Journal of
Research in Pharmacy

Research Article
www.jrespharm.com

Investigation of vehicle-induced whole-body vibration with experimental rat models

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Received: 04 November 2023 / Revised: 15 November 2023 / Accepted: 18 November 2023

ABSTRACT: This comprehensive study delves into the profound impact of low frequency whole-body vibrations (WBV) on health, focusing on the utilization of rat models for understanding this complex phenomenon. It highlights the adverse effects of low frequency vehicle vibrations on human health, encompassing musculoskeletal discomfort, fatigue, concentration deficits, potential gastrointestinal issues, hearing impairment, and psychological stress. WBV's influence extends to physiological and cognitive consequences, affecting multiple systems. Prolonged WBV exposure, particularly in the lumbar region, is associated with spinal disorders. To navigate ethical challenges in studying WBV in humans, rat models are crucial tools. These models, with customized parameters, offer insights into various health aspects, including bone density, muscle strength, hormonal responses, cardiovascular parameters, and more. Advantages and disadvantages of using low-frequency vibrations in rat models are discussed. While demonstrating WBV's potential effect in research, further exploration is essential to optimize parameters and applications, always prioritizing ethical considerations and regulations. The article concludes by proposing measures to mitigate vehicle vibration impacts on drivers, emphasizing the collaboration of manufacturers, drivers, and regulators for safer and healthier driving experiences.

KEYWORDS: Whole-body vibration; WBV; low-frequency vibration; vehicle vibrations; rat experiments.

1. INTRODUCTION

Every time you step into your car and hit the road, you become exposed to a myriad of factors that can influence your health and well-being. While most drivers are aware of the importance of seatbelts, airbags, and other safety features, one aspect often overlooked is the impact of vehicle vibrations on driver health. This article delves into the world of vehicle vibrations and their potential effects on the health of those behind the wheel.

Vehicle vibrations can be categorized into two main types: whole-body vibrations (WBV) and hand-arm vibrations (HAV). WBV are transmitted through the seat, floor, and steering wheel, affecting the whole-body of the driver. Hand-arm vibrations, on the other hand, are localized to the hands and arms and are often caused by the operation of tools or equipment in the vehicle [1-3]. Studies in the literature concluded that low-frequency WBV produced by vehicles have potential adverse effects on human health. These main adverse effects are listed in Table 1.

How to cite this article: Hazar-Yavuz AN, Yavuz A. Investigation of vehicle-induced whole-body vibration with experimental rat models. J Res Pharm. 2023; 27(6): 2310-2329.

ISSN: 2630-6344
http://dx.doi.org/10.29228/jrp.519

Table 1. The main adverse effects of low frequency vehicle vibrations on health

Adverse Effects	Explanations
Musculoskeletal Discomfort	Prolonged exposure to vehicle vibrations, especially whole-body vibration (WBV), can lead to musculoskeletal discomfort. Drivers may experience pain and stiffness in their back, neck, and shoulders due to constant exposure to vibrations [4-6].
Fatigue and Reduced Concentration	Vibrations can contribute to driver fatigue, making long journeys more tiring. Fatigue can lead to reduced concentration, slower reaction times, and an increased risk of accidents [7-9].
Gastrointestinal Problems	While not as well-documented, some studies suggest that WBV may be associated with gastrointestinal and digestive problems in drivers. These may include indigestion and other discomfort during or after driving [10-12].
Hearing Damage	Excessive vehicle vibrations can contribute to hearing damage over time, particularly in heavy-duty vehicles or those with loud engines. This could affect drivers' long-term hearing health [13, 14].
Psychological Stress	The continuous exposure to vehicle vibrations may contribute to psychological stress, potentially affecting drivers' mental health and overall well-being [15-19].

Whole Body Vibration (WBV) constitutes a significant consideration in the design and operation of various vehicles, especially those deployed in transportation, construction, agriculture, and industrial settings. Exposure to WBV is a major contributing factor to the development of diverse symptoms and disorders, encompassing fatigue, low back pain, hand-arm vibration syndrome (HAVS), fertility issues, and gastrointestinal problems [20]. Individuals engaging in vehicular activities, both occupationally and in non-occupational contexts, such as vehicle drivers, operators, and off-road machine operators, experience WBV exposure [20-23]. Despite the existence of established standards aiming to limit WBV exposure, a notable gap persists in the comprehension of the associated risks among safety and health professionals. This knowledge deficit results in enduring adverse effects and impairments arising from vehicular-generated WBV, affecting both occupational contexts and daily life [24-25].

Physiologically and cognitively, WBV exerts a range of detrimental effects on the human body. The transmission of low-frequency vibrations from vehicles to the ocular system diminishes visual tracking performance and exacerbates noise-induced hearing loss [25]. Prolonged exposure to WBV is linked to mental fatigue, evidenced by reduced performance in attention-demanding tasks during driving, impairment in cognitive functions, and an increased susceptibility to drowsiness [25-27].

While the predominant physical impairments associated with WBV are musculoskeletal, it is crucial to recognize that other bodily systems are not exempt from its effects. In the realm of occupational medicine, documented reports identify neurological, gastrointestinal, cardiovascular, and reproductive symptoms attributed to WBV exposure [28]. These findings underscore the complex and multifaceted nature of consequences resulting from prolonged or recurrent exposure to vehicular-generated WBV, prompting critical concerns about the well-being and safety of individuals regularly subjected to such environmental stressors. This collective understanding underscores the necessity for further research, comprehensive risk assessment, and heightened awareness among safety, health, and occupational medicine professionals to mitigate adverse impacts and develop effective prevention and intervention strategies.

A pivotal issue associated with WBV exposure is its detrimental effects on the spine and related musculature, leading to low back pain. WBV subjects the spine to compression, tension, rotation, and stretching, thereby engaging back muscles and inducing fatigue. Electromyographic (EMG) studies on the erector spinae muscle have revealed increased EMG signals and decreased signal frequency during WBV, particularly at the resonance frequency of 5 Hz, indicating muscle fatigue [29].

