing devices, constitute a class of directed-energy systems designed to incapacitate or deter individuals through the controlled emission of sound waves. These technologies exploit the physiological effects of elevated sound pressure levels on the human auditory system and adjacent anatomical structures (16). Unlike conventional weaponry, their primary objective is not to inflict permanent physical injury but rather to induce a temporary, disorienting, and often painful sensory experience capable of disrupting behavior and facilitating crowd control (17). Such systems are deliberately engineered to produce frequencies and intensities that are irritating or debilitating rather than lethal, although the potential for harm under specific conditions remains a significant concern (18).

The scientific foundations of acoustic weapons are grounded in the physics of sound propagation and its interaction with biological tissues. Their effectiveness is contingent upon multiple parameters, including frequency, intensity, pulse duration, and the auditory sensitivity of the exposed population (19). Frequencies within both the infrasonic range, below 20 Hz, and the ultrasonic range, above 20 kHz, have been shown to elicit a spectrum of physiological responses, such as nausea, disorientation, and headaches. Nevertheless, frequencies within the audible range are more commonly employed due to their direct and immediate impact on human hearing. The Long-Range Acoustic Device (LRAD), for instance, utilizes highly focused and directional sound waves to deliver intense acoustic stimuli over considerable distances, thereby disrupting auditory processing and inducing discomfort (20).

The development and deployment of non-lethal acoustic weapons give rise to substantial ethical and operational challenges. Although these systems offer a potentially less destructive alternative to lethal force, the absence of standardized testing protocols and comprehensive regulatory frameworks introduces a heightened risk of unintended adverse outcomes (21). Documented health effects, including temporary or permanent hearing loss, tinnitus, and other auditory disturbances, underscore the need for rigorous safety considerations. Moreover, the potential misuse of such devices for coercive purposes, including torture or the suppression of freedom of expression, raises serious concerns regarding violations of fundamental human rights (22). Compounding these issues, the long-term health consequences of repeated or high-intensity exposure remain insufficiently understood, thereby necessitating further systematic and interdisciplinary investigation (23). Accordingly, the deployment of acoustic weapons must be governed by clearly defined operational guidelines and ethical standards to mitigate the risks of misuse and harm.

LRAD: Benefits, challenges, and ethical dilemmas

The Long-Range Acoustic Device (LRAD) represents an advanced technological system primarily employed for communication and deterrence across a range of operational contexts, including military engagements and civilian crowd management. By harnessing highly directional sound, LRAD systems are capable of projecting intelligible voice commands and deterrent tones over substantial distances, thereby offering distinct advantages in environments where conventional communication modalities may prove ineffective.

One of the principal advantages of LRAD systems lies in their capacity to enhance situational awareness. In complex and dynamic operational settings, particularly within military contexts, LRAD facilitates the clear transmission of commands without necessitating close physical proximity to potential threats (24). In parallel, the long-range projection of acoustic signals can disrupt adversarial behavior, thereby reinforcing operational control over contested environments (25).

In addition, LRAD systems function as a non-lethal alternative to traditional crowd-control measures. During instances of civil unrest or large-scale public gatherings, these devices can be used to broadcast warnings and dispersal orders, potentially reducing reliance on physical force and, consequently, minimizing the risk of injury (26). his application aligns with contemporary military and law enforcement doctrines that prioritize the reduction of collateral harm and the proportional use of force (27).

Notwithstanding these advantages, the deployment of LRAD systems is accompanied by several notable challenges. Foremost among these is the risk of auditory injury. Exposure to high-intensity directional sound can result in significant discomfort and, in some cases, irreversible hearing damage, thereby raising legitimate safety concerns (28). This risk underscores the necessity for stringent operational protocols to ensure that LRAD systems are deployed within established safety thresholds.

Furthermore, the operational effectiveness of LRAD systems may be diminished in acoustically complex environments. In urban settings or during high-intensity confrontations, ambient noise can interfere with sound propagation, thereby reducing the clarity and impact of transmitted signals (29). Under such conditions, reliance on LRAD alone may prove insufficient, necessitating the integration of complementary communication strategies.

