# Whole-Body Vibration

## Building Awareness in SH&E

By Helmut W. Paschold and Alan G. Mayton

**Whole-body vibration (WBV)** comprises the transfer of relatively low-frequency environmental vibration to the human body through a broad contact area. These frequencies are in the range of 0.5 to 80 Hz (ISO, 1997; ANSI, 2002). Transmission occurs through the feet when standing, the buttocks when sitting (most common scenario) or the entire body length when reclining in contact with the vibrating surface. WBV exposures exist in many occupational settings.

**IN BRIEF**
- **Whole-body vibration (WBV) contributes to low-back pain and is a major source of lost time in occupational environments.**
- **Issues in the U.S. include inadequate professional awareness and knowledge of WBV, limited exposure assessment data and lack of mandatory standards.**
- **Exposure assessments can be made using a human vibration meter/data logger, and results compared with the health guidance presented in ISO and ANSI standards.**

The body as a whole and each individual organ have natural frequencies that can resonate with vibration energy received at their natural frequencies. Resonance of the body or its parts due to WBV is suspected to cause adverse health effects, primarily with chronic exposure.

Presently, most evidence supporting this relationship is epidemiological. Direct medical evidence is scarce, especially when compared to the greater amounts of data available for hand-arm vibration (HAV) illnesses that occur at higher frequency ranges. HAV exposures occur with higher vibration frequencies applied to the fingers and hands using powered hand tools, resulting in known adverse health effects such as "white finger" (Janicak, 2004).

In the U.S., standards are available for reference, however, no specific regulations (such as the Code of Federal Regulations) mandate WBV identification, monitoring and control. In Europe, WBV monitoring and exposure limits have been addressed in mandatory standards and regulatory directives.

The methodology used to monitor WBV is similar to that used to monitor occupational noise. Accelerometers are used in place of a microphone, and recording the direction of vibration waves is critical. WBV level is measured as oscillation about a fixed point and recorded in $m/s^2$; noise energy is measured as rapid variations in air pressure and is recorded in decibels.

Assessing noise and WBV exposure levels relative to mandatory levels (noise) or ISO/ANSI guidance levels can be fairly simple using devices such as a dosimeter and a human vibration meter/data logger, which are available from various manufacturers. Identifying probable sources of adverse noise and WBV exposure levels can be more difficult and tedious, and involves more complex data collection procedures with more sophisticated instrumentation and data-logging capabilities.

A 2006 survey of U.S. safety and health professionals was conducted to determine knowledge and awareness of WBV. Analysis of the data revealed a relatively low knowledge of the topic. Of the respondents, 69.5% self-reported less than a basic understanding of WBV (Paschold, 2008).

Many positive steps can be taken to eliminate or reduce harmful WBV exposure. These methods can include engineering redesign, procedural changes and employee training. However, before these corrective actions can be undertaken, WBV exposure must be identified and assessed.

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### Basics of Vibration

WBV is caused by the transmission of environmental vibration waves to the human body. Periodic motion is motion that repeats itself in an interval of time called its period (Griffin, 1990). Vibration frequency is expressed as the reciprocal (or inverse) of the period in Hz (or cycles of motion per second) and is characterized by magnitude (displacement, velocity or acceleration) and wavelength. In reality, we are not normally exposed to a vibration of a pure, simple, single wave; exposures include a multitude of simultaneous waves of differing frequency, magnitude, and direction.

As noted, the relevant frequency range for WBV is 0.5 to 80 Hz. Motion sickness is associated with frequencies below 1 Hz (Mansfield, 2005) and specifically from 0.1 to 0.5 Hz (ISO, 1997; ANSI, 2002). The relevant frequency range for HAV is 5 to 1500 Hz (Bruce, Bommer & Moritz, 2003). Figure 1 shows that the relevant frequency ranges for sound and ultrasound exposure are even higher.