Epidemiological evidence spanning decades establishes an association between WBV and low back pain, as well as other spinal pathologies. Longer exposure durations (exceeding 5 years) to WBV have been linked to an increased risk of spinal pathologies, with a higher incidence in the lumbar region compared to the thoracic region [30]. Among military staff, a cohort study on helicopter pilots identified an association between cervical and lumbar degenerative changes and accumulated flight hours [31]. A meta-analysis concluded that cervical pathology is associated with WBV exposure in ground vehicles and fixed-wing aircraft [32]. Age-related degenerative changes in the spine may exacerbate WBV-related low back pain in older individuals [30]. Occupational exposure to WBV is also associated with an increased risk of degenerative changes, including disc herniation and nerve damage, although diagnostic imaging does not consistently correlate with symptoms [20]. Retrospective studies lack specific vibration parameter measurements associated with diseases, making it challenging to quantify symptoms and estimate individual risk. Despite the widely accepted causal link between WBV and spinal pathology, quantitative evidence from cohort studies is insufficient to comprehensively clarify biological associations between WBV exposure and spinal health [33]. Obtaining complete data on occupational exposure to WBV in a cohort and determining the risk of spinal disorders would take decades and is unlikely to be feasible. These and other limitations in experiments to study the WBV exposure-response relationship in humans, primarily due to ethical concerns, emphasize the need for relevant experimental animal models to assess spinal pathologies from vibrations. The majority of existing models have been used to study WBV as a treatment for conditions such as bone fracture healing [34], osteoporosis [35] and spinal cord injury [36], but have not examined the harmful effects of WBV. Exposure criteria for humans are not necessarily the same for other species, making it difficult to compare human and animal research. Therefore, there is a need for models to transfer WBV exposure criteria from other species to humans and a holistic assessment of the evidence provided by existing models

Given the impracticality of obtaining comprehensive data on occupational WBV exposure in a cohort over decades, due to logistical constraints and ethical considerations, experimental animal models become imperative for studying WBV-induced pathologies. Existing models for WBV-induced pathologies vary based on applied mechanical stimuli, vibration modes, and evaluated time points. Understanding how vibrational inputs from WBV lead to deleterious changes in health, particularly affecting musculature and the spine, enhances our comprehension of these pathologies, informing diagnoses and treatments for associated injuries.

The objectives of this study encompass investigating the adverse effects of low-frequency vehicle vibrations on driver health, exploring physiological and cognitive consequences of WBV, evaluating the impact of WBV on the spine and musculature, addressing ethical challenges in WBV exposure-response studies with a focus on rat models, examining customized WBV parameters aligned with research objectives and ethics, highlighting the versatility of rat models in studying various physiological aspects of WBV, acknowledging limitations of rat models, and emphasizing the need for further exploration. The study concludes by proposing practical measures to reduce vehicle-induced vibrations for positive human health outcomes.

2. WHOLE-BODY VIBRATION MODEL DESIGNS IN RAT EXPERIMENTS

WBV models for rat experiments involve exposing rats to mechanical vibrations to study the effects of these vibrations on various physiological and pathological aspects. These models can be used to investigate the impact of vibrations on bone health, muscle strength, metabolism, and other physiological parameters. An overview of some common WBV models used in rat experiments is given in Table 2 [37-41].

Table 2. Common whole-body vibration models used in rat experiments

Researches	Objectives	Protocols
Osteoporosis	To study the effects of vibrations on bone density, strength, and bone remodeling.	Rats are exposed to controlled low-frequency vibrations to simulate the mechanical loading on bones. This can help researchers understand how vibrations influence bone health.
Muscle Strength and Wasting	To assess the impact of vibrations on muscle strength, mass, and function.	Rats undergo WBV to induce muscle contractions and improve muscle strength. This can be beneficial in models of muscle wasting and rehabilitation.
Metabolism and Obesity	To investigate the effects of WBV on metabolic parameters, including fat accumulation, glucose metabolism, and lipid profiles.	Rats with diet-induced obesity or metabolic disorders are subjected to WBV to examine changes in metabolism and body composition.
Joint Diseases and Arthritis	To explore the influence of WBV on joint health and mobility, particularly in models of arthritis or joint diseases.	Rats with joint conditions are exposed to vibrations to assess their effects on joint inflammation, pain, and mobility.
Aging and Rehabilitation	To evaluate how WBV affects physical performance, coordination, and rehabilitation in aging or injured rats.	Aged or injured rats are subjected to WBV to determine its potential in enhancing mobility and overall well-being.
Neurological and Cognitive Function	To investigate the impact of WBV on neurological and cognitive functions in rat models of neurodegenerative diseases.	Rats with neurodegenerative conditions receive WBV to assess its effects on neuronal health, learning, and memory.
Cardiometabolic Health	To study the effects of WBV on cardiovascular and metabolic parameters, such as blood pressure, lipid profiles, and glucose metabolism.	Rats with cardiometabolic conditions are exposed to WBV to examine its potential benefits for heart health and metabolism.

It's important to note that the specific parameters of WBV, such as frequency, amplitude, duration, and intensity, can vary depending on the research objectives and the health status of the rats. Additionally, ethical considerations and animal welfare guidelines must be strictly followed when using WBV in rat experiments. Researchers conducting rat experiments with WBV should carefully design their protocols, monitor the animals' well-being, and consider the potential impacts on the study outcomes.

Studies in experimental animals are available to manage and minimize WBV in vehicles due to its impact on human health [42]. Several rat WBV models have been developed to investigate the effects of WBV on physiological, anatomical and biochemical parameters. These models differ in terms of vibration parameters, exposure duration and the specific aspects of health and physiology they aim to investigate. These models provide insights into the effects of continuous or repetitive WBV on musculoskeletal, cardiovascular, neurological and other systems. Of these models, the chronic exposure model, which involves continuous exposure of rats to WBV over long periods of time, usually several weeks or months, is used to study the long-term effects of WBV on musculoskeletal health, cardiovascular function and neurological outcomes, and mimics occupational scenarios where individuals are regularly exposed to WBV, such as vehicle drivers or heavy machinery operators [43].

In contrast to chronic exposure, the acute exposure model involves short but intense WBV exposures and researchers use it to study immediate physiological responses to vibration, such as changes in heart rate, blood pressure and muscle contraction. The acute exposure model can mimic scenarios such as those experienced during certain vehicle accelerations or accidents and sudden jolts or impacts [44]. Some rat models are called frequency-specific models and focus on specific vibration frequencies to investigate their effects on different physiological systems [45]. In amplitude variation models, the amplitude of vibrations is varied to understand the effects of varying degrees of amplification on outcomes. These models use specially designed platforms that generate controlled vibrations and rats are usually placed in cages or restraints on these platforms.

As a result, the frequency and amplitude of the vibrations to which the rats are exposed can be adjusted to mimic specific real-life scenarios. Rats can be exposed to WBV for varying durations and frequencies. Below we describe the rat models in which the features of WBV are customized according to the purpose and the results obtained from these models.

2.1 One-Week Whole-Body Vibration Models

In a study aimed at elucidating the expression of neurotrophins, specifically brain-derived neurotrophic factor (BDNF) and nerve growth factor (NGF), in cervical intervertebral discs following painful Whole Body Vibration (WBV), male Holtzman rats underwent 7 days of repeated WBV (15 Hz, 30 min/day) or sham exposure, followed by a 7-day rest period. The investigation revealed a significant increase in BDNF levels and total NGF levels in response to vibration. The protein expression of both BDNF and NGF exhibited an approximate 4-fold and 10-fold increase, respectively. Notably, the heightened expression of BDNF and NGF occurred in aneural regions of the cervical discs, consistent with reports of hyperinnervation. The observed neurotrophin expression also correlated with behavioral sensitization, implying the involvement of both neurotrophins in the development of disc pain [46].

