HHS Public Access
Author manuscript
J Toxicol Environ Health B Crit Rev. Author manuscript; available in PMC 2019 March 13.

Published in final edited form as:
J Toxicol Environ Health B Crit Rev. 2018 ; 21(5): 320–334. doi:10.1080/10937404.2018.1557576.

Health effects associated with occupational exposure to hand-arm or whole body vibration

K. Krajnak
Health Effects Laboratory Division, National Institute for Occupational Safety and Health, Morgantown, WV 26501

Abstract

Workers in a number of different occupational sectors are exposed to workplace vibration on a daily basis. This exposure can come through use of powered-hand tools or hand-transmitted vibration (HTV). Workers can also be exposed to whole body vibration (WBV) by driving delivery vehicles, earth moving equipment, or through the use of tools that generate vibration at low dominant frequencies and high amplitudes, such as jack hammers. Occupational exposure to vibration has been associated with an increased risk of musculoskeletal pain in the back, neck, hands, shoulders and hips. It may also contribute to the development of peripheral and cardiovascular disorders and gastrointestinal problems. In addition, there are more recent data suggesting that occupational exposure to vibration may increase the risk of developing certain cancers. This paper provides a review of the occupations where exposure to vibration is most prevalent, and a description of the health effects associated with occupational exposure to vibration. The various experimental methods used to measure and describe the characteristics of vibration generated by various tools and vehicles, the etiology of vibration-induced disorders, and how these data have been used to assess and improve intervention strategies and equipment that reduces the transmission of vibration to the body. Finally, there is a discussion of the research gaps that need to be investigated to further reduce the incidence of vibration-induced illnesses and injuries.

Keywords

occupational sector; hand-arm vibration syndrome; musculoskeletal

Introduction

Workers can be exposed to occupational vibration through the use of power or pneumatic hand tools or other machinery, or by driving large transportation, construction or agricultural vehicles. Vibration that is generated through the use of powered hand tools, and is transmitted from the tool to the hand-arm system is referred to as hand-transmitted vibration (Griffin 1996). However, recent studies have also demonstrated that vibration can be transmitted through platforms workers are standing on, and in these situations, the point of contact is the feet (House et al. 2011; Eger et al. 2014; Thompson et al. 2010). Workers can also be exposed to whole body vibration (WBV). WBV exposure occurs in occupations where workers are driving trucks, large earth moving vehicles, or where they are using hand tools where the amplitude of the vibration is great enough to be transmitted to other portions of the body, such as in workers using jack-hammers (Bovenzi 2015, 2010; Griffin 2015, 2004; Huang,Griffin 2014).

Exposure to WBV is of concern within the workforce because it's associated with the development of a number of negative health consequences including back and neck pain (Basri,Griffin 2013; Beard,Griffin 2016; Bovenzi 2010, 1996; Charles et al. 2018; Du et al. 2018; Palmer et al. 2012; Bovenzi 2015; Bovenzi et al. 1991), and potentially, cardiovascular disease (Hering, Lachowska,Schlaich 2015; Bovenzi 1990), the development of various neuropathies (Bovenzi, Ronchese,Mauro 2011; Bovenzi et al. 2004; Stoyneva 2016; Stoyneva et al. 2016), digestive problems (Bovenzi 2006, 2005; Ronchese,Bovenzi 2012), headaches, dizziness, motion sickness (Butler,Griffin 2009; Donohew,Griffin 2010; Griffin,Newman 2004; Haward, Lewis,Griffin 2009; Howarth,Griffin 2003; Joseph,Griffin 2007; Webb,Griffin 2003) and possibly cancer (Jones et al. 2014; Nadalin et al. 2012; Waugh et al. 2016; Young et al. 2009). However, workers exposed to WBV are often also exposed to a number of other risk factors that may contribute to the development of these negative health effects. These risk factors include maintaining a static posture for a long-period of time (Antle et al. 2018; Tachi et al. 2004), torque or twisting of the abdomen to view the area around the vehicle (Palmer et al. 2008), and heavy lifting that often occurs when a vehicle is being loaded or unloaded (Palmer et al. 2012; Palmer et al. 2008). In addition to vibration and the physical exposures associated with a job, there may be other co-exposures to chemicals or certain environmental conditions that contribute to the development of disease or injury in workers. Because most workers are exposed to multiple factors that may induced injury or illness, it's difficult to determine which factors pose the greatest risk for inducing injury or illness. Experimental studies, examining the effects of each of these factor individually on health outcomes can provide additional information that will help determine the contribution of each exposure factor to various health problems.