### WBV Health Effects

The transmission of WBV to the human body at the natural frequency of the body as a whole or of its individual parts will result in resonance. The result is a condition in which the body or a part of the body will vibrate at a magnitude greater than the applied vibratory force.

In response, muscles will contract in a voluntary or involuntary manner and cause fatigue or a reduction in motor performance capacity (Chaffin & Andersson, 1984). This response may be considered adverse in the occupational realm; however, some view WBV as a means to achieve body strengthening as part of an exercise regimen. WBV platforms are now popular and in widespread use for athletic training (Cardinale & Rittweger, 2006).

Many adverse health effects are linked to WBV. These include interference with or irritation to the lungs, abdomen or bladder (Kroemer & Grandjean, 1997). Also, ISO/ANSI standards assume WBV adversely affects the digestive, genital/urinary and female reproductive systems (ISO, 1997; ANSI, 2002).

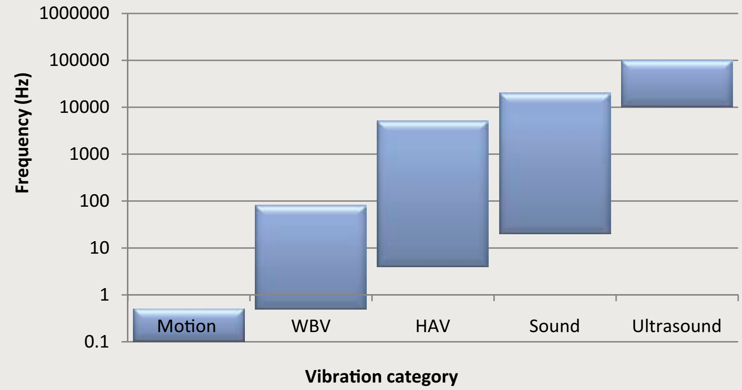
Effects of WBV on vision were reported as early as 1965 by Dennis (1965). A 1994 Australian study by Cross and Walters identified WBV and vehicle jarring as a contributing factor to back pain in the mining industry and as a significant risk to mobile equipment operators. During the 4-year period (July 1986 to March 1990), compensation claims totaling 28,306 were reviewed for surface and underground mining environments. Of the 8,961 claims relating to the head, back and neck, 11% (986) were related to vehicular jarring. Underground transporters and shuttle cars accounted for 53% of all injuries attributed to vehicle jarring (Cross & Walters, 1994).

A predominant adverse health effect is low-back pain (LBP). In a review of 19 WBV studies, NIOSH (1997) reported 15 studies to support positive association between WBV exposure and LBP. With this, NIOSH assigned its highest ranking descriptor of "strong evidence" to the WBV-LBP relationship. The following studies support the LBP relationship with WBV in specific industry studies:

- heavy construction (Kittusamy & Buchholz, 2004);
- forklift operation (Hoy, Mubrarak, Nelson, et al., 2005);
- vehicle operators (Schwarze, Notbohm, Dupuis, et al., 1998);
- professional drivers (Bovenzi, Rui, Negro, et al., 2006);
- farmers (Solecki, 2007).

**Figure 1**

**Frequency Ranges of Concern for Various Exposures**




WBV is caused by the transmission of environmental vibration waves to the human body.

Belgium, Germany, Netherlands and France acknowledge WBV exposure with resultant LBP as a compensation-qualifying occupational disease. These countries differ significantly in their criteria regarding compensation relative to exposure in excess of standard limits (Hulshof, Van der Laan, Braam, et al., 2002).

About 8 million U.S. workers have occupational vibration exposure. Of these, an estimated 6.8 million are exposed to WBV and the remainder to HAV (Bruce, Bommer & Moritz, 2003; ACGIH, 2001). These estimates of WBV exposure are based on a study published in 1974 (Wasserman, Badger, Doyle, et al., 1974). The 1974 study was limited because vibration levels were not measured and no WBV standard existed to determine relative risks.