Subsequently, the same research team conducted another study investigating the impact of WBV at different frequencies and amplitudes on rats. Rats were exposed to vibrations at 8 Hz with a 5 mm amplitude and 15 Hz with a 1.5 mm amplitude. The study addressed several questions, including the resonance frequency of the rat spine for WBV along the spinal axis, the effects of WBV frequency on spinal compression/extension, the persistence of pain after a single exposure at resonance, alterations in protein kinase C epsilon (PKCε) response in the dorsal root ganglia (DRG), and changes in calcitonin gene-related peptide (CGRP) expression in the posterior horn of the spine. The results demonstrated that WBV in resonance induced prolonged pain and widespread activation of nociceptive and neuroimmune responses compared to non-resonant WBV [47].

Utilizing the same rat model, the research team investigated the effects of different WBV exposures on hind paw behavioral sensitization and neuroinflammation in the lumbar spinal cord. Rats were exposed to WBV at 8 Hz with a 5 mm amplitude and 15 Hz with a 1.5 mm amplitude. Both WBV exposures induced mechanical allodynia one day after WBV, but only 8 Hz WBV caused a sustained decrease in withdrawal threshold through day 14. Moreover, increased activation of microglia, macrophages, and astrocytes in the superficial posterior horn of the lumbar spinal cord was evident only after painful 8 Hz WBV. The study also highlighted heightened extracellular signal-regulated kinase (ERK) phosphorylation in neurons and astrocytes, with the most pronounced phosphorylation occurring in the 8 Hz group. These findings suggest that exposure to WBV inducing persistent pain also triggers enduring neuroimmune cellular activation responses. This study establishes a nuanced understanding of injury-induced responses based on vibration parameters, offering a valuable platform for studying the mechanisms of painful spinal cord injuries [48]. In all three studies conducted by this research team, vibration was applied along the x-axis, and the diverse effects of vibrations of varying frequencies and amplitudes on rats were comprehensively elucidated.

2.2 Two-Week Whole-Body Vibration Models

In the pursuit of identifying diagnostic markers for low back pain, a rat model featuring repetitive Whole-Body Vibration (WBV) followed by a recovery period was employed to assess the impact of vibration frequency on hind paw withdrawal threshold, circulating nerve growth factor concentration, and intervertebral disc degeneration. Male Sprague-Dawley rats were exposed to vibrations at either 8 Hz or 11 Hz for 30 minutes every other day over a two-week period, succeeded by a one-week recovery phase devoid of vibration. The mechanical sensitivity of the hind paw was evaluated using the von Frey test every other day. Serum nerve growth factor concentration was measured at four-day intervals, and at the conclusion of the three-week study, intervertebral discs were histologically graded for degeneration.

The findings revealed a threefold increase in nerve growth factor concentration in the 8 Hz group and a twofold increase in the 11 Hz group. Notably, the nerve growth factor concentration failed to return to baseline levels following the one-week recovery period in the 8 Hz group. Mechanical sensitivity exhibited a general decline over time across all groups, indicative of a habituation (desensitization) effect. The researchers posit that nerve growth factor may serve as a potential diagnostic biomarker for low back pain induced by WBV [49].

2.3 Whole-Body Vibration Model Caused by Internal Combustion Engine Vehicle Vibrations

Motor vehicle-induced WBV (MV-WBV) is used to understand internal combustion engine vehicle-induced WBV and to study its health effects [48]. A study on insidious cumulative brain damage from MV-WBV investigated whether WBV over long periods of time causes cumulative brain damage and impaired brain function. Sprague-Dawley rats were used in this WBV-mimicking study and the experiment consisted of 2-, 4- and 8-week periods. The rats were divided into 9 groups (n=8) and subjected to vibration as described below, and it was noted that the vibration parameters in this study were similar to the most common driving conditions:

- 2 weeks normal control
- 2-weeks sham control (in non-vibrating tube)
- 2 weeks of vibration (exposure to WBV at 30 Hz and 0.5 g acceleration for 4 h/day, 5 days/week for 2 weeks)
- 4-weeks sham control (in non-vibrating tube)
- 4 weeks of vibration (exposure to WBV at 30 Hz and 0.5 g acceleration for 4 hours/day, 5 days/week for 4 weeks)
- 4 weeks of vibration with human apolipoprotein A-I molecule mimetic (4F) preconditioning (exposure to WBV at 30 Hz and 0.5 g acceleration for 4 h/day, 5 days/week for 4 weeks)
- 8-weeks sham control
- 8 weeks of vibration (exposure to WBV at 30 Hz and 0.5 g acceleration for 4 h/day, 5 days/week for 8 weeks)
- 8 weeks of vibration with 4F-preconditioning (exposure to WBV at 30 Hz and 0.5 g acceleration for 4 h/day, 5 days/week for 8 weeks)

In the study, all rats were evaluated by behavioral, physiological and histological studies on the brain. According to the results obtained, vibration-induced brain damage is a cumulative process that starts with cerebral vasoconstriction, compression of endothelial cells, increase in free radicals, decrease in nitric oxide, insufficient blood supply to the brain and repeated reperfusion damage to brain neurons. In the 8-week vibration group showing chronic brain edema, the reduced neuron numbers increased and all neurons atrophied, which was strongly associated with neural functional impairment. No significant brain neuron damage was found in the groups receiving 4F as treatment [50].

In a study conducted by a different team but using the same vibration parameters, rats were exposed to WBV for 8 and 12 weeks. A rat willingly ventures into a PVC tube, demonstrating its curiosity and exploration instincts. Subsequently, the rat's tail is gently secured to the side of the tube using tape while it remains on the platform (Figure 1). In this study, brain tissue from rats showed thickened, irregular and damaged capillary walls, as well as edema surrounding the narrowing of capillaries. The narrowing of capillaries reduced oxygen supply to cerebral neurons, leading to neuronal damage. In the 12-week vibration group, each effect was more pronounced compared to the 8-week vibration group. No significant cerebral capillary damage was found in the 4F-peptide conditioning groups, and this study demonstrated the preventive effect of 4F-peptide conditioning on cumulative brain damage caused by MV-WBV [51].

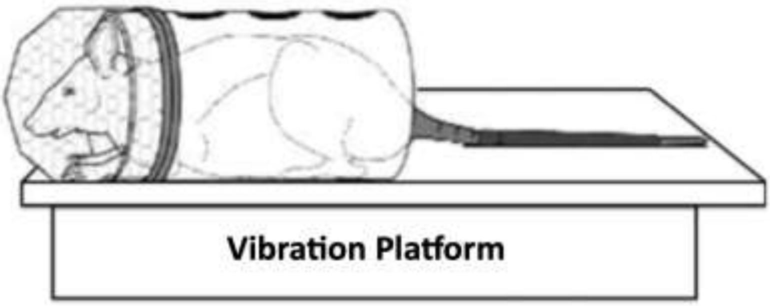

Figure 1. Whole-body vibration test setup [51].