The ethical implications associated with LRAD deployment are equally significant. The potential for misuse across diverse operational contexts introduces complex moral considerations. For example, the application of LRAD systems in crowd-control scenarios may inadvertently escalate tensions if affected individuals respond adversely to the discomfort induced by the device (30). Consequently, maintaining an appropriate balance between public order and the protection of individual rights remains a contentious and unresolved issue.

Moreover, the use of LRAD systems in civilian environments, particularly in the absence of robust oversight mechanisms, raises concerns regarding potential infringements on civil liberties. The possibility of arbitrary or disproportionate use against peaceful demonstrators or vulnerable populations highlights the urgent need for comprehensive regulatory frameworks governing their application in non-military contexts (31). In summary, while LRAD systems offer clear operational benefits in both military and civilian domains, their deployment is inherently associated with technical limitations, health risks, and ethical complexities. Ensuring their responsible use requires the establishment of rigorous operational standards, sustained ethical scrutiny, and adherence to international human rights principles. As these technologies continue to evolve, ongoing research and informed policy development will be essential to guide their appropriate and accountable application.

LRAD systems are increasingly integrated into hybrid warfare strategies for a range of non-lethal applications, including crowd control, perimeter security, and psychological operations, as summarized in Table 1. By emitting high-intensity, directional sound waves, these devices enable rapid deployment and broad area coverage, thereby enhancing operational flexibility (32). In urban environments, LRAD systems have demonstrated effectiveness in dispersing crowds; however, their use is accompanied by risks of auditory injury and ethical concerns (33). In maritime contexts, LRAD systems contribute to piracy deterrence, although environmental variables, such as wind and atmospheric conditions, may attenuate their effectiveness

Table 1. Applications and challenges of LRAD in hybrid warfare.

Application	Operational Scenario	Advantages	Challenges	Source
Crowd Control	Dispersing crowds in urban hybrid warfare settings (e.g., protests, riots)	Non-lethal, immediate effect, wide coverage (up to 3 km)	Risk of hearing damage, ethical concerns about civilian exposure	(32)
Perimeter Security	Protecting military bases or checkpoints from unauthorized intrusion	Long-range communication, deterrence without physical force	Limited effectiveness in noisy environments, high power consumption	(35)
Psychological Operations (PSYOPS)	Broadcasting messages to influence enemy or civilian behavior	Targeted audio delivery, psychological impact	Cultural and language barriers, potential for psychological distress	(34)
Maritime Operations	Deterring piracy or unauthorized vessels in naval hybrid warfare	Effective over water, long-range deterrence	Environmental factors (wind, waves), equipment maintenance	(36, 37)
Urban Combat	Disorienting adversaries in close-quarters combat scenarios	Rapid deployment, non-lethal incapacitation	Risk of collateral damage, difficulty targeting specific individuals	(33)

(34). Within psychological operations, LRAD systems can be employed for targeted messaging, although cultural and contextual factors may limit their impact.

Despite their versatility, several operational challenges persist, including physiological risks, particularly auditory and stress-related effects, as well as high energy requirements and maintenance constraints under field conditions. Table 1 provides a structured overview of these applications and associated limitations, underscoring the need for further empirical research to optimize the deployment of LRAD systems within hybrid warfare frameworks.

Physiological effects of LRAD

The most immediate incapacitating effects of LRAD exposure are mediated by direct mechanical overstimulation of the vestibular system pathway. Intense acoustic pressure, particularly from low-frequency components capable of penetrating cranial structures, may partially bypass conventional auditory processing and couple directly with the fluid-filled compartments of the inner ear. More specifically, this acoustic energy induces excessive displacement of the stereocilia within the otolith organs, namely the saccule and utricle, which are responsible for detecting linear acceleration and gravitational forces. Such aberrant mechanical stimulation of the vestibular apparatus generates conflicting afferent signals transmitted via the vestibular nerve to the cerebellum and brainstem. The resulting neural discordance manifests as pronounced spatial disorientation, vertigo, nausea, and impaired postural stability, findings that are consistent with the rapid incapacitation observed in exposed individuals (38). A distinct, non-auditory mechanism involves activation of the trigeminal nerve pathway, corresponding to cranial nerve V. High-intensity acoustic energy, even when not within the ultrasonic spectrum, can mechanically stimulate the sensitive peripheral endings of the trigeminal nerve, which innervates the facial and cranial regions. This mechanical or vibratory stimulation irritates afferent sensory fibers, initiating a cascade of neurochemical events, most notably the release of calcitonin gene-related peptide (CGRP), a key mediator in migraine pathophysiology (39). Consequently, LRAD exposure may acutely precipitate severe headaches or migraine episodes independently of cochlear injury. This mechanism also provides a plausible explanation for the persistence of cranial pain reported by some individuals well after the cessation of acoustic exposure.

