Occupational Hazards

Whole-Body Vibration

An emerging topic for the SH&E profession

By Helmut W. Paschold

WHOLE-BODY VIBRATION (WBV) involves the exposure of the entire human body to direct contact with environmental vibration. Mechanical vibrations combined with the physical attributes of the human body can amplify the incoming energy and present the potential for negative health effects. Chronic WBV exposure can result in adverse health effects (presented in detail later) such as spinal injuries, abdominal and digestive problems, and cardiovascular disorders; manifest indirectly as an accident cause factor; or simply result in discomfort or distraction.

NIOSH (1997) reported strong evidence that WBV exposure is associated with low-back disorders. Within the SH&E profession, the topic of WBV is not always well known or understood. It is an emerging topic of interest and research, especially in the U.S. A May 2007 survey of ASSE members confirmed the relative obscurity of the topic—38.6% of total respondents said they "haven't heard of WBV" and only a few others reported expertise in the topic. WBV hazard abatement can be accomplished by eliminating or reducing vibration combined with work administrative controls.

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Vibration is a mechanical wave motion that can cause a transfer of energy from one object to another. A simple sine wave is characterized by frequency and amplitude. Wave frequency is the distance between the waves; amplitude is the height of the waves (Figure 1). Frequency is expressed in hertz (Hz), the number of cycles per second. The magnitude or strength of vibration is its acceleration, measured in meters per second squared (m/s^2). In the work environment, humans are exposed to multiple waves of differing frequencies, amplitudes, periods and directions with graphical results far more complex than the simple wave depicted in Figure 1. The total impact of this integrated vibration is of concern in determining the potential for human illness in WBV.

The frequency range of concern for WBV is 0.5 to 80 Hz (ISO, 1997). Frequencies below 1 Hz with relatively high accelerations of 0.5 to 10 m/s^2 are associated with motion sickness (Mansfield, 2005). Hand-arm vibration syndrome (HAVS) involves direct exposure to handheld vibrating tools at higher frequency ranges of 8 to 500 Hz or as high as 4 to 5000 Hz; like WBV, HAVS is also measured in m/s^2 (Janicak, 2004).

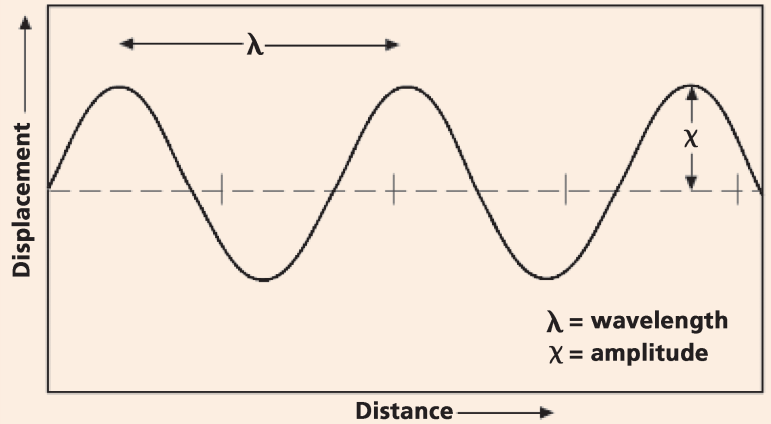
Sound vibration is transmitted to the human body indirectly from the energy source as rapid variations in air pressure; its magnitude is measured in decibels. A person without hearing damage can detect sound frequencies as low as 20 Hz and in the upper limit of 16000 to 20000 Hz (Olishifski & Standard, 1988). Ultrasound describes sound frequencies near or above the upper range of human hearing, with the lower boundary at 10000 Hz and the upper boundary 50000 to 100000 Hz (Bruce, Bommer & Moritz, 2003).

Vibration is oscillation about a fixed point, with negative and positive values assigned to respective directions of travel above and below this fixed point. However, the simple addition of both negative and positive travel values will essentially sum to zero over time. To compensate, vibration is measured by the root-mean-square (*RMS*) using units of m/s^2. The *RMS* is the mean of the squared individual vibration wave values reduced by the square root to eliminate the positive-negative canceling effect, a method similar to the statistical standard deviation function (Mansfield, 2005).