2.4 Vertical Whole-Body Vibration Model

To delineate the specific impacts of distinct frequency and acceleration magnitudes on musculoskeletal responses, a study was conducted applying Whole Body Vibration (WBV) vertically. The investigation aimed to elucidate the bone effects resulting from different vibration frequencies while maintaining a constant gravitational (g) level. Adult male rats were subjected to vertical WBV at 0.7 g, employing sinusoidal vibrations at frequencies of 8, 52, or 90 Hz. The vibration sessions lasted for 10 minutes per day, five days per week, over a span of four weeks.

Peak accelerations were assessed using skin- or bone-mounted accelerometers at the L2 vertebral and tibial crest levels, revealing comparable values between adjacent skin and bone sites. Local accelerations were notably higher at 8 Hz compared to 52 and 90 Hz, with greater magnitudes observed in the vertebra compared to the tibia for all frequencies tested. At 52 Hz, bone responses were predominantly observed in the L2 vertebral body, characterized by trabecular reorganization and a stimulated mineral attachment rate (MAR) without alterations in bone volume. Conversely, at 90 Hz, both axial and appendicular skeletons, as well as cortical and trabecular compartments, were affected. This entailed decreased porosity, increased cortical thickness in the femoral diaphysis (17%), augmented trabecular bone volume in the distal femoral metaphysis (23%), and a more pronounced increase in the L2 vertebral body (32%). Additionally, there was a decrease in structural model index (SMI) and an enhancement in trabecular connectivity. Trabecular thickness experienced an increase in the proximal metaphysis of the tibia. Bone cellular activities indicated a higher rate of bone formation, particularly pronounced in vertebrae (300%) compared to long bones (33%). Active bone resorption surfaces remained unaffected.

Conversely, at 8 Hz, deleterious effects were observed, including hyperosteoidosis with increased resorption surfaces and decreased MAR in the tibia. Similar effects were noted in the L2 vertebra, demonstrating hyperosteoidosis and a decreasing trend in MAR. Notably, trabecular bone mineral density decreased in the femur and tibia at this frequency. Consequently, the study suggests that, while the optimal regime for beneficial effects is at 90 Hz, harmful skeletal effects are evident at 8 Hz. Researchers propose that frequencies of 52 and 90 Hz may hold therapeutic potential and could be considered for treatment purposes [52].

3. EFFECTS OF LOW FREQUENCY WHOLE-BODY VIBRATIONS ON RATS

Various WBV rat models, as mentioned above, have been used in research to investigate the effects of vibration on various physiological and pathological processes. The results of these experimental studies may vary depending on factors such as vibration frequency, duration, and amplitude and specific health parameters measured. Below are some of the effects and potential consequences of WBV observed in the literature on rats.

Bone Density and Strength: Some studies suggest that WBV can improve bone density and strength in rats. This is relevant for research related to osteoporosis and bone health.

• Minematsu et al. investigated the effects of WBV on bone properties in growing male rats. Rats were exposed to WBV at different frequencies (15, 30, 45, 60, and 90 Hz) for 8 weeks. WBV at 45 Hz and 60 Hz showed a tendency to enhance trabecular bone mass and microstructure, but it didn't affect the maximum load of tibias. However, the 45-Hz WBV group had higher levels of bone resorption markers. The study suggests that WBV at 45-60 Hz may be a promising approach to increase bone mass during the rapid growth phase and could potentially serve as a strategy for preventing osteoporosis, but further research is needed to determine the optimal WBV conditions for peak bone mass and microstructure enhancement. [53]

• Minematsu et al. aimed to determine optimal conditions for WBV to enhance bone properties in aged rats. Rats were subjected to WBV at different frequencies and magnitudes for 7 weeks. Lower frequency WBV (15 Hz) at 0.5 g appeared to damage trabecular bone, while high-magnitude WBV (0.7 g and 1.0 g) at 45 Hz showed potential for improving cortical bone properties without affecting bone geometry. These findings emphasize the need for caution in selecting WBV conditions, particularly for elderly individuals [54].

• Ogawa et al. examined the impact of low-magnitude, high-frequency (LMHF) loading using WBV on peri-implant bone healing and implant osseointegration in rat tibiae. Rats with custom-made titanium implants were subjected to LMHF mechanical vibration for varying durations. Results showed that LMHF loading significantly increased bone-to-implant contact (BIC) and peri-implant bone fraction (BF). This suggests that LMHF loading through WBV has a bone-stimulating effect, promoting better peri-implant bone healing and osseointegration [55].

• Pasqualini et al. aimed to investigate the effects of WBV on bone in mature male rats at different frequencies but with a constant g-level. Results showed that 52 Hz WBV primarily affected the vertebral body, stimulating mineral apposition rate without altering bone volume. In contrast, 90 Hz WBV affected both axial and appendicular skeletons, increasing cortical thickness, trabecular bone volume, and bone formation rate. However, 8 Hz WBV had negative effects, leading to hyperosteoidosis and reduced mineral apposition in the tibia. The study suggests that a frequency of 90 Hz is favorable for bone health, while caution is needed for frequencies below 10 Hz, at least in rats [56].

• Yang et al. investigated the effects of WBV on bone in a rat model of microgravity using hind-limb unloading (HLU). WBV with variable parameters reduced bone mineral density (BMD) losses in the femur and tibia during HLU but had no effect on the lumbar spine. It maintained serum alkaline phosphatase (ALP) levels. However, WBV didn't have a significant impact on BMD during the recovery period following HLU. Interestingly, the mechanical properties of the femur were influenced by WBV in both control and unloaded bones. WBV showed potential as a countermeasure to limit bone density reduction during unloading in this rat model [57].

• Nowak et al. performed the effects of a 6-month WBV program on bone mass and metabolic markers in male Wistar rats. The WBV program, consisting of brief daily vibratory sessions at 50 Hz and 4.92 g acceleration, reduced the concentration of C-terminal telopeptide of type I collagen, indicating decreased bone resorption. However, it had no significant impact on areal bone mineral density, osteocalcin, or sRANKL levels. In summary, high-frequency, high-magnitude WBV reduced bone resorption but did not affect bone formation or bone mineral density in the study [58].

• Minematsu et al. explored the potential of WBV as a primary preventive measure for osteoporosis in adult rats. Rats subjected to WBV at low frequencies (15 and 30 Hz) with a magnitude of 0.5 g for 8 weeks exhibited increased muscle weight and improved trabecular bone thickness and width. However, there were no differences in bone mechanical strength or bone formation/resorption markers among the groups. These findings suggest that low-frequency WBV may have potential as a strategy for the primary prevention of osteoporosis in adults [59].