The only other comprehensive assessment in the U.S. since 1974 was performed by NIOSH as a part of the National Occupational Exposure Survey (NOES) of 1981 to 1983, resulting in an estimate of 1.8 million U.S. workers as potentially exposed to WBV. These facts suggest the need for an updated assessment in the U.S.

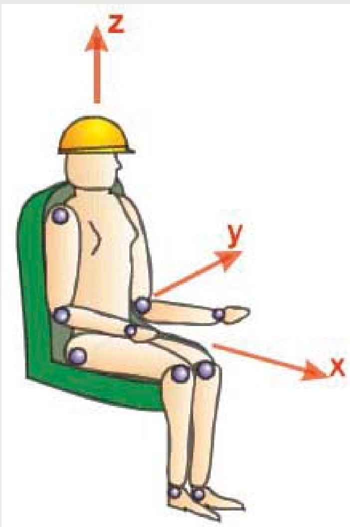
### WBV Standards & Regulations

Standards and regulations for WBV include the following:

- ISO 2631-1:1997 (Mechanical vibration and shock: Evaluation of human exposure to whole-body vibration—Part 1: General requirements);
- BS 6841:1987 (Guide to measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock);
- ANSI S3.18:2002 (adoption of ISO 2631);
- Documentation of the Threshold Limit Values for Physical Agents (2010) TLVs and BELs [American Conference of Governmental Industrial Hygienists (ACGIH)];
- European Directive 2002/44/EC (Occupational vibrations);
- The Control of Vibration at Work Regulations (CVWR) (OPSI, 2005).

WBV standards originated in Europe. Develop-

Figure 2
## Triaxial Coordinate System for a Seated Person




*Note.* Adapted from Guide to Good Practice on Whole-Body Vibration (v. 6) by M.J. Griffin, H.V.C. Howarth, P.M. Pitts, et al., 2006, Brussels, Belgium: European Commission.

ment of ISO 2631 began in 1966 and was first published in 1974. About this time, the U.K. disagreed with ISO 2631 on technical issues and initiated its own standard, ultimately resulting in BS 6841 (Griffin, 1990).

In the U.S., both ANSI and ACGIH adopted the ISO WBV standard for measurement and suggested exposure action and limit values. Although ANSI adopted ISO, ACGIH continues to base the TLVs on the 1985 ISO standard, which the 1997 version canceled and replaced. ISO (1997) adds that despite the "changes, improvements and refinements in ISO 2631, the majority of reports or research studies indicate that the guidance and exposure boundaries recommended in ISO (1985) were safe and preventive of undesired effects." Moreover, ACGIH reported in its 2001 publication that neither NIOSH nor OSHA had recommended or issued WBV standards. A contemporary search of NIOSH and OSHA websites confirmed that this has not changed.

WBV is measured in a three-axis coordinate system. The axes represent vibrations as fore and aft (x-axis), side to side (y-axis), and vertical (z-axis)

The European Directive issued in 2002 served to establish the methods for WBV monitoring and setting action and limit values for the control of occupational vibration across Europe (Nelson & Brereton, 2005). European Directive 2002/44/EC (Mansfield, 2005) and the CVWR of 2005 set the exposure action value (EAV) at 0.50 m/s$^2$ and the daily exposure limit value (ELV) at 1.15 m/s$^2$ (8-hour daily exposure), based on the ISO and British standards.

The other standards present similar action levels and exposure limits; however, these are presented in graphic or tabular form that is frequency dependent and more difficult to assess than a single frequency-integrated value. With regard to human comfort, magnitudes of WBV less than 0.315 m/s$^2$ are generally "not uncomfortable" (ISO, 1997; ANSI, 2002).

Photo 1: The seat pad accelerometer is connected via cable to a monitor.