This review will describe the industrial sectors where vibration exposure is most prevalent and the health effects associated with exposure to HTV and WBV. Experimental methods used to measure and characterize vibration generated in various occupational settings are discussed, and models that have been used to uncover the etiology of vibration-induced injuries. Although numerous studies have been published on both HTV and HBV, there are new epidemiological studies showing an increased risk of specific cancers with exposure to WBV. Therefore additional etiological studies need to be performed. New avenues for research are discussed below.

Occupational Exposures to Vibration:

Transportation, Warehousing and Utilities (TWU): Workers in the TWU sector make up approximately 3.2 % of the workforce. The people in this industry transport goods and passengers by air, road, rail, and water. In 2015 approximately 774,900 workers (or 22.3% of all workers in the TWU industry) missed days of work because of injury or illness (Bureau of Labor Statistics (BLS), 2016). Common injuries and illness for workers in this sector include back, neck and shoulder pain, headaches and dizziness, motion sickness, and gastrointestinal, cardiovascular and peripheral sensory problems (Bovenzi 1996, 2005; Hulshof et al. 2006; Young et al. 2009; Zeeman et al. 2015). There is also some evidence that WBV may increase the risk of workers developing specific cancers (Jones et al. 2014; Nadalin et al. 2012; Waugh et al. 2016; Young et al. 2009). Approximately 24% of the workers in this industry are women (BLS, 2016). Women working in the TWU sector primarily work as public transit drivers (37.1%), in the air transportation industry (40%), or in the water transportation industry (22%). Because many worker in the TWU sector are not only exposed to WBV, but they are often performing jobs where they must sit for long periods of time, there may be an increased risk for developing disorders in the lower abdomen, including reproductive problems. (Bovenzi 2006, 2005). Because there are data suggesting that WBV may have systemic effects and increase the risk of developing certain diseases, and because of the increase in the number of women working in this industry, additional studies need to be done to assess the risk of WBV on the development of other disorders (e.g., cardiovascular, reproductive) in this industry.

Agriculture, Forestry and Fisheries (AgFF): Approximately 8% of the workforce is employed in the AgFF sector (BLS, 2016). In the agricultural industry, animal husbandry, and crop production and maintenance are the primary occupations (74.1% males, 24.9% females), and in the forestry sector the majority of the workers are in the logging industry (97.2% males, 2.8% females). Workers performing these jobs are likely to be exposed to both HTV and WBV. The primary exposure to WBV in these industries is through the use of vehicles such as tractors, combines and bulldozers, and the primary exposure to HTV is through the use of vibrating hand tools (e.g. chainsaws). Approximately 15.25 % of the workers in these industries incur an injury or occupationally associated illness that results in days of missed work (BLS, 2016). Workers in these industries are most likely to miss work because of physical injuries, or because of various musculoskeletal disorders due to heavy lifting, maintaining static or awkward postures over an extended period time, and vibration exposure (Bovenzi et al. 1990; Morgan,Mansfield 2014; Bovenzi et al. 1998; Bovenzi et al. 1995; Bovenzi, Giannini,Rossi 2000; Giannini et al. 1999; Heinonen et al. 1987; Yung et al. 2017). However, these workers also are exposed to other factors such as pesticides and extreme temperatures. These exposures, along with vibration, may increase the risk of developing certain cancers, respiratory problems and neurodegenerative diseases (Suratman, Edwards,Babina 2015; Manyilizu et al. 2016; Kachuri et al. 2017; Bencko,Yan Li Foong 2017; Prado et al. 2017; Piel et al. 2017; Darcey et al. 2018; Prudente et al. 2018; Ramirez-Santana et al. 2018; Anderson et al. 2018). Studies need to be performed to determine how exposure to these various factors affect the risk of developing these vibration-induced illnesses.