Muscle Strength and Mass: WBV may lead to increased muscle strength and mass in rats, making it relevant for studies related to muscle atrophy or physical performance.

• Maddalozzo et al. investigated the effects of WBV on body composition in female rats. After 12 weeks of vibration at 30-50 Hz, the vibration group had lower body weight, reduced body fat, lower percentage of body fat, and decreased serum leptin levels compared to the control group. There were no significant changes in lean mass, bone mass, bone density, muscle function, or food consumption. However, the vibration group showed an increase in vertebral bone mass and density, suggesting localized bone benefits from WBV [60].

• Lin et al. studied the effects of WBV training on middle-aged mice. Mice subjected to WBV showed improved body composition, exercise performance, and reduced fatigue. WBV increased muscle and brown adipose tissue weight, grip strength, and core temperature while decreasing serum lactate, ammonia, and creatine kinase levels after exercise. Additionally, WBV improved tissue morphology in skeletal muscle, liver, and kidneys. These findings suggest that WBV training has the potential to promote health, enhance exercise performance, and mitigate age-related changes in middle-aged individuals, although further research is needed to understand the underlying molecular mechanisms [61].

• Sandhu et al. searched the effects of low-magnitude, high-frequency WBV on intact flexor carpi ulnaris tendons in rats. Rats subjected to WBV for five weeks showed a 32% increase in tendon cross-sectional area and a 41% increase in structural stiffness compared to control rats. Additionally, there was a trend toward increased ultimate load in the vibrated tendons. These findings suggest that WBV may stimulate tendon growth and could potentially accelerate tendon healing, similar to its effects on bone and muscle [62].

Hormonal Changes: Vibration exposure may affect hormone levels, such as increased secretion of growth hormone and insulin-like growth factor 1 (IGF-1), which can have various physiological effects.

• Hoffmann et al. investigated the effects of whole-body vertical vibration (WBVV), parathyroid hormone (PTH), and strontium ranelate (SR) in a rat model of osteoporosis. PTH significantly improved bone quality, including bone mineral density and trabecular bone quality. SR had mild effects, primarily affecting cortical thickness. WBVV, whether as a single or adjunctive therapy, did not significantly improve bone properties. In conclusion, PTH was found to be more effective than SR or WBVV in improving bone quality in osteoporotic rats [63].

• Luan et al. examined the effects of local vibration and passive exercise on the hypothalamic-pituitary-adrenal (HPA) axis-related hormones in tail-suspended rats, which simulate the effects of spaceflight-induced bone loss. The results indicated that 35 Hz local vibration did not induce a stressed state in rats and may not inhibit the HPA axis function. Instead, it appeared to protect the HPA axis function, helping tail-suspended rats transition from a stressed to an adaptive state [64].

• Pawlak et al. performed the effects of three and six months of WBV training on blood cell counts and immunological parameters in rats. The results showed that there were no significant differences between the trained groups and the control group in terms of blood cell counts or immunological parameters. This suggests that the specific short-lasting WBV used in the study did not disrupt the balance of these indices related to inflammatory processes [65].

Circulatory Effects: WBV can influence cardiovascular parameters, including heart rate and blood pressure. It may contribute to improved cardiovascular health or have adverse effects, depending on the study parameters.

• Nakamura et al. carried out the effects of WBV on normal pregnancy in rats. Exposure to vibration led to a significant decrease in uterine blood flow, with increased corticosterone levels. While angiotensin II (AII) pretreatment increased uterine blood flow initially, it was reduced after vibration exposure. Vibration decreased progesterone and prostaglandin E2 levels, with or without AII treatment, suggesting an impact on uterine and ovarian function. These changes were attributed to the indirect effects of vibration [66].

• Ariizumi et al. investigated the effects of WBV on the central nervous system in rats. The results showed that both acceleration and vibration frequency had dose-related effects on brain levels of serotonin (5-HT) and 5-hydroxyindoleacetic acid (5-HIAA). Brain levels of 5-HT and 5-HIAA increased as acceleration and vibration frequency increased. Plasma corticosterone levels also increased with higher acceleration and vibration frequency. A significant correlation was observed between brain 5-HT and plasma corticosterone levels as acceleration increased [67].

• Shekarforoush et al. examined the effects of WBV training on myocardial ischemia-reperfusion (IR) injury in a rat model. Rats subjected to WBV showed a smaller myocardial infarct size and a reduction in ischemia-induced arrhythmias, including ventricular tachycardia and ventricular fibrillation, compared to the control group. Vibration training increased cardiac tolerance to IR injury, leading to improved outcomes in the rat model [68].

• Oroszi et al. aimed to compare WBV and exercise in female rats with isoproterenol-induced myocardial damage. Both WBV and exercise reduced cardiac collagen deposition and had regional effects on neuroinflammation and BDNF expression in the hippocampus. Although both WBV and exercise improved aspects of brain function and neuroinflammation, concerns remained regarding cardiac collagen reduction. WBV may provide an alternative to physical exercise for individuals with cardiovascular disease [69].

Metabolic Effects: Vibration exposure may impact metabolic processes in rats, potentially affecting glucose metabolism, insulin sensitivity, and fat metabolism.

• Andrade et al. found that WBV exercise had contrasting effects on metabolic parameters in rats with obesity induced by monosodium l-glutamate (MSG). The control group exposed to WBV showed reductions in creatine kinase and liver triacylglycerol and increases in glucose, lactate, total cholesterol, liver cholesterol, and low-density lipoprotein (LDL). In contrast, the MSG-exposed group that underwent WBV showed an increase in total triacylglycerol, very-low-density lipoprotein (VLDL), lactate, creatine kinase, liver cholesterol, and additional liver lipid peroxidation, with reductions in total cholesterol and CK-MB. The results suggest that WBV exercise can mobilize substrates and may be beneficial for metabolic rehabilitation in individuals with metabolic diseases like obesity and diabetes [70].

• Liu et al. used a rat model of type 2 diabetes mellitus (T2DM) with insulin resistance induced by a high-fat diet (HFD) and low-dose streptozotocin. Rats subjected to vibration exercise (VE) showed improvements in metabolic markers, including blood glucose, triglycerides, and cholesterol levels. VE also activated the phosphoinositide 3-kinase (PI3K)/protein kinase B (AKT) insulin signaling pathway and increased glucose transporter protein type-4 (GLUT4) expression, suggesting that VE could be a therapeutic intervention for insulin resistance and T2DM by ameliorating the metabolic issues associated with diabetes mellitus [71].

• Higaki et al. investigated the effects of WBV on body composition in male Wistar rats fed standard or HFD. WBV significantly reduced body fat accumulation in rats fed a HFD but had no such effect in those fed a standard diet. Additionally, WBV increased the mass of several skeletal muscles. This suggests that long-term WBV may be a safe and promising approach for preventing and treating obesity, particularly under conditions that promote obesity. Further research is needed to understand the mechanisms and determine optimal WBV protocols for maximum benefits [72].