### WBV Monitoring

Detecting and measuring vibrations requires the use of an accelerometer, which is connected to an electronic instrument used to amplify, analyze and store vibration data. WBV monitoring equipment can be assembled from components or purchased as an integrated instrument. NIOSH field research investigations in underground and surface mining and farming (Mayton, Kittusamy, Jobes, et al., 2009; Mayton, Jobes & Miller, 2008; Mayton, Kittusamy, Ambrose, et al., 2008) have used a methodology similar to that described in this article.

The ISO/ANSI standards provide information on WBV monitoring. WBV is measured in a three-axis coordinate system. When seated, the axes represent vibrations as fore and aft (x-axis), side to side (y-axis), and vertical (z-axis) (Figure 2).

Vibration is measured with a triaxial accelerometer placed at the interface between the vibrating surface and the human body. For seated measurement, the accelerometer is placed between the seat and ischial tuberosities (ISO, 1997; ANSI, 2002).

Seat pad accelerometers are commercially available and designed for relative comfort during monitoring. These pads are slightly pliable and measure 9.25 in. in diameter and slightly less than 0.5-in. thick at the center. Care must be taken to ensure proper alignment of the seat pad accelerometer with the x-, y- and z-axes. Photo 1 shows the placement of an accelerometer seat pad. The accelerometer is connected via cable to the vibration monitor, which is secured from movement in a location where it will likely not be damaged.

Vibration is measured as the variation with time of the magnitude of a quantity (e.g., distance) about a point that describes the motion or position of a mechanical system (Griffin, 1990). With simple addition, the positive and negative distances traveled from the reference point would cancel each other and equal zero. For this reason, vibration is expressed as the root-mean-square (RMS) of the vibration accelerations (m/s$^2$) and is calculated by finding the square root of the arithmetic mean of the squares of individual vibration wave values.

Measurement should last long enough to adequately describe or estimate the typical daily exposure of a worker and may require separate analyses of variable exposures during work tasks (ISO, 1997; ANSI, 2002). Some limitations of measurement duration may exist due to the data logging capacity of the instrument.

Analysis of exposure data should include the following metrics: crest factor, frequency-weighted RMS and vibration dose value (VDV). Crest factor is the ratio of the peak amplitude of the frequency-weighted acceleration signal to its RMS value (ISO, 1997; ANSI, 2002). The basic WBV evaluation method using frequency-weighted RMS may not be adequate to determine the vibration sever-

Table 1

## Summary of Responses to WBV Knowledge Study

| Questions asked | ($KL_{1-5}$) |
|---|---|
| Define or explain WBV? | 1.94 |
| Describe WBV health effects? | 1.84 |
| Identify WBV illness trend? | 1.63 |
| Identify WBV sources? | 1.92 |
| Monitor WBV levels? | 1.59 |
| Know ISO 2631-1:1997 standard? | 1.22 |
| Know BS 6841:1987 standard? | 1.10 |
| Know ANSI S3.18:2002; ISO 2631-1:1997 standard? | 1.36 |
| Know ACGIH TLV for physical agents standard? | 1.53 |

ity on humans if the crest factor is more than 9. When this occurs, VDV (a fourth power cumulative dose method), which is more sensitive to mechanical shock than the basic RMS method, should be included in the analysis. The European Directive 2002/44/EC, which is based on ISO (1997), has set a VDV EAV of 9.1 m/s$^{1.75}$ and a VDV limit value of 21 m/s$^{1.75}$.

As noise exposure levels are weighted according to noise standards, ISO- and ANSI-recommended weightings are applied to WBV frequencies for evaluating health, comfort, perception and motion sickness. Two weightings are prescribed by ISO during seated exposure monitoring. One is applied to the z (vertical) measures and the other is applied to the x (fore-aft) and y (side-to-side) measures (ISO, 1997; ANSI, 2002). These weightings can be easily set and applied in a WBV personal vibration monitor.

Health assessment of WBV exposure is made with respect to each axis. According to ISO (1997)/ANSI (2002), if RMS values for two or more axes are similar, a vector sum may be used to determine potential health risk, although how similar the values must be is not explicitly stated. These values can then be compared with regulations such as the European Directive or CVWR to evaluate potential health risk and required remedial actions.