If a spring-mass system were set into motion under completely controlled isolated conditions and only affected by gravity and its inherent spring rate, the system would oscillate indefinitely at a natural frequency. But, no such ideal system exists and the oscillations would eventually be reduced or dampened over time (Yerges, 1969). If an externally applied vibration approaches the system's natural frequency,

Figure 1

Wave Amplitude & Frequency



a resulting forced system vibration greater than the applied will occur. This is known as resonance, a multiplier of the incoming vibration magnitude.

An accelerometer measures vibration. Because environmental vibration is found in three dimensions, three measurement axes identified as x, y and z are used for WBV; these vibrations are measured with a triaxial accelerometer. In WBV for the seated and standing positions, the x-axis is a line passing through the body front and rear (forward to rear); the y-axis is lateral (side-to-side); and z-axis is vertical (head-to-toe) (Bruce, et al., 2003). In the prone position, the z-axis is a line from head-to-toe and horizontal.

Weighting of the three axes' vibration signals is performed and, as with vibration, analyzed for noise exposure using dBA, with designated weightings of Wk for the z-axis and Wd for the x-axis and y-axis (ISO, 1997). The signals generated by the accelerometer are amplified, analyzed and stored by computer.

Integrated instruments are available to provide and record direct read-out of acceleration magnitude in a manner consistent with WBV measurement standards. Photo 1 shows an example of an integrated instrument with a seat-pad accelerometer in a passenger car. The integrated instrument, while facilitating ease of use, is limited in its ability to store acceleration wavelengths. Without this information, the researcher may not be able to investigate abnormalities in readings or use the wavelength data to identify, analyze and correct a problem source (Mansfield, 2005). Furthermore, the integrated instrument must be properly set up for issues such as weighting factors, multipliers, and instrument or accelerometer calibrations to comply with testing protocol.

Human Exposure to WBV

Environmental WBV is transmitted from the contact surface to the whole human body while standing, sitting or reclining. Occupational seated exposure is found with operators of various vehicle categories such as cars, buses, forklifts, tractors, trucks and heavy machinery either on or off paved roads (Paddan & Griffin, 2002). Other transportation vehicles with seated WBV exposures include locomotives (Johanning, Landsbergis, Fischer, et al., 2006) and aircraft, especially helicopters. Standing exposures can be found among operators of cranes and forklifts, or workers walking and standing on vibrating floors. The prone position is encountered least frequently; exposures can include ambulance transport patients or persons in sleeping quarters in dwellings subject to ground or floor vibrations (Turunen-Rise, Brekke, Hårvik, et al., 2003).

The human body as a whole and its individual organs have differing natural frequencies. If the transmitted external vibration frequency approaches or equals the natural frequency, resonance will occur. The entire body or affected body organ can vibrate at an amplified magnitude that is greater than the external source vibration entering the body, especially if the entering vibration is not dampened by other parts of the body before reaching a target organ (Brauer, 1994; Wasserman, 1996). During resonance, numerous voluntary and involuntary contractions of muscles occur, contributing to fatigue or a reduction in motor performance ability (Chaffin & Andersson, 1984).

Human legs are fairly efficient at attenuating vibrations transmitted through the feet of a standing person. Body tissue is effective in dampening frequencies above 30 Hz; Kroemer and Grandjean (1997) reported that the tissue of the hands and arms can reduce an induced 35 Hz frequency to 1/10 of its initial magnitude from finger to shoulder. Frequencies below 30 Hz are most likely to affect parts of the body beyond the point of application; frequencies above are more likely to have localized impact. Various references list natural frequencies for the body and its organs. Table 1 (p. 54) provides a summary presentation of natural frequency values published by different sources; note the variations. Natural frequency for the whole body is dependent on the body's posture. The eyes and head respond to higher frequencies for resonance than the whole body, trunk and organs within the trunk.