Furthermore, the sudden, intense, and non-contingent nature of LRAD-generated sound activates the limbic system and associated autonomic response pathways. Auditory input is rapidly processed by the amygdala, the brain’s principal center for threat detection, thereby initiating an immediate fight-or-flight response (40). This process, in turn, engages the hypothalamic–pituitary–adrenal (HPA) axis, resulting in a surge of stress hormones, including adrenaline and cortisol (41). The ensuing state of acute hyperarousal compromises prefrontal cortical functions, including attention, working memory, and executive decision-making. When exposure is repeated or occurs within unpredictable, high-stress environments, these neurophysiological responses may contribute to the development of chronic anxiety disorders and post-traumatic stress disorder (PTSD) (42). Table 2 presents a comprehensive synthesis of these physiological mechanisms and outcomes, highlighting the urgent need for continued interdisciplinary research to elucidate their long-term consequences and to inform the development of effective mitigation strategies within the context of hybrid warfare.

Hearing Effects

One of the most immediate consequences of LRAD exposure is acute auditory injury. The extremely high sound pressure levels emitted by these devices can induce temporary or permanent threshold shifts in auditory sensitivity.

Table 2. Physiological Effects of LRADs in Hybrid Warfare.

Physiological Effect	Mechanism of Effect	Severity/Duration	Studied Population	Source
Hearing Loss or Damage	High-intensity sound waves (up to 150 dB) causing temporary or permanent threshold shift in auditory system	Temporary (hours to days) or permanent at prolonged exposure	Military personnel, civilians in urban settings	(38)
Stress and Anxiety	Activation of HPA axis due to intense auditory stimuli	Acute stress response, lasting minutes to hours	Military personnel, crowd control subjects	(43, 44)
Disorientation/ Balance Disruption	Acoustic pressure affecting vestibular system, leading to dizziness or loss of balance	Temporary (seconds to minutes)	Civilians, protesters in hybrid warfare scenarios	(42)
Pain and Discomfort	High-frequency sound causing pain in ears or head, triggering avoidance behavior	Immediate, subsiding after exposure cessation	Military trainees, riot control subjects	(45)
Psychological Distress	Prolonged exposure to LRAD inducing fear, panic, or psychological fatigue	Short-term (hours) to medium-term (days)	Civilians in conflict zones	(6, 46)

Individuals may experience sudden hearing loss or a sensation of aural fullness immediately following exposure, often accompanied by tinnitus, a persistent perception of ringing, buzzing, or hissing in the absence of external stimuli (47).

Tinnitus is among the most frequently reported sequelae of exposure to high-intensity sound. This condition is characterized by the perception of phantom auditory signals, which may vary in pitch and intensity. Repeated or sustained exposure to elevated sound levels can precipitate or exacerbate tinnitus, which, in turn, may lead to significant emotional distress, sleep disruption, and impaired concentration (48).

Accumulating evidence indicates that prolonged exposure to intense acoustic stimuli may result in irreversible hearing loss. Such impairment is primarily attributable to damage to the mechanosensory hair cells of the cochlea, which play a critical role in transducing sound vibrations into neural signals. Given the limited regenerative capacity of these cells, their destruction results in permanent auditory deficits that substantially compromise quality of life, particularly by impeding effective communication and social interaction (49).

In addition to direct auditory damage, LRAD exposure may adversely affect higher-order auditory processing. Affected individuals may exhibit deficits in sound localization and in the discrimination of complex auditory signals, thereby impairing communication and environmental awareness (50). These functional limitations can contribute to frustration, social withdrawal, and diminished interpersonal engagement.

The psychological ramifications of LRAD-induced auditory impairment are equally significant. The experience of hearing loss or persistent tinnitus is frequently associated with increased levels of anxiety and depression, as well as a diminished sense of self-efficacy. Such outcomes may arise from both the functional limitations imposed by auditory deficits and the anticipatory fear of recurrent exposure (51).