• Huang et al. aimed to investigate the effects of WBV training on exercise performance, physical fatigue, and obesity in mice with HFD-induced obesity. After 4 weeks of diet induction and 6 weeks of WBV, results showed that WBV increased grip strength and reduced serum lactate, ammonia, and creatine kinase levels while increasing glucose levels after exercise. WBV also led to a slight reduction in body weight and dose-dependent decreases in fat pad weights and several metabolic markers. These findings suggest that WBV can improve exercise performance, reduce fatigue, and prevent obesity-related health issues in obese mice, making it a potential intervention for health promotion and obesity prevention [73].

• WBV improved insulin sensitivity and reduced liver steatosis in mice with insulin resistance. It achieved these effects by reducing the expression of SREBP1c, increasing glutathione peroxidase (GSH-Px) expression, and suppressing oxidative stress. WBV is considered a promising treatment for individuals with central obesity and insulin resistance [74].

• A study exposed albino rats to chronic WBV at 5.0 g acceleration and 20 Hz frequency for 3 hours daily over 3 months. The research found that this vibration caused significant negative effects on the rats' immune system. These effects included a decrease in total white blood cell count, a notable reduction in lymphocytes (lymphopenia), an increase in stress hormone (plasma corticosterone) levels, and heightened neutrophil function, as indicated by increased candida phagocytosis and Nitroblue tetrazolium reduction. In conclusion, chronic WBV was identified as a potent stressor in albino rats, with significant adverse effects on their immune system [75].

• In this study, rats exposed to sound-vibration stress using a vibro-graver tool exhibited a significant increase in plasma corticosterone. Diazepam reduced the stress response, while CGS-8216, administered before diazepam, negated its protective effects. CGS-8216 alone also elevated corticosterone levels, but to a lesser degree. This study highlights the tool's utility for consistent stress induction, diazepam's stress-reducing effects, CGS-8216's ability to counteract diazepam, and its partial agonist properties. The experiments were conducted on conscious male Sprague-Dawley rats, and the findings offer insights into stress modulation [76].

• This study investigated the hormonal responses of Sprague-Dawley rats to confinement and lateral vibration stress. The findings revealed that epinephrine inhibits insulin release and that insulin levels quickly returned to baseline despite elevated glucose levels during vibration. Corticosterone levels responded rapidly but in an opposite phase to insulin. Immuno-assayable growth hormone levels dropped significantly after vibration exposure, but it's unclear whether this reflects a genuine decrease in the hormone or an immunologically deficient form [77].

Exposure to WBV can elicit a spectrum of effects on rats, encompassing various aspects of their physiology and behavior. Notably, rats subjected to WBV may display alterations in balance and posture control, which hold relevance for investigations pertaining to neuromuscular disorders and balance-related issues. Furthermore, the influence of WBV extends into the realm of neurological effects, with some studies suggesting potential impacts on neural adaptations, thereby holding implications for neuroplasticity and cognitive function. In addition, vibration exposure has the capacity to induce changes in inflammatory responses in rats, potentially offering insights into studies involving chronic inflammatory conditions.

Reproductive and endocrine parameters in rats may also be affected by WBV exposure, potentially impacting fertility and hormonal balance. High-intensity vibration can result in microdamage to tissues, prompting a healing response, which is of particular interest in the context of musculoskeletal injuries. Moreover, WBV can instigate cellular and molecular changes, potentially influencing gene expression and signaling pathways. Lastly, behavioral changes are observable in rats exposed to WBV, which may manifest as altered activity levels, increased anxiety, or modified stress responses. The comprehensive understanding of these multifaceted effects of WBV on rats highlights its relevance for a broad spectrum of research areas, from neuromuscular disorders to reproductive health and musculoskeletal injuries, underscoring the importance of further exploration and investigation in each of these domains.

It's important to note that the specific outcomes of WBV in rats can vary based on the parameters of the vibration exposure, including frequency, duration, and amplitude. The field of WBV research in rats is still evolving, and researchers continue to investigate its potential applications in various areas of health and medicine. When conducting such experiments, ethical considerations, safety, and the welfare of the animals should be a top priority, and all relevant regulations and guidelines should be followed.

4. ADVERSE AND BENEFICIAL EFFECTS OF LOW FREQUENCY WHOLE-BODY VIBRATIONS ON RATS

Low-frequency vibrations representing vehicle-induced vibrations in rats can have both positive and negative effects, depending on various factors such as vibration frequency, duration, and intensity.

4.1 Beneficial Effects

Here are some potential positive effects associated with low-frequency vibrations on rats:

Bone Density and Strength: Low-frequency vibrations, often referred to as WBV therapy, have been studied for their potential to enhance bone density and strength in rats. This is particularly relevant for conditions such as osteoporosis, where WBV can help mitigate bone loss and improve bone health.

Muscle Mass and Strength: WBV can lead to muscle contractions and stimulate muscle growth. It may help rats build muscle mass and improve muscle strength, making it potentially beneficial for muscle-related conditions.

Circulation and Lymphatic Drainage: Vibrations can promote blood circulation and lymphatic drainage in rats. Improved circulation can help deliver nutrients to tissues and remove waste products more efficiently.

Balance and Coordination: Low-frequency vibrations can improve balance and coordination in rats. This is relevant for motor skills and mobility, particularly in studies involving neurological conditions.

Enhanced Hormonal Responses: Vibrations may stimulate the release of growth factors and hormones that can have positive effects on tissue repair and regeneration in rats.

Reduced Fat Accumulation: Some studies suggest that low-frequency vibrations can reduce fat accumulation in rats, making it a potential intervention for obesity and metabolic disorders.

Pain Relief: In some cases, low-frequency vibrations may have analgesic effects, helping to reduce pain and discomfort in rats.

Joint Health: Vibration therapy can improve joint health and mobility by stimulating the production of synovial fluid and reducing stiffness.

Stress Reduction: While chronic exposure to vibrations can induce stress, short-term exposure to low-frequency vibrations has been found to reduce stress levels in rats. It may promote relaxation and well-being.

Neurological Function: Some studies have shown that low-frequency vibrations can have a positive impact on neurological function, potentially aiding in the recovery of rats with neurological disorders.

It's important to note that the effects of low-frequency vibrations can vary based on the specific parameters of vibration used, the duration of exposure, and individual rat characteristics. Researchers carefully design studies to optimize the benefits and minimize potential negative effects when using low-frequency vibrations in experimental settings.

4.2 Adverse Effects

While some studies suggest potential benefits of low-frequency vibrations on rats, there can be negative effects associated with these vibrations as well. The specific adverse effects may vary depending on factors such as vibration frequency, duration, and intensity. Here are some potential negative effects of low-frequency vibrations on rats:

Skeletal Stress: Prolonged exposure to low-frequency vibrations may lead to skeletal stress and damage, particularly in the bones and joints. This could result in bone fractures, joint pain, and musculoskeletal injuries.