The greatest concern involving WBV exposure is low back pain (LBP). Heavy construction equipment operators experience a high rate of LBP, without reported lifting events or traumatic injury. WBV combined with awkward posture is a critical risk factor in these injuries (Kittusamy & Buchholz, 2004). Hoy, Mubarak, Nelson, et al. (2005) found LBP more prevalent among forklift drivers than nondrivers, and concluded that WBV acted dependently with posture, where the operator's trunk was turned or leaning forward, to incur the greatest risk for LBP. Bovenzi and

Abstract: *Whole-body vibration involves the exposure of the entire human body to direct contact with environmental vibration in the 0.5 to 80 Hz frequency range. Chronic exposure can increase the potential for negative health effects such as spinal injuries, abdominal and digestive problems, and cardiovascular disorders; manifest indirectly as an accident cause factor; or simply result in discomfort or distraction.*

Photo 1: WBV monitoring instrument with a seat-pad accelerometer. Note the use of tape to mark direction and assist in the proper alignment of the seat pad accelerometer.

Table 1

Natural Frequencies of the Body & Its Organs

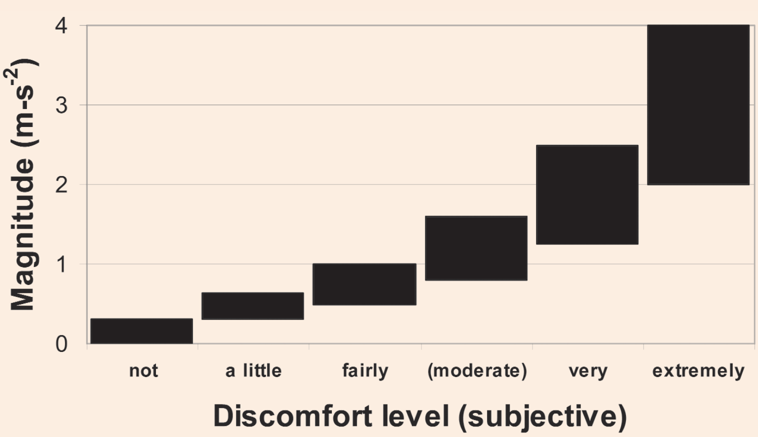
The natural frequencies of the human body and its select parts and organs have been reported in multiple sources. Data from Kroemer and Grandjean is for seated posture.

Body: whole, part or organ	Natural frequency (Hz)	Study source
Whole body, standing	12.3	Randall
Whole body, seated	4 to 6	Brauer
Whole body, prone	3 to 4	Brauer
Whole trunk, vertical	4 to 8	Wassermann
Lumbar vertebrae	4	Kroemer and Grandjean
Head relative to body	20 to 30 5 to 30 20 to 30	Brauer Kroemer and Grandjean SafetyLine Institute
Eyes	20 20 to 70 20 to 90	Mansfield Kroemer and Grandjean SafetyLine Institute
Shoulder girdle	5	Kroemer and Grandjean
Stomach	3 to 6 4 to 5	Kroemer and Grandjean SafetyLine Institute
Heart	4 to 6	Kroemer and Grandjean
Bladder	10 to 18	Kroemer and Grandjean

Figure 2

Passenger Reactions to Vibration

Discomfort reactions of passengers on public transportation in response to increasing levels of vibration magnitude ranges [ISO 2631-1:1997(E) C.2.3].



Hulshof (1998) reviewed WBV epidemiological studies and concluded that clear evidence links occupational WBV with increased risk of LBP.

Exposure is not only the daily dose, but should include the cumulative number of months or years in the exposed occupation. It was found in a recent epidemiological study of professional drivers that LBP frequency, intensity and disability increased significantly with increasing cumulative WBV exposure (Bovenzi, Rui, Negro, et al., 2006). Schwarze, Notbohm, Dupuis, et al. (1998) determined in a study of 388 vehicle operators that 27 to 35% of LBP was linked to WBV, with the driver group exposed to high vibration doses having an LBP risk 1.55 times greater than the control group with low vibration doses.

WBV effects on the natural diurnal change of body height were reported by Hampel and Chang (1999), with the implication of contribution to increased risk for LBP. In a study of musculoskeletal disorders and workplace factors, NIOSH (1997) reviewed 19 WBV studies and found 15 to show positive associations between WBV and LBP and assigned its highest ranking of "strong evidence" to the association. In its conclusions about WBV, NIOSH (1997) states:

> Laboratory studies have demonstrated WBV effects on the vertebra, intervertebral discs and supporting musculature. Both experimental and epidemiologic evidence suggests that WBV may act in combination with other work-related factors such as prolonged sitting, lifting and awkward postures to cause increased risk of back disorder (pp. 6-33).