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Given these risks, the implementation of protective measures is imperative. The use of appropriate hearing protection, including earplugs and noise-attenuating or noise-canceling devices, can substantially reduce the likelihood and severity of auditory injury. In operational contexts where LRAD deployment is unavoidable, adherence to established safety protocols is essential to mitigate adverse auditory outcomes (52).

Neurological Effects

Among the most immediate neurological consequences of LRAD exposure is disorientation. Intense acoustic stimulation can overwhelm the vestibular system, which is integral to maintaining balance and spatial orientation. This disruption frequently manifests as dizziness, vertigo, and impaired postural control, thereby compromising the ability to stand or ambulate effectively (53). In certain cases, these symptoms are accompanied by nausea and vomiting, particularly following prolonged exposure or when individuals are situated in close proximity to the sound source.

Another commonly reported neurological effect is the induction of migraines or severe headaches. High-intensity acoustic energy can stimulate the trigeminal nerve, a key component of migraine pathophysiology, thereby precipitating acute headache episodes. This effect is especially pronounced in individuals with a predisposition to migraines or a history of chronic headache disorders (54). Notably, such symptoms may persist well beyond the period of exposure, significantly impairing functional capacity.

In more severe instances, LRAD exposure has been associated with seizure activity. Intense auditory stimulation may lower the seizure threshold in individuals with epilepsy or other neurological susceptibilities, thereby increasing the likelihood of seizure onset (55). This risk is particularly concerning in densely populated settings, where seizure events may precipitate secondary injuries or contribute to crowd panic. Even in individuals without a documented seizure history, acute neurological stress may, under certain conditions, provoke atypical neurological responses.

LRAD exposure may also induce transient cognitive impairment. The overwhelming sensory input associated with high-intensity sound can disrupt attentional processes, working memory, and executive function. Such impairments are especially problematic in operational environments, including military and law enforcement contexts, where rapid decision-making, coordination, and effective communication are critical (56). Under these conditions, affected individuals may experience difficulty processing instructions or executing complex tasks, thereby potentially compromising operational effectiveness.

In addition, the psychological stress associated with LRAD exposure may exert secondary neurological effects. Repeated or chronic exposure to intense acoustic stimuli can elevate circulating cortisol levels, reflecting sustained activation of the stress response system. Prolonged elevation of cortisol has been linked to detrimental effects on brain function, including impairments in memory consolidation, emotional regulation, and cognitive performance (57). These changes may contribute to enduring neurological sequelae, particularly among individuals subjected to repeated exposure in high-stress environments.

Furthermore, the pronounced startle response elicited by sudden, high-intensity sound has important neurological implications. Activation of the sympathetic nervous system triggers a cascade of physiological responses, including increased heart rate, heightened arousal, and the release of catecholamines. While adaptive in the short term, repeated activation may impose cumulative strain on the nervous system, potentially leading to fatigue, reduced resilience, and, over time, functional impairment (58).

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In summary, the neurological effects of LRAD exposure are multifaceted, encompassing acute disorientation, headache syndromes, seizure risk, and cognitive disruption. These findings underscore the necessity for cautious deployment, particularly in environments where vulnerable populations, including individuals with pre-existing neurological conditions, may be present.

Neurobiological Underpinnings of Stress Response to LRAD Exposure

Exposure to the distinctive auditory and vibratory characteristics of LRAD systems in hybrid warfare contexts can elicit profound stress responses that extend beyond immediate physiological reactions to encompass enduring neurobiological alterations. A comprehensive understanding of these mechanisms is essential for elucidating the full spectrum of psychological and neurological outcomes associated with such exposure. Central to this response are two interrelated systems: the hypothalamic–pituitary–adrenal (HPA) axis and processes of amygdalar sensitization.

The HPA axis constitutes the principal neuroendocrine pathway mediating the stress response. Upon the perception of a threat, the hypothalamus secretes corticotropin-releasing hormone, which stimulates the anterior pituitary gland to release adrenocorticotropic hormone. This hormone subsequently acts on the adrenal cortex to induce the secretion of glucocorticoids, primarily cortisol in humans (59). Cortisol plays a critical role in mobilizing metabolic resources and modulating immune function, thereby facilitating adaptation to acute stressors, as illustrated in Figure 1.