Vibration-Induced Stress: Vibrations can induce stress in rats, affecting their overall well-being. Chronic stress can lead to adverse health outcomes, including changes in hormonal balance, immune system suppression, and behavioral alterations.

Reduced Reproductive Success: Studies have shown that exposure to low-frequency vibrations can negatively impact reproductive success in rats. It may lead to reduced fertility, lower birth rates, and developmental abnormalities in offspring.

Neurological Effects: Vibrations can affect the central nervous system, potentially leading to neurological disturbances, altered sensory perception, and balance issues.

Increased Risk of Osteoarthritis: Long-term exposure to low-frequency vibrations has been associated with an increased risk of developing osteoarthritis in rats. This condition can lead to joint pain and decreased mobility.

Gastrointestinal Disturbances: Vibrations may affect the gastrointestinal system, leading to digestive disturbances, altered gut motility, and other gastrointestinal issues.

Inner Ear Damage: Low-frequency vibrations can potentially damage the delicate structures of the inner ear in rats, leading to hearing impairments.

Cognitive and Behavioral Changes: Chronic exposure to vibrations may result in cognitive impairments and behavioral changes in rats. This could include increased anxiety, altered learning ability, and changes in social behavior.

Respiratory Effects: Vibrations may impact respiratory function in rats, potentially leading to respiratory distress and other pulmonary issues.

It's important to note that the severity and occurrence of these negative effects can vary depending on the specific conditions of exposure and the individual characteristics of the rats. Researchers and regulators need to consider these potential adverse effects when assessing the safety of low-frequency vibrations in research or industrial settings.

5. EVALUATION OF WHOLE-BODY VIBRATIONS ON HUMAN BODY

Extended exposure to intense Whole Body Vibration (WBV) has been associated with an elevated risk of disorders, primarily affecting the lumbar spine and the associated nervous system. The evidence linking WBV to disorders in other anatomical regions, such as the neck-shoulder region, gastrointestinal system, female reproductive organs, peripheral veins, and the cochleo-vestibular system, is comparatively weaker. Hand-transmitted vibration exposure, typically stemming from the use of powered tools, has been correlated with symptoms and signs indicative of vascular, neurological, and musculoskeletal disorders in the upper limbs, recognized as hand-arm vibration syndrome. The comprehensive article also delves into protective measures and health surveillance protocols for workers exposed to vibrations, aligning with European directives and guidelines [78]. In the realm of occupational medicine, the repercussions of WBV have been extensively investigated. Chronic exposure to WBV has been identified as a potential catalyst for spinal degeneration, with low back pain emerging as a prevalent cause of industrial disability in the population under 45 years of age, particularly in certain industrial settings exposed to WBV.

Recent research suggests a dual role for WBV, proposing its utility as both an exercise intervention and a non-pharmacological intervention for low back pain. Short-term exposure to WBV has demonstrated an increase in serum levels of testosterone and growth hormone, hinting at potential therapeutic applications for sarcopenia and osteoporosis. Despite these potential benefits, the article emphasizes the imperative of developing safe exercise protocols due to the hazards associated with prolonged WBV exposure [79].

The maritime context introduces a unique dimension to vibration exposure, especially for ships' crews. While exposure to hand-arm vibrations aligns with land-based trades, seafarers additionally contend with vibrations to the feet when standing on vibrating surfaces aboard ships. Limited knowledge exists regarding the exposure of ship crews to vibrations and the associated risks. Anecdotal reports, drawing parallels to conditions such as "white feet" observed in mining, warrant further investigation in the maritime setting. Unlike the well-established correlation between back disorders and high levels of WBV among, for instance, tractor drivers, epidemiological evidence for such relations among seafarers is lacking, except for fishermen who encounter additional recognized physical risk factors at work. The assessment and reduction of vibrations by naval architects focus on technical implications for ship construction, but their expressions of vibration intensity differ from medical contexts, limiting their value in estimating health risks [80].

The prediction of health risk in the context of vibration exposure primarily relies on two key factors: the magnitude of the vibration along the dominant axis and the duration of exposure within a given day. In this regard, a graphical representation known as the Health Guidance Caution Zone (HGCZ) provided in Annex B of ISO 2631-1 (1997) is employed to evaluate the risk of exposure (Figure 2). The HGCZ is defined as the area located between two sets of parallel lines that represent lower and upper limits [81].

The evaluation process involves considering the duration of exposure (plotted on the x-axis) and the magnitude of acceleration in RMS values (Aw) along the x and y coordinates, respectively. This assessment is conducted based on the following criteria:

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1. Exposure below the HGCZ: In this region, there is a lack of clear documentation regarding health effects, as indicated by the "minimal/no" risk assessment in the table. Essentially, it suggests that there is minimal evidence or documented risk associated with this level of exposure.

2. Exposure within the HGCZ: When a data point (x, y) falls within the HGCZ, it implies a moderate level of health risk, marked as "moderate" in the risk assessment table. This suggests that there is a probability of vibration-induced injury occurring, although it is not guaranteed.

3. Exposure above the HGCZ: Points located above the HGCZ indicate a higher likelihood of health risk, marked as "high" in the risk assessment table. This signifies that there is a significant potential for vibration-induced injury in such cases.

In summary, the HGCZ, defined by these parallel lines, is a crucial tool for assessing health risks associated with vibration exposure. It provides a clear visual representation of the relationship between exposure duration and vibration magnitude, allowing for the classification of risks into minimal, moderate, or high categories based on the position of data points within or outside the HGCZ [82]. The comfort zones corresponding to different frequency-weighted RMS acceleration values are classified in the ISO 2631-1 (Table 3).

Table 3. Comfort zones from ISO 2631-1 [81].

Frequency-weighted RMS acceleration (m/s^2)	Comfort Index
< 0.315	Not uncomfortable
$0.315 - 0.63$	A little uncomfortable
$0.5 - 1$	Fairly uncomfortable
$0.8 - 1.6$	Uncomfortable
$1.25 - 2.5$	Very uncomfortable
> 2	Extremely uncomfortable

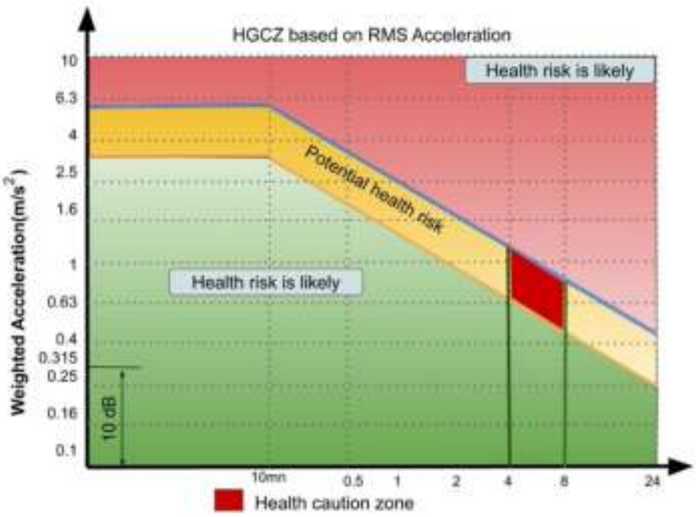

Figure 2. Health Guidance Caution Zone [81, 83].