When the three axes are combined, two additional and different weighting factors are applied in the computation of the vector sum. One weighting is applied to the z (vertical) measures and the other is applied to the x (fore-aft) and y (side-to-side) measures (ISO, 1997; ANSI, 2002).

To determine whether WBV exposures present potential health risks to workers, weighted RMS and VDV values can be checked and compared with the health guidance caution zones graphically displayed in the ISO (1997)/ANSI (2002) standards or the specified values of EAV (weighted RMS = 0.50 m/s$^2$; VDV = 9.1 m/s$^{1.75}$) and ELV (weighted RMS = 1.15 m/s$^2$; VDV = 21 m/s$^{1.75}$) in the European Directive 2002/44/EC. Griffin, et al. (2006), is another source for details on assessing vibration exposures.

### WBV Awareness Lacking Among U.S. Industry Professionals

As noted U.S. safety and health professionals have self-reported less than a basic understanding of WBV (Paschold, 2008). Survey particpants were asked to self-rate their level of WBV knowledge using a 5-point scale: 1) None: couldn't identify; 2) Few: awareness but without a depth of understanding; 3) Limited: basic understanding, about half; 4) Very well: most aspects lacking some detail issues; 5) Clearly, completely, competently, comprehensively.

The responses (approximately 2,600) were tabulated and described as Knowledge Level ($KL_{1-5}$), none of which averaged greater than 2.00. The highest knowledge areas were "ability to define or explain WBV" (1.94) and "identify WBV sources" (1.92). Knowledge and awareness of WBV standards was generally very low (Paschold & Sergeev, 2009). Table 1 presents a summary of question responses ($KL_{1-5}$).

Clearly, knowledge of WBV topics is not strong in the U.S. A limited survey of SH&E professionals in the U.K. revealed much higher knowledge levels regarding the CVWR and WBV (Edwards & Holt, 2007). This most likely can be attributed to the U.K. implementation of a WBV standard as law, as opposed to the U.S., which does not have a standard.

A survey of U.S. safety and health professionals was conducted to determine knowledge and awareness of WBV. Analysis of the data revealed a relatively low knowledge of the topic.

### Jobs Tasks That Present WBV Exposures

Many job tasks expose workers to WBV. The great variability in equipment, operational methods, maintenance, worksites, roadways, etc., compounds the difficulty in attempting to rank the most likely jobs to involve WBV exposure. However, the sidebar below presents equipment types that should alert employers to the potential for WBV exposures (Griffin, 1990).

### A WBV Case Study

NIOSH is active in research that focuses on human interactions with workplace vibration and includes WBV and HAV (Dong, McDowell & Welcome, 2005; Dong, Rakheja, McDowell, et al., 2005; Dong, Welcome, McDowell, et al., 2004). Field investigations have included WBV exposures for operators of underground mining equipment, off-road heavy vehicles in mines/quarries and farming operations (Mayton, et al., 2009; Mayton, Jobes, et al., 2008; Miller, et al., 2000; Miller, et al., 2004; Mayton, Kittusamy, et al., 2008). Mining equipment routinely

## Where Is WBV Found?

**Road transport**
Trucks
Buses
Cars, vans
Motorcycles

**Off-road vehicles**
Agricultural tractors
Construction earth-movers
Forestry machines
All-terrain vehicles
Mining equipment

**Rail transport**
Trains, light and heavy rail
Monorails

**Aircraft**
Fixed and rotary wing

**Industrial**
Cranes
Forklifts

**Marine**
Ships, boats

Photo 2 (a, top): Existing design for low-seam shuttle car seat; and (b, bottom) NIOSH's experimental design.

operates on rough surfaces under harsh operating conditions that produce WBV and mechanical shock with possible adverse health effects.