However, chronic or repeated activation of the HPA axis, as may occur under conditions of sustained or intermittent LRAD exposure, can result in significant dysregulation (60).

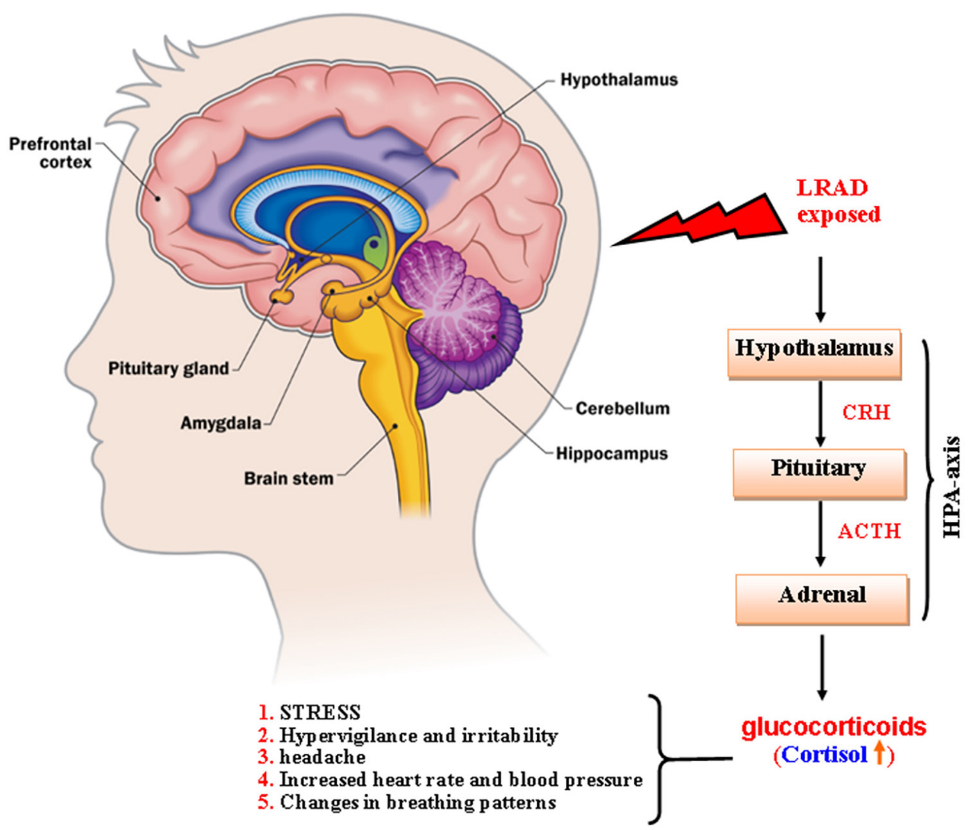

Figure 1. Schematic overview of the HPA-axis. LRADs activates the HPA-axis and thereby enhances the secretion of glucocorticoids from the adrenals.

Persistently elevated cortisol levels have been associated with structural and functional alterations in the hippocampus, including atrophy, which adversely affects memory formation and learning processes and contributes to executive dysfunction (61). Conversely, certain individuals, particularly those with chronic stress exposure or post-traumatic stress disorder, may exhibit attenuated cortisol responses, reflecting a complex and heterogeneous pattern of HPA axis dysregulation (62). Such neuroendocrine disturbances create a neurobiological milieu conducive to the development of anxiety disorders, depressive syndromes, and cognitive impairment, thereby highlighting the long-term consequences of repeated exposure to high-intensity acoustic stressors.

Amygdala Sensitization and Fear Circuitry

The amygdala, a central structure within the limbic system, plays a pivotal role in the processing of emotions, particularly fear and anxiety. Functioning as a neural threat detector, it rapidly evaluates potentially harmful stimuli and initiates appropriate defensive responses (63). In the context of LRAD exposure, the intense and non-habituating nature of the acoustic stimulus, often coupled with a perceived threat, can induce hyperactivation and subsequent sensitization of the amygdala (64).