6. DISCUSSION AND CONCLUSION

In conclusion, this comprehensive article delves into the intricate world of WBV and their profound impact on health, with a primary focus on the utilization of rat models to understand this phenomenon. The adverse effects of low-frequency vehicle vibrations on driver health, including musculoskeletal discomfort, fatigue, concentration deficits, potential gastrointestinal issues, hearing impairment, and psychological stress, are thoroughly explored. WBV's influence extends beyond mere physical discomfort, encompassing a cascade of physiological and cognitive consequences, affecting neurological, gastrointestinal, cardiovascular, and reproductive systems. Of particular concern is its detrimental effect on the spine and musculature, leading to low back pain and spinal pathologies, especially in the lumbar region.

Recognizing the ethical challenges in studying the WBV exposure-response relationship in humans, this article emphasizes the essential role of experimental animal models, particularly rat models. These models are tailored to investigate various aspects of health and physiology, contributing valuable insights into the effects of WBV. Customized parameters for WBV, such as frequency, amplitude, duration, and intensity, align with research objectives and ethical considerations.

Several rat WBV models are discussed, highlighting their versatility in examining different physiological and pathological aspects. These models have provided crucial data on the effects of WBV on bone density, muscle strength, hormonal responses, cardiovascular parameters, metabolic aspects, balance, neuroplasticity, inflammation, and more.

In summary, the outcomes of WBV studies in rats reveal a wide range of effects on various physiological and pathological processes. These studies offer valuable insights into the potential of WBV in various research domains, from musculoskeletal health to neurological adaptations. However, further exploration and investigation are essential to better understand the optimal parameters and applications in each area while steadfastly prioritizing ethical considerations and adhering to relevant regulations and guidelines.

The prominent models in the literature are described above and the health effects of WBV are purposefully studied by taking tissue samples from rats for histological and molecular investigations [84]. WBV research using these rat models could help assess the risks associated with occupations with prolonged exposure to vibrations, such as truck drivers or heavy machinery operators. The findings from rat models, in which researchers manipulated various parameters including vibration frequency, amplitude, duration and other stressors to design experiments that addressed their hypotheses and objectives, provide insights into the effects of WBV on human health and the development of preventive and therapeutic strategies against it. While rat models provide insights into the effects of WBV, there are limitations in translating the findings directly to humans. Therefore, studies on human subjects are also necessary to confirm and extend the relevance of the research to human health and safety [85].

Low-frequency vibrations used in rat models have both advantages and disadvantages. These effects can vary depending on the specific parameters of the vibration protocol, the goals of the study, and the health status of the rats. Some advantages and disadvantages of using low-frequency vibrations for rat models in literature are given in Table 4.

Table 4. Advantages and disadvantages of using low-frequency vibrations for rat models

Advantages of low frequency vibrations used in rat models	
Bone Health	Low-frequency vibrations can improve bone density and bone strength in rats. This is particularly useful for studying osteoporosis and bone-related conditions.
Muscle Strength	Vibrations can induce muscle contractions, leading to increased muscle strength and mass. This can be beneficial for studies on muscle wasting or rehabilitation.
Enhanced Circulation	Low-frequency vibrations can improve blood circulation and lymphatic drainage, potentially aiding in nutrient transport and waste removal.
Tissue Regeneration	Some studies suggest that low-frequency vibrations may stimulate tissue regeneration and the release of growth factors, which can be useful in injury recovery models.
Joint Mobility	Vibrations at low frequencies can help improve joint mobility and reduce joint stiffness, which can be advantageous for models related to arthritis or joint diseases.
Reduced Swelling	Low-frequency vibrations may have an anti-inflammatory effect, reducing swelling in some rat models with inflammatory conditions.

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Disadvantages of low frequency vibrations used in rat models	
Stress and Discomfort	Vibrations can be stressful and uncomfortable for rats, especially when exposed to prolonged or intense vibrations. This stress can lead to physiological and behavioral changes.
Ethical Considerations	The use of vibrations in animal experiments raises ethical concerns, and researchers must follow strict guidelines to ensure the well-being of the animals.
Variation in Responses	The effectiveness of low-frequency vibrations can vary among individual rats, making it challenging to achieve consistent results in experiments.
Long-Term Effects	Some studies have suggested that prolonged exposure to low-frequency vibrations may have negative effects on the musculoskeletal system and overall health, particularly if the protocol is not well-optimized.
Experimental Complexity	Conducting experiments with low-frequency vibrations can be logistically challenging, as it requires specialized equipment and expertise.
Limited Applicability	Low-frequency vibrations may not be suitable for all types of rat models, and their benefits and disadvantages should be carefully considered based on the research goals.

In summary, low-frequency vibrations can offer several advantages for specific rat models related to bone health, muscle strength, and circulation. However, researchers should be mindful of the potential disadvantages, including stress, ethical considerations, variation in responses, and the need for specialized equipment. Proper planning and ethical oversight are essential when incorporating vibrations into rat experiments.

Low frequency vibration amplitudes on whole-body from vehicles can be reduced by taking some precautions. Thus, positive results can be obtained in terms of human health by reducing the amplitudes exposed to vehicle vibrations. To prevent and mitigate the impact of vehicle vibration amplitudes on whole-body, some measures and precautions can be taken:

- Seat and Suspension Quality: Investing in vehicles with quality seats and suspension systems designed to absorb and dampen vibrations can significantly reduce their impact on drivers.
- Regular Maintenance: Ensuring that vehicles are well-maintained, with properly balanced tires and suspension systems, can help minimize vibrations.
- Ergonomic Design: Vehicle manufacturers should consider ergonomic design principles to reduce the risk of musculoskeletal discomfort and fatigue for drivers.
- Taking Breaks: On long journeys, drivers should take regular breaks to stretch and relax their muscles, reducing the impact of prolonged exposure to vibrations.
- Seat Cushions and Accessories: Using ergonomic seat cushions and accessories designed to reduce vibrations can be an effective way for drivers to improve their comfort and well-being.

While the health impact of vehicle vibrations on drivers may not be as immediately noticeable as other road safety concerns, it is a critical factor that should not be underestimated. Manufacturers, drivers, and regulatory authorities should work together to reduce the potential negative effects of vibrations and promote safe, comfortable, and healthy driving experiences. By understanding the relationship between vehicle vibrations and driver health, we can make our time on the road safer and more enjoyable.

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