Workers in the fishing industry are exposed to WBV and HTV vibration generated by the motor and lift equipment on boats, or by the motion of the boat, especially in rough waters. Workers on fishing vessels in large bodies of water, along with workers who perform water rescues, can be exposed to impact or shock vibration when traveling through rough waters (Howarth,Griffin 2015; Ye et al. 2012; Zhou,Griffin 2017). Exposure to this impact can result in injury to the spine, knees and hips (Howarth,Griffin 2015). Workers in this industry can also experience fatigue, headaches and motion sickness due to the motion of the vessel generated by the waves (Haward, Lewis,Griffin 2009; Joseph,Griffin 2007). However these effects often decline over time with work.

Construction and mining.—Approximately 4% of the workers in the United States are in the construction industry and 0.4% are in mining. Of these workers 90.9% are male and 9.1% are female within the construction industry and 87.5% are male and 12.5% are female in mining (these data do not include workers in mining administration, only workers that are involved in mining). The percentage of employees that missed days of work due to a work-related illness or injury was 0.3% and 5.8% for mining and construction, respectively. Workers in these sectors can regularly be exposed to WBV and HTV by driving large earth moving equipment such as bulldozers and dump trucks, or by using hand tools such as drills, jack hammers, and sanders. The combination of vibration exposure and having to maintain awkward or static postures, and lifting heavy loads contributes to the development of injuries and musculoskeletal disorders in workers in these sectors (Yung et al. 2017; Eger et al. 2014; Morioka,Griffin 2010; Smets, Eger,Grenier 2010; Thompson et al. 2010). In addition, these workers are exposed to inhaled toxicants including various dusts and chemicals (coal dust, diesel, concrete wood, organic solvents). These mixed exposures may contribute to the development of many diseases seen in miners and workers in the construction industry (Weissman,Howard 2018).

Manufacturing.—Overall, the number of workers employed in manufacturing is 7.9%. Approximately 74% of those workers are employed in occupations where they may be exposed to vibration, and 29% of those workers are women. In 2015, 12.5% of the people employed in this sector missed days of work due illness or injury (BLS 2016). The majority of the workers exposed to vibration in this sector are exposed to HTV. Workers in various manufacturing settings use many different types of hand tools, including but not limited to grinders, impact wrenches, sanders and drills (Bovenzi 1988; McDowell et al. 2016; Bovenzi et al. 2005). Workers in this industry may also be exposed to awkward postures, repetitive motion, and various chemicals that can be inhaled or absorbed through the skin (Kijko, Jolliet,Margni 2016; Su et al. 2013; Bovenzi 1988).

Health Effects:

Exposure to both segmental and WBV results in an increased risk of developing MSDs, peripheral vascular and sensorineural problems, and other diseases. Repetitive exposure to long-term vibration results in a reduction in tactile sensitivity, loss of manual dexterity and cold-induced vasospasms that induce blanching of the fingers and hands (Griffin 1996; Bovenzi 2010, 2006; Rui et al. 2008; Eger et al. 2014; House et al. 2011; House, Krajnak,Jiang 2016; Thompson et al. 2010; Whitehouse, Morioka,Griffin 2006). Together these symptoms have been referred to as hand-arm vibration syndrome. Workers exposed to tools with a dominant frequency in the range of 60–300 Hz are more likely to develop the symptoms of HAVS (Bovenzi 1998; Bovenzi et al. 2008; Bovenzi et al. 1995). In contrast, workers using hand-tools that emit a lower dominant frequency (i.e., 10 – 60 Hz) can display symptoms of HAVS. However, the tools with a lower dominant frequency are more likely to induce a loss of muscle mass, and joint injuries in the elbow and shoulder (Pyykko et al. 1981; Bovenzi 2006, 2005; Sekkay et al. 2018; Malchaire et al. 1986; Roquelaure et al. 2009).

Data from both human and animal studies suggest that exposure to segmental vibration may also have systemic effects. For example, repeated exposure to HTV has been associated with hyperactivity of the sympathetic nervous system, hearing loss (independent of noise), and an increased risk of cardiovascular disease (Harada 1994; Pyykko et al. 1981; Stoyneva et al. 2016; Wong,Figueroa 2018). There is also evidence that segmental vibration is associated with changes in the transcription of genes involved in cell cycle and the development of cancer (Waugh et al. 2016; Krajnak et al. 2017; Krajnak,Waugh 2018 (in press)). These changes may be due to an increase in systemic inflammation and oxidative activity, or they may be the result of changes in blood flow to various organs (Krajnak,Waugh 2018 (in press)). These data provide a basis for examining the risk associated with exposure to segmental vibration and the development of chronic diseases.