Amygdalar sensitization is characterized by an exaggerated responsiveness to subsequent stressors, including those that would ordinarily be perceived as benign. This heightened reactivity contributes substantially to the core symptomatology of post-traumatic stress disorder, including exaggerated startle responses, hypervigilance, and intrusive recollections (65). Moreover, sustained amygdalar hyperactivity can disrupt its functional connectivity with the prefrontal cortex, a region essential for the top-down regulation of emotional responses. This disruption impairs fear extinction processes and compromises emotional regulation, thereby perpetuating maladaptive stress responses.

Interactions and Long-Term Psychoneurological Outcomes

Dysregulation of the hypothalamic–pituitary–adrenal axis and sensitization of the amygdala do not occur in isolation; rather, they are dynamically interconnected within a bidirectional feedback loop. Chronic elevations in cortisol may potentiate amygdalar reactivity, thereby amplifying threat perception, while persistent amygdalar hyperactivity can, in turn, sustain activation of the stress response system (66). This self-reinforcing cycle underlies the persistence of neurobiological alterations associated with chronic stress and contributes to the development and maintenance of severe psychiatric conditions.

In the context of LRAD exposure, these neurobiological changes may manifest as persistent deficits in auditory processing, anhedonia, sleep disturbances, and increased vulnerability to subsequent stressors (67). In the context of LRAD exposure, these neurobiological changes may manifest as persistent deficits in auditory processing, anhedonia, sleep disturbances, and increased vulnerability to subsequent stressors.

Psychological Effects

A growing body of evidence indicates that LRAD systems, owing to their high-intensity acoustic output, pose significant risks to psychological well-being. Exposure to high-decibel sound can induce acoustic stress, encompassing both physiological and psychological dimensions. Immediate responses may include tachycardia, elevated blood pressure, and heightened anxiety (68). When exposure is prolonged or repeated, these acute reactions may evolve into chronic health disturbances that adversely affect overall well-being.

In addition, LRAD exposure can elicit a pronounced startle reflex, an involuntary response to sudden and intense auditory stimuli. This reflex frequently gives rise to acute feelings of panic and confusion, particularly in already stressful environments (69). The unpredictability of such exposure further amplifies perceived vulnerability, thereby intensifying psychological distress.

Individuals subjected to LRAD exposure commonly report overwhelming sensations of fear and helplessness. These responses may arise from an impaired ability to interpret situational cues due to the intrusive and disorienting nature of the acoustic stimulus, compounded by the stress inherent in crowd-control scenarios (70). Such acute emotional experiences may leave enduring psychological imprints.

Moreover, high-intensity acoustic exposure can disrupt cognitive processes, including attention, concentration, and situational awareness. Empirical studies have demonstrated that exposure to elevated noise levels is associated with diminished performance on tasks requiring sustained cognitive effort (71). This impairment may critically undermine decision-making capacity under pressure, thereby exacerbating stress responses.

The highly directional sound produced by LRAD systems can also induce disorientation. Affected individuals may experience difficulty processing auditory information, resulting in confusion regarding their surroundings and reduced comprehension of critical instructions. This disorientation may escalate panic and destabilize crowd dynamics, thereby increasing the likelihood of chaotic outcomes (72).

With respect to long-term consequences, repeated exposure to LRAD has been associated with symptoms consistent with post-traumatic stress disorder. These may include intrusive recollections, heightened anxiety, and persistent hyperarousal (73). Such chronic psychological sequelae can substantially diminish quality of life.

Additionally, LRAD exposure may result in auditory disturbances, including tinnitus, characterized by persistent internal noise perception. This condition can further exacerbate psychological distress by imposing continuous sensory disruption that interferes with daily functioning (74).

Furthermore, the psychological burden associated with LRAD exposure may lead to social withdrawal. Individuals may avoid public spaces or social interactions due to anticipatory fear of re-exposure, thereby fostering isolation and compounding existing mental health challenges. This pattern may initiate a self-perpetuating cycle of distress and disengagement (75).

Clinical Incidences

Although epidemiological data specific to LRAD exposure remain limited, a substantial body of research on populations exposed to analogous acoustic traumas, including blast events and severe environmental noise, provides relevant clinical insight. Studies of combat veterans and trauma-exposed populations consistently report elevated prevalence rates of post-traumatic stress disorder and related anxiety disorders. Reported PTSD prevalence in war-exposed populations ranges from approximately 10% to 30%, with auditory triggers frequently exacerbating symptom severity (76, 77). Similarly, investigations involving individuals exposed to extreme noise events, such as industrial accidents or terrorist incidents, have documented acute stress reactions in up to 50% of affected populations, with a significant proportion progressing to chronic PTSD (78). Case reports further illustrate that exposure to intense warning signals or industrial alarms may condition the auditory stimulus itself as a traumatic cue, thereby reinforcing pathological fear responses (79).

The underlying neurobiological mechanisms, including chronic dysregulation of the hypothalamic–pituitary–adrenal axis and heightened amygdalar excitability, provide a robust explanatory framework for these clinical manifestations. These mechanisms contribute to hallmark PTSD symptoms, including re-experiencing, avoidance, negative alterations in cognition and mood, and dysregulation of arousal and reactivity (80). Epidemiological evidence also suggests that individuals exposed to chronic environmental noise or occupational stressors exhibit an increased risk of depressive disorders, with reported odds ratios exceeding 1.5 in certain populations (81). Observational reports from protest settings in which LRAD systems have been deployed further indicate the emergence of persistent depressive symptoms, including anhedonia and hopelessness, in the weeks following exposure (82).

Clinical data from military personnel exposed to impulse noise or sustained high-intensity acoustic environments demonstrate a high prevalence of chronic tinnitus, with reported rates ranging from 20% to 30% (83). These conditions are associated with substantial impairments in quality of life, including sleep disruption, reduced concentration, and exacerbation of anxiety and depressive symptoms (84). Diagnostic evaluation typically involves audiometric testing, comprehensive clinical history, and validated assessment instruments, such as the Tinnitus Handicap Inventory and the Hyperacusis Questionnaire (85).

Neuroanatomical alterations involving structures such as the hippocampus and prefrontal cortex, which are critical for memory and executive functioning, suggest the potential for long-term cognitive deficits (86). Longitudinal studies of individuals exposed to chronic stress, including caregivers and residents of high-noise environments, have demonstrated measurable impairments in working memory, attention, and executive functioning (87). Although these deficits are often subtle, their cumulative impact on daily functioning and overall quality of life is substantial.

The diagnosis of these conditions adheres to established clinical guidelines and requires comprehensive neuropsychiatric assessment, including structured diagnostic interviews, symptom inventories, audiological evaluations, and, where indicated, neuroimaging or neurophysiological testing. Given the relatively recent and expanding use of LRAD systems, precise incidence data directly attributable to such devices remain scarce. This limitation underscores a critical need for prospective epidemiological investigations and systematic clinical surveillance to delineate the long-term neuropsychiatric and auditory sequelae associated with LRAD exposure. Future research should prioritize rigorous methodological approaches to establish reliable incidence estimates, identify specific diagnostic markers, and inform the development of effective preventive and therapeutic strategies.

Ethical and Legal Analysis

Although LRADs are frequently classified as “non-lethal” or “less-lethal,” their demonstrated capacity to inflict severe pain, permanent hearing loss, vestibular dysfunction, and profound psychological trauma, as detailed in the preceding sections, raises substantial concerns regarding their compliance with established legal and ethical principles (88). For instance, the deployment of LRADs against civilian populations during protests may be construed as indiscriminate or disproportionate, particularly in contexts where the distinction between genuine threats and peaceful demonstrators is blurred (36). Moreover, if LRAD use results in injuries that constitute “unnecessary suffering” or “superfluous injury” beyond what is strictly required to achieve legitimate military objectives, such use may contravene obligations under International Humanitarian Law (IHL). Notably, the long-term psychological sequelae, including post-traumatic stress disorder (PTSD), may themselves be interpreted as forms of enduring harm falling within the scope of these prohibitions (89)<.

The intentional deployment of LRADs to inflict severe physical or psychological suffering for purposes such as coercion, intimidation, or punishment, particularly when such suffering is intense or prolonged, may rise to the level of torture or cruel, inhuman, or degrading treatment (90). Several human rights organizations have expressed concern that the auditory pain and disorientation induced by LRADs, when used offensively, exceed the threshold of permissible force and enter the domain of prohibited ill-treatment (91). The resultant psychological distress, panic, and sensory overload, especially under conditions of confinement or prolonged exposure, bear a striking resemblance to interrogation techniques that are universally condemned.

Compounding these concerns is the absence of specific, universally accepted international guidelines governing the development and deployment of “non-lethal” weapons, including LRADs, thereby creating a regulatory vacuum that exacerbates existing ethical and legal challenges (91). Although the World Health Organization (WHO) and various United Nations bodies have addressed the health implications of conventional weapons and environmental noise, comprehensive and targeted guidance for acoustic crowd-control devices remains insufficiently developed. This gap underscores the urgent need for a robust international framework to evaluate both the health impacts and ethical ramifications of such technologies (92). Ideally, such a framework would establish evidence-based exposure thresholds, mandate transparent impact assessments, and delineate clear operational parameters that prioritize public health and human rights over tactical expediency (93). Ultimately, the ethical and legal legitimacy of LRAD deployment hinges not solely on its technological design but, more critically, on its application in strict accordance with international humanitarian and human rights standards, with due regard for the dignity, integrity, and well-being of all individuals.

New insights and Future prospects

LRAD technology has emerged as a prominent component of modern hybrid warfare doctrine, offering distinct tactical advantages through its capacity for long-range communication and the projection of highly directional deterrent force. Nevertheless, when these operational benefits are weighed against the documented physiological and psychological consequences, a marked ethical and clinical imbalance becomes apparent. Although LRADs are routinely categorized as “non-lethal,” the evidence presented herein demonstrates that their capacity to generate acoustic outputs approaching 160 dB fundamentally challenges this classification. Indeed, acute and permanent auditory injury, as reported across multiple studies (94), should not be regarded merely as incidental but rather as a highly probable outcome under suboptimal exposure conditions.

Comparative evaluation with conventional crowd-control measures further underscores that LRADs constitute a high-risk modality with the potential to inflict irreversible harm. While not necessarily equivalent in lethality, their effects may be broader in scope, encompassing debilitating and often non-reversible sequelae such as chronic tinnitus and PTSD. Beyond direct physical injury, however, the most consequential dimension of LRAD deployment lies in its psychological impact. Functionally, the device operates as an instrument of psychological operations (PSYOPS), leveraging acoustic shock to induce panic and enforce compliance. The ensuing physiological stress responses, characterized by activation of the hypothalamic–pituitary–adrenal (HPA) axis and sustained elevations in cortisol, establish a neurobiological substrate for chronic conditions, including cognitive impairment and PTSD (94).

This raises a critical normative question: does the transient operational advantage conferred by LRAD deployment justify the risk of precipitating long-term neurocognitive and psychological morbidity among affected populations? From the perspective of IHL, particularly the principles of necessity and proportionality, the answer appears deeply problematic. The indiscriminate exposure of civilian populations to such extreme stressors undermines the foundational obligation to minimize collateral harm, especially in densely populated urban environments where acoustic propagation is inherently unpredictable and often amplified by ambient noise conditions (58).

Conclusion

In summary, this review systematically elucidates the multifaceted physiological and psychological effects associated with LRAD exposure, revealing a potential cascade of acute and chronic health consequences that extend well beyond auditory impairment. The cumulative evidence necessitates a fundamental reassessment of how LRAD technology is conceptualized and operationalized. Specifically, it calls for moving beyond the reductive "non-lethal" designation and acknowledging the technology's intrinsic capacity to produce widespread and enduring harm.

This reconceptualization underpins an urgent and actionable agenda spanning three interdependent domains: policy, clinical practice, and research. From a policy standpoint, there is a pressing need to establish rigorously defined, evidence-based exposure limits, coupled with mechanisms for independent ethical oversight of LRAD deployment. Clinically, practitioners should implement comprehensive screening and monitoring protocols, particularly for populations at elevated risk of exposure. From a research perspective, the current paucity of longitudinal data necessitates well-designed prospective studies aimed at elucidating the molecular, cellular, and systemic mechanisms underlying both immediate and delayed morbidity. Only through such an integrated, multidisciplinary approach can the use of LRADs be responsibly governed, or where necessary, restricted, in order to mitigate their impact on human health and uphold fundamental humanitarian principles.

Conflict of Interest

The authors declare no conflicts of interest.

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Authors' Contribution

ANM and MRMR conceived and designed the study. ANM drafted the manuscript. MRMR conducted the literature search and background section writing. ANM reviewed and approved the final version of the manuscript.

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