One WBV-critical component of the vehicle system is the seat. NIOSH researchers, in a systematic study, evaluated the seat designs (Photos 2 a, b and 3 a, b) on low- and mid-seam shuttle cars during production operations at underground coal mines in southern West Virginia (Mayton, et al., 2009). The objective was to support earlier findings that NIOSH seat designs, with notable ergonomic features (viscoelastic foam padding and low-back support), were improved designs for coal mine shuttle cars.

Eight shuttle car operators evaluated seven seat designs—one already in use on each of two vehicles and five NIOSH designs. Operators' perceptions of vehicle jarring/jolting and discomfort were measured using a visual analog scale (VAS) and questionnaire ratings.

These results were then compared to measured WBV levels and to the fatigue-decreased proficiency (FDP) limits of the former ISO (1985) standard to allow direct comparison with an older study of WBV exposure on shuttle cars and other mining equipment (Remington, Andersen & Alakel, et al., 1984).

Objective and subjective data indicated that NIOSH seat designs (with added adjustability, low-back support, improved seat padding) performed better to reduce vehicle jarring/jolting levels and that shuttle car operators favored them over existing seat designs. The low- and mid-seam seats showed 45% to 77% better performance in FDP and 9% to 60% better performance overall for operators' ratings.

Considering the VAS results for low- and mid-seam shuttle cars, under no-load conditions, operators rated the level of jarring/jolting 18% to 89% lower with the NIOSH seats. Reductions in measured vehicle jarring/jolting were 19% to 46% for the three-directional vector sum accelerations relative to the existing seats on the low- and mid-seam shuttle cars.

Questionnaire responses indicated that operators for both shuttle car models rated NIOSH seat designs as more comfortable overall. Moreover, the authors noted the use of seat foam padding alone is not the ultimate answer in providing optimum isolation for vehicle operators considering that seat foams will amplify vibration at lower frequencies (1.7 to 5.5 Hz) (Jobes & Mayton, 2006). Nevertheless, the NIOSH seat designs showed definite improvements over the existing seat designs for the shuttle car models studied.

The seat designs are now marketed by a mining equipment manufacturer that includes the improved seat design in its current product line. The manufacturer independently tested the new design and affirmed the results of the NIOSH studies. In terms of the U.S. market for low-seam shuttle cars, an estimated 51% of shuttle cars are now equipped with the improved seat design. Since 1999, estimates indicate that the improved seat designs may have positively impacted the safety and health of nearly 1,980 shuttle car operators (Mayton, et al., 2009).

## General Remedies for WBV

SH&E professionals must use a systematic approach to recognize, anticipate, evaluate and control the hazard. As demonstrated through the knowledge survey, the inability of SH&E professionals to recognize and evaluate WBV may hamper remediation efforts.

WBV exposure may be reduced or minimized in the following ways:

- Purchase newer technology and equipment.
- Install vibration dampeners on equipment and vehicles.
- Maintain equipment.
- Redesign equipment, vehicles or roads.
- Use transportation alternatives.

WBV control may include the following administrative tasks:

- job rotation to reduce individual exposure time;
- training that covers a) proper mirror adjustments and usage to assess ground conditions for objects (e.g., rocks or potholes) that may result in jarring or jolting the driver/operator as a vehicle backs up; and b) lower vehicle speeds;
- removal of employees completely from WBV environments.

## Conclusion

The results of the WBV knowledge and awareness survey suggest that U.S. safety and health professionals have inadequate knowledge or awareness of the topic. Since WBV is prevalent in U.S. occupations, with many workers exposed and with the absence of mandatory standards, effort should be made to increase knowledge and awareness of the subject through professional education. Interventions, such as seat redesign, can positively affect WBV exposure and improve operator comfort. **PS**

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Photo 3 (a, top): Existing design for mid-seam shuttle car seat; and (b, bottom) NIOSH's experimental design.

**Disclaimer**

The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of NIOSH.