Exposure to WBV has primarily been associated with an increase in lower back, neck and shoulder pain (Bovenzi,Betta 1994; Bovenzi 1996; Bovenzi,Hulshof 1999; Hulshof et al. 2006; Bovenzi 2009). Along with vibration, other exposure factors that may induce musculoskeletal pain in workers include maintaining statistic positions for a long-period of time and twisting or torque while seated (Tachi et al. 2004; Stewart, Taneja,Medow 2007; Antle et al. 2018). These factors, along with vibration from the truck, and impact from driving on rough roads, can result in compression of the disks and soft tissue strain, which both contribute to back pain (Cann, Salmoni,Eger 2004; Smets, Eger,Grenier 2010; Grenier, Eger,Dickey 2010). WBV has also been associated with fatigue, motion sickness (from vibration and impact that is transmitted to the neck and head), and the development of a number of chronic diseases including cardiovascular disease, type II diabetes and/or metabolic disorder, and prostate cancer (Bovenzi,Hulshof 1999; Hulshof et al. 2006; Young et al. 2009; Nadalin et al. 2012; Harris et al. 2012; Jones et al. 2014; Yung et al. 2017; Pollard et al. 2017). Although other factors such as long work hours, stress, and exposure to toxic chemicals may also contribute to the development of these diseases, animal studies suggest that vibration exposure alone can increase the expression of biomarkers for these diseases (Krajnak et al. 2010; Krajnak, Miller, et al. 2012; Krajnak, Riley, et al. 2012; Krajnak,Waugh 2018 (in press); Curry et al. 2002; Matloub et al. 2005; Govindaraju et al. 2006).

Inhalation and WBV.

Some of the sensorineural and cardiovascular effects associated with WBV exposure may also be in part due to inhalation of various toxic chemicals. For example, truck drivers and construction workers are often exposed to diesel fumes emitted by the machinery they are driving. Inhalation of diesel fumes has been associated with the development of respiratory and cardiovascular problems, asthma, and the development of certain types of cancer (Mauderly et al. 2014; Darcey et al. 2018). At construction sites, workers may also inhale dust during earth moving and wood cutting processes or while mixing concrete. Studies have found that the inhalation these different types of dust are associated with an increase in respiratory, and in some cases cardiovascular disease in workers (Heinonen et al. 1987; Iavicoli et al. 2017). Agricultural workers can be exposed to vibration and various pesticides. Pesticide exposure has been associated with the development of peripheral neuropathies, neurodegenerative disorders, and reproductive problems in workers (Suratman, Edwards,Babina 2015; Iavicoli et al. 2017; Kab, Moisan,Elbaz 2017; Prudente et al. 2018; Ramirez-Santana et al. 2018; Anderson et al. 2018). Understanding how these various exposures may contribute to the development of health problems is important determining the best actions to take to reduce exposure and the incidence of injury and disease.

Models for assessing health effects

Computational Modeling:

Computational models have been developed to examine the effects of the various mechanical forces of hand-transmitted vibration on the development of and back pain and injury in workers exposed to WBV. These models have included variables to examine the effects of vibration and mechanical stressors, including load, mass and posture on the hips, spine and intervertebral disks with exposure to WBV (Zhang, Qiu,Griffin 2015; Wang et al. 2010; Taskin et al. 2018), and grip strength, vibration frequency and amplitude in workers exposed to HTV (Wu et al. 2006; Wu et al. 2007; Wu et al. 2008). The published computational models are consistent with data collected in humans showing that the resonant frequency of the human body is between 5–10 Hz (Zeeman et al. 2015; Matsumoto,Griffin 2002; Qiu,Griffin 2010; Basri,Griffin 2011), and that the resonant frequency of the human hand-arm system is between 100–300 Hz depending on the location of the measurement (Dong, Welcome, et al. 2004; Dong, Welcome,Wu 2005; Dong et al. 2006; Wu et al. 2007; Wu et al. 2008). These models, along with experimental data collected in human and animal subjects have helped predict how various interventions may reduce the transmission of vibration from a vehicle or tool to the body (Krajnak et al. 2015; Hewitt et al. 2015; Md Rezali,Griffin 2016; Welcome et al. 2016; Md Rezali,Griffin 2017; Basri,Griffin 2014; Qiu,Griffin 2012; Jonsson et al. 2015; Beard,Griffin 2013; Ji, Eger,Dickey 2017; Du et al. 2018; Johnson et al. 2018).

Epidemiology:

Epidemiological studies performed examining the effects of HTV and WBV have shown that there is an increased risk of developing specific musculoskeletal disorders of the lumbar spine, neck and shoulder with exposure to either HTV or WBV (Bovenzi 2006, 2015, 1998; Charles et al. 2018; Palmer et al. 2008). There is also an increased incidence of peripheral and cardiovascular disease in workers exposed to vibration (Bovenzi 2006; Stoyneva 2016; Stoyneva et al. 2016), and possibly an increased incidence of prostate cancer (Filon et al. 2013; Jones et al. 2014; Nadalin et al. 2012; Waugh et al. 2016; Young et al. 2009). With more women entering jobs where they may be exposed to either HTV or WBV, it will be important to understand the how these exposure affect women's health. There are very few studies examining the effects of either HTV or WBV on women in the workforce (Bovenzi et al. 2005). As mentioned above, there are a number of other personal and exposure factors, that depending upon a workers occupation, can add to or alter the effects of vibration, and contribute to the development of vibration-induced injuries and disorders. Multi-variate analyses of some of the most prevalent factors have been performed to determine the potential contribution to the development of various musculoskeletal disorders (Charles et al. 2018; Bovenzi, Prodi,Mauro 2016; Bovenzi 2015; Bovenzi et al. 2011). Few epidemiological studies have been performed to examine the relationship between vibration exposure and other diseases such as cancer and cardiovascular disease (Kachuri et al. 2017; Jones et al. 2014; Nadalin et al. 2012; Schayek et al. 2009; Young et al. 2009)

Experimental Studies of HTV in humans and animal models:

Experiments examining the effects of single bouts of vibration in humans have shown that both the physical response and the physiological/biological response to vibration are frequency dependent (Dong et al. 2007; Dong, McDowell,Welcome 2005; Dong, Welcome, et al. 2004; Dong et al. 2014; Dong, Welcome,Wu 2005, 2005). Frequencies at or near the resonant frequency of the human hand-finger system (i.e., between 100 – 300 Hz) generate an increased biodynamic response of the exposed tissue (Dong et al. 2007; Dong, Schopper, et al. 2004; Dong et al. 2012; Dong, Welcome,Wu 2005). The increased responsiveness of the exposed tissues at these frequencies is associated with a greater reduction in blood flow in the exposed tissues (Bovenzi 2012, 1998; Bovenzi et al. 1996, 1995), and workers that use tools that have a dominant frequency in this range are associated with a higher incidence of cold-induced finger blanching, or vibration white finger disease (Bovenzi 2010, 2008; Bovenzi et al. 1998; Bovenzi et al. 1995; Bovenzi, Giannini,Rossi 2000), and that exposures at these frequencies are more likely to induce pain and a reductions in tactile sensitivity (Bovenzi, Giannini,Rossi 2000; Bovenzi,Zadini 1989; Giannini et al. 1999). Other studies examining the effects of lower frequency vibration (10–60 Hz) have found that vibration at these lower frequencies is transmitted to the elbow, shoulder, wrist and neck (Bovenzi 2015, 2006; Bovenzi, Fiorito,Volpe 1987; Bovenzi, Petronio,DiMarino 1980; Bovenzi et al. 2005). Exposures at these frequencies also result in faster fatigue of the muscles of the upper arm and shoulder (Tachi et al. 2004; Stewart, Taneja,Medow 2007) and reports of increased discomfort (Wyllie,Griffin 2007; Thuong,Griffin 2011; Huang,Griffin 2014; Bovenzi,Hulshof 1999; Griffin,Bovenzi 2002; Zeeman et al. 2015; House, Krajnak,Jiang 2016). This has lead researchers and other members of standards committees to suggest that the frequency weighting curve should be revised, and either different curves should be generated for different tools, or different curves should be generated for different portions of the hand-arm system (Bovenzi, Lindsell,Griffin 2000; Dong et al. 2001; Griffin, Bovenzi,Nelson 2003; Organization 2005; Morioka,Griffin 2010).

Animal studies have also shown that there are frequency-dependent effects of vibration exposure on the peripheral vascular (Krajnak et al. 2010; Curry et al. 2005; Krajnak, Riley, et al. 2012) and sensorineural system (Krajnak, Riley, et al. 2012; Krajnak, Miller, et al. 2012). Characterization of a rat tail model of segmental vibration has shown that the resonant frequency range of the rat tail and human finger are in the same range (Welcome et al. 2008). As in humans, vibration at or near the resonant frequency results in increases in oxidative stress and inflammation, along with changes in vascular morphology, gene expression and physiological function that consistent with early signs of peripheral vascular disease (Curry et al. 2005; Krajnak et al. 2010; Krajnak et al. 2009; Krajnak et al. 2014). Vibration tested at all frequencies affected sensorineural function in the rat-tail model. However, inflammation, oxidative stress and changes in gene expression are more pervasive with exposure at or near the resonant frequency (Govindaraju et al. 2006; Krajnak, Miller, et al. 2012; Krajnak et al. 2016; Loffredo et al. 2009; Matloub et al. 2005; Yan et al. 2005). Data collected in human and animals studies have been used to improve the diagnosis of

HAVS (House, Krajnak,Jiang 2016; Poole, Mason,Harding 2016; Kao et al. 2008; Terada et al. 2007; Krajnak et al. 2007), improve tool and glove design (Welcome et al. 2016; Krajnak et al. 2015; Hewitt et al. 2015; Dong et al. 2014; Xu et al. 2011), and help modify standards that suggest limitations regarding exposures based on the frequency, amplitude and duration of hand-tool use (Kwong et al. 2001; Dong, Welcome,Wu 2005; Dong et al. 2012; Bovenzi, Petronio,Di Martino 1980; Bovenzi, Griffin,Hagberg 2008; Bovenzi 2010).

Experimental Studies of WBV in humans and animal models:

Studies in both humans and animals have shown that there are a number of different factors that contribute to the development of back and neck pain, sciatica, and shoulder pain in workers exposed to WBV. For example twisting or torque, posture in the seat, and muscle forces and stiffness generated to maintain posture, affect the ligaments, tendons and muscles of the back, and in addition, may affect the spinal load and the risk of incurring an injury (Morgan,Mansfield 2014; Rakheja, Mandapuram,Dong 2008; Wang et al. 2010). Because many patients seen for back pain do not have injuries to their spine or disks, which are can be detected using imaging methods, understanding the contribution of soft tissue injury (i.e., skeletal muscle, tendons, ligaments) to the incidence of back pain is critical for identifying interventions that will prevent injuries (Du et al. 2018; Bovenzi et al. 2015; Bovenzi 2010; Palmer et al. 2003; Bovenzi 1996; Bovenzi,Zadini 1992). Data collected in humans, have been used to alter seat design to reduce vibration transmission and improve comfort in vehicles (Qiu,Griffin 2012; Beard,Griffin 2013; Basri,Griffin 2014; Jonsson et al. 2015; Ji, Eger,Dickey 2017; Du et al. 2018; Johnson et al. 2018). Mental fatigue and stress can also exacerbate pain, therefore, taking breaks to stretch and help maintain mental alertness may also improve pain perception (Yung et al. 2017; Tachi et al. 2004).

Conclusions

Exposure to both HTV and WBV are associated with a number of serious health consequences, and newer epidemiological studies indicate that WBV may increase the risk of developing prostate cancer (Jones et al. 2014; Kachuri et al. 2017; Nadalin et al. 2012; Schayek et al. 2009; Society 2018; Young et al. 2009). Because occupational exposure to vibration occurs in conjunction with other exposures, such as the inhalation of toxins, studies done to examine the precise risk associated with each variable are important because these data will help determine which exposure variables are most dangerous and the best interventions for reducing or preventing exposure to these factors. These data will also provide information that can be used to help revise standards published by the International Standards Organization and American National Standards Institute.

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