Gastric motility was found to be affected by WBV, with variable effects dependent on differing vibration frequencies (Ishitake, Miyazake, Noguchi, et al., 2002). Worker health complaints have been reported for interference with respiration at 1 to 4 Hz, chest and abdominal pain between 4 to 10 Hz, and bladder and intestinal irritation at 10 to 20 Hz (Kroemer & Grandjean, 1997). Healthy men with seated exposure to WBV at 3, 4.5 and 6 Hz incurred elevated metabolic and respiratory responses which were physiological responses that corresponded to light work (Maikala, King & Bhambhani, 2006). WBV exposure has been shown to result in hormonal changes in men (Bosco, Iacovelli, Tsarpela, et al., 2000; Cardinale & Pope, 2003).

Vibration frequencies associated with WBV are much lower than those typically incorporated in noise assessment for hearing loss. However, WBV may also be implicated in the loss of hearing. Seidel, Harazin, Pavlas, et al. (1988) found that WBV in conjunction with noise increased hearing thresholds slightly, but the temporary threshold shift effects with WBV exposure at 6 and 10 Hz were significant. In another experiment, guinea pigs were exposed to relatively high levels of 10 Hz vibration for 30, 90 and 180 days; all animals subjected to WBV were found to have inner ear damage caused by vibration (Bochnia, Morgenroth, Dziewiszek, et al., 2004). The inner ear damage would also reduce hearing ability in higher frequency ranges such as speech.

Vision can become unsteady or blurred from WBV exposure, generally upon exposure to frequencies in the 10 to 30 Hz range. Dennis (1965) reported an increase in visual error rates of 88% with exposure to less than 7 Hz and discussed similar experiments conducted by researchers as early as 1939. A 50% reduction in visual acuity has been observed for exposure to 50 Hz vibrations with an acceleration of 2 m/s^2 according to a 1985 study by Guignard (as cited in Kroemer & Grandjean, 1997, p. 348). Initial reduction of visual acuity upon exposure was reported by Seidel, et al. (1988); however, the contribution of WBV solely to visual acuity reduction was low compared to exposures combining noise with WBV.

The International Organization for Standardization (ISO) (1997) reports in its WBV standard that prior literature suggests a higher health risk of LBP with WBV exposure. ISO notes that while an objective dose-effect relationship is assumed, there is no quantification of this relationship. Furthermore, ISO states that a lower probability association is assumed for WBV and health effects of the digestive system, genital or urinary system and female reproductive organs. As of 2002, WBV exposure and resultant LBP has been recognized as an occupational disease qualifying for compensation in four European countries; however, each country's regulations differ significantly with regard to compensation and WBV exposure relative to standards (Hulshof, van der Laan, Braam, et al., 2002).

Based on the preceding, it appears to be a fair assumption that WBV can cause negative human health effects. However, it is also believed that positive health effects can be obtained from proper doses of WBV, where muscles are stimulated and strengthened as the voluntary and involuntary contractions occur. A commercially available WBV conditioning platform is shown in Photo 2. Proponents advocate the use of WBV for body strengthening, and it is gaining popularity for athletic training, especially after endorsements by famous athletes and movie stars (Cardinale & Rittweger, 2006).

Research involving the use of WBV for conditioning is still relatively new. In a literature review, Luo, McNamara and Moran (2005) concluded that WBV appears to have short and long beneficial effects; outcomes in strength increases are dependent on vibration characteristics, elite athletes may achieve greater results than others; and additional studies are needed to examine the interdependent variables, especially chronic exposure. A 24-week training regimen with untrained female participants using WBV and traditional resistance training found both groups to have achieved strength increases (Roelants, Delecluse, Goris, et al., 2004). Cardinale and Rittweger (2006) supported WBV as an exercise method for the elderly to increase muscle strength and possibly bone mass because of its ease of use and low demands on the user. The obvious differences between WBV as a strength training method and occupational exposure are the willingness of the affected person and the duration of exposures, which are typically measured in minutes for trainees and hours for workers.

