WHOLE-BODY VIBRATION – REVIEW OF AUSTRALIAN AND INTERNATIONAL STANDARDS AND THE FUTURE

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Abstract

A review of Whole-Body Vibration (WBV) assessment methodologies is presented showing that a definitive assessment methodology for health effects is not yet available. Issues confronting the assessor using International and Australian Standards are highlighted. A description of the recent International Standard for WBV containing shocks is included along with some results and advice regarding this standard compared with others. This standard is specific to spine related health effects and includes dynamic analysis to model mechanical stress on vertebral endplates. The shift in theory behind health effects resulting from exposure to WBV containing shocks is discussed. The paper concludes with comments about the future direction of WBV standards.

Introduction

The effects of vibration and mechanical shock on the human body require further understanding before comprehensive assessments can be made regarding WBV and health effects. Although few will argue that regular vibration exposure can damage the body, the definition of the relationship between cause and effect is uncertain. In particular, the description of vibration that is relevant, the level of exposure to cause physical damage and the nature of this damage are aspects that remain unresolved.

Current Australian and International Standards for measurement of WBV are used to determine whether a particular occupational vibration exposure is acceptable. These standards exist despite incomplete understanding, which is evident when implementing the standards. They present different measurement analysis methods and require user interpretation in some areas. Furthermore, the standards provide guidance only (not criteria) for assessment of health risks and many industrial exposures fall within a caution zone, exceeding vibration exposure known to be safe but below that categorised as likely to cause long-term health effects.

It is encouraging that recent developments have warranted the release of another International Standard for WBV in February 2004. However, despite its “state-of-the-art” context, this standard does not supersede the previous standard and effectively adds another assessment approach to existing methodologies.

This paper aims to review the current standards for assessing the effects of WBV on people. In doing so, WBV will be presented as an area of continuing understanding that, based upon recent developments, is moving toward assessment that requires relatively complex measurement and analysis coupled with assumptions and statistical representation of health risks. The intention of this paper is to describe different analysis methods recognised for WBV assessment, to discuss issues facing the assessor of WBV health effects and to indicate possible trends for the future.

Whole-Body Vibration

WBV refers to vibration transmission to the human body occurring whilst the body is supported by a surface that vibrates. Vibration may affect the body through the feet of a standing person, the supporting area of a recumbent person, or the buttocks of a seated person. This occurs in many environments such as in vehicles, buildings and in the vicinity of operating machinery [1]. The human body will respond to WBV with varying degrees of relative motion of its parts. This creates stresses in these body parts that can be damaging, particularly for long-term exposure in occupational environments. WBV can affect humans in a variety of ways that are of concern to governing bodies and industries, ranging from annoyance to health impairment.

History of WBV

It was suggested by Rosegger and Rosegger (1960) that WBV and shock might be one of the causes of health problems as discovered by early occupational health surveys [2]. Frequent attempts have been made to establish supportable and demonstrable links between WBV and shock with physiological damage [3,4]. Difficulty arises in correlating this relationship due to the long-term nature of the resulting health effects. This is partly because vibration is not the only factor attributable to the health effects that are associated with WBV. The same health degeneration has also been linked to posture [3,5] and prolonged sitting [4,6].

The most common health effect reported due to WBV is that of back disorder, which has been broadly classified as “lumbar syndrome” [7]. This generalised classification reflects the lack of knowledge of health degeneration resulting from WBV. Although there is an overwhelming quantity of data and injury claims suggesting that WBV and shock probably do lead to health effects [8,9], epidemiological research has still not yet provided convincing and compelling evidence of the process whereby health degeneration occurs [9,10].

The mechanism describing health degeneration of the spine based on a material fatigue approach is well supported [9]. Sandover (1981) hypothesised that vertebral endplates display fatigue type behaviour, similar to engineering materials, when exposed to vibration containing shocks [11]. Fatigue failure of endplates can lead to reduced nutrition and degeneration of the lumbar spine, which may be caused directly or via callus formation [9,10]. In the last decade, the material fatigue concept has received considerable approval [4,12,13]. Sandover (1998) notes this concept "*offers the possibility of developing prototype dose response relationships for use in epidemiological and other research*" [9]. Through collaboration of current research amongst leading experts, particularly Morrison et al [14], this general concept has been released in the form of an International Standard [10] for assessing the impact of WBV containing shocks on the human body.

WBV Standards

Standards are a critical component of today's engineering world. Standards and codes were acknowledged in the top ten of the greatest mechanical engineering achievements of the 20th century by engineers surveyed by the American Society of Mechanical Engineers [15]. Standards are developed from scientific and experimental data and continue to evolve as greater evidence and information is discovered.

Current WBV standards reflect the formative nature of understanding in this area. These standards are solely definitions of measurement and analysis techniques, to identify the characteristics of vibration that are important to human response. The techniques typically differ in the signal processing of measured acceleration data, namely the combination or separation of vibration directions, the frequency range of data, the type of data averaging, the type of frequency weighting and whether individual bandwidth or overall spectral content is important.

Assessment of vibration severity and health risk is provided as guidance only in the standards, which state there are no proven quantitative relationships between vibration exposure and risk of health effects. Although it is evident our knowledge is progressing by the continual release of WBV standards over the last 30 years, the absence of a standard assessment methodology indicates that our certainty in current measurement, analysis and predictive techniques remains incomplete.

Evolution of WBV Standards

Early International Standards - ISO 2631

The first guidance for the evaluation of human exposure to WBV was published in 1974 as International Standard ISO 2631. After several amendments this was republished in 1985 under a new title. These early standards possessed similar characteristics. Griffen (1998) stated that versions *"were based on (root-mean-square) RMS acceleration and two frequency weightings (defined from 1-80 Hz by straight lines on a logarithmic graph of acceleration versus frequency) and a complex time dependency (from 1 min to 24 h)"* [16]. Frequency weighting in the vertical axis was greatest between 4 and 8 Hz, coinciding with resonances in the "lumbar" area. In the horizontal axes, frequency weighting was most