Vibration Standards

At the present time, the dominant WBV standard appears to be ISO 2631-1 (1997) Mechanical Vibration and Shock—Evaluation of Human Exposure to Whole-Body Vibration—Part 1: General Requirements. Another widely observed standard is the British Standards Institution's BS 6841 (1987). The standards differ in methods and rarely result in identical outcomes upon use, highlighting the difficulty of operating with different standards (Mansfield, 2005).

ANSI has published ANSI S3.18-2002 ISO 2631-1-1997, which is an adaptation of the ISO standard. In addition, American Conference of Governmental Industrial Hygienists (2001) has published thresholds for exposures that are based on the ISO standard. It must be noted that in the U.S., these are voluntary standards. A search of OSHA's general industry, maritime and construction standards found no inclusion of WBV. Most standards, research and publications for WBV have originated in Europe, although not unknown in the U.S. In November 2006, an online search for the ISO WBV standards by the Ohio University's health sciences librarian revealed that only two copies were listed in library catalogs in the U.S, one in Canada, and none of the three were available for circulation.

ISO 2631-1 (1997) provides requirements and guidelines for WBV measurement and evaluation. Its annexes provide guidance on exposure limits for health and comfort or perception interference. The caution zone for an 8-hour exposure duration starts at a weighted acceleration of 0.5 m/s^2. Figure 2 presents information from the ISO standard regarding passenger discomfort levels when subjected to varying magnitudes of WBV acceleration. The median value of vibration perception occurs at a Wk weighted peak magnitude of 0.015 m/s^2. An enforceable standard in Europe is the European Union (EU) physical agents (vibration) directive of June 25, 2002 (Mansfield, 2005). For WBV exposure, this directive establishes 0.5 m/s^2 as the action value and 1.15 m/s^2 as the limit value for an 8-hour time weighted average.

Photo 2: A WBV platform used for strength conditioning.

The Known & Unknown About WBV

At the First American Conference on Human Vibration hosted by NIOSH in June 2006, opening keynote speaker and WBV expert Michael Griffin, discussed the "known and unknown" of vibration health effects (Griffin, 2006). He explained that it is:

- *known* that people have LBP and some are exposed to WBV;
- *claimed to be known* that there is a system of WBV measurement that predicts exposure severity based on frequency and magnitude;
- *not known* exactly how and to what degree WBV causes LBP.

Another basic question is, "What does the SH&E professional know about WBV?" Based on the scarcity of available standards, relatively few published articles or seminar presentations in the U.S., and informal observation of conversations with SH&E professionals relative to WBV, an assumption was made that the topic is not well known or understood in the U.S.

To evaluate the level of WBV knowledge among U.S. SH&E professionals, an online survey questionnaire about WBV knowledge was prepared. The three main sections of the survey were self-rated knowledge of WBV, employment sector and personal experience (including length of employment, training or education, and certifications). With support from ASSE, on May 14, 2007, a broadcast e-mail was sent to 21,292 U.S.-based ASSE members (at all

Table 2

WBV Survey Results

A summary of results from a May 2007 survey of ASSE members.

Survey question	Expertise level	Response rate (%)
Have you heard of WBV?	None	38.6%
Can you define or explain WBV?	Basic Expert	22.4% 1.0%
Can you measure and quantify WBV?	Expert	0.9%
Do you know the ISO, ANSI, BS or ACGIH standards? (all combined)	Expert	1.0%

levels of membership, excluding students) requesting participation in the survey. The e-mail included a link to a host web survey site. A total of 2,764 persons completed the survey for a response rate of 13.0%.

Among respondents, 38.6% reported they "haven't heard of WBV" (Table 2). Of those initially having been made aware of WBV by a single source such as a journal, class, course or conversations, an additional 17.8% of the total respondents did not hear "about WBV from anywhere else."

Other questions required respondents to self-evaluate and rank themselves in five categories of WBV expertise from none to expert. In response to the question "What is your ability to define or explain WBV?" only 1.0% of all participants affirmed an expert ability to do so "clearly, completely, competently, comprehensively"; 22.4% reported a basic understanding. A similar 0.9% responded that they could measure and quantify WBV clearly and competently. Only one person claimed expertise in the British WBV standard; four persons reported expert knowledge of the ISO and ANSI WBV standards; and 18 claimed expertise with the ACGIH threshold limit values.

How might WBV affect workers in ways unknown to safety professionals? Possibilities include its role either as an underlying or perhaps primary accident causative factor. Often, work-related injuries can occur with no apparent cause and are explained in vague or inaccurate terms. Some of these injury or illness scenarios may include:

- "How could he hurt his back? All he does is cruise on his forklift all day and doesn't lift a thing by hand."
- "How could he hurt his back getting off of the bulldozer? He didn't fall; the handhold and footstep systems are the best available."
- "Why couldn't the driver read the warning sign clearly posted on the road? It was daytime and the windshield was clean."
- "How can this employee claim hearing loss due to occupational exposure when we have documented that the time-weighted averages are under the 85 dBA action levels?"
- "We sampled the air for chemicals and mold, could not find anything, and increased airflow to the workplace with a new heavy-duty filtration system. Why do the employees continue to complain of respiratory distress and bad air?"

As noted, WBV health effects can include LBP, visual acuity reduction, inner ear damage or respiratory interference.

WBV Action

To reduce adverse health effects from WBV, action is needed along three tracks:

1) Conduct further scientific research to resolve issues of WBV exposure and illness causation.

2) Expand SH&E professional WBV education in the U.S.

3) Minimize workplace exposures.

The connection between WBV and occupational illness appears in epidemiological studies (strong evidence according to NIOSH) and in the general consensus of safety professionals. Continued medical research is needed to confirm the precise effects of WBV on the human body. NIOSH is currently funding research to understand the mechanisms of vibration injury at cellular and molecular levels. Also, with an increase in data from field measurements of WBV exposures, perhaps enhanced analysis may lead to improved dose-effect understandings. The U.S. scientific community had its first conference on human vibration in June 2006 and a second conference is scheduled for June 2008; the gathering and dissemination of WBV research in this venue will advance knowledge.

Professional education regarding WBV must expand. As research provides more answers to the questions surrounding WBV, more information will likely reach the safety community. The safety and health community will become more aware of WBV as the topic appears in journals and seminar agendas. Vibration is a topic of interest for NIOSH; its research initiatives will lead to the dissemination of educational materials as well.

As awareness of WBV increases, SH&E professionals will be better equipped to discover situations where employee exposures may occur and follow a systematic approach to recognize, evaluate and control the hazard. Evaluation following recognition is needed to measure the magnitude of exposure; with the attendant technical issues and costs of monitoring instruments, quantification may be beyond the realm of many SH&E professionals and be performed by consultants or government agencies. Quantified exposures are needed to identify problem issues and establish control methods and priorities.

After WBV has been identified and evaluated, controls must be implemented according to the traditional hierarchy of hazard treatment—elimination or reduction, isolation, training or PPE. Elimination of WBV exposure to humans can be accomplished by engineering the source of vibration such as the equipment, vehicle or road to eliminate the vibration, or removing the employee from vibration-prone workplaces. Reduction or isolation of exposure entails reducing vibration at its source, transmission to the person and the duration of exposure. Steps to accomplish this can include the following:

- Replace old equipment with new equipment that incorporates low-vibration features.
- Ship by train instead of truck.
- Reduce vehicle speeds on rough terrain such as dirt roads and construction sites.

- Use dampening devices on equipment that generates vibration.
- Maintain equipment in optimal operating condition.
- Eliminate unnecessary steps in the job to reduce exposure times, especially with travel.
- Install vibration-reducing devices for the wheels, cab and seat of vehicles with seated operators.
- Inspect, maintain and repair as needed the operator's antivibration seats to optimize dampening.
- Apply ergonomic principles to locate controls and mirrors in a seated vehicle to allow the operator to sit in a forward-looking straight posture.
- Implement job rotation to reduce an individual's exposure time.
- Implement rules and operating procedures that prohibit jumping from large vehicles to the ground; require proper mirror adjustments and usage to prevent excessive turning; enforce strict lower speed limits.
- Train employees about WBV hazards and control.

Conclusion

WBV is a topic of emerging importance to the U.S. SH&E community. Current research here and abroad is attempting to answer questions of the unknown. As more scientific and medical facts arise, better workplace guidelines can be developed to educate SH&E professionals and reduce workplace exposure. Until then, a precautionary approach is warranted; WBV should be eliminated or reduced and employee exposure kept at a minimum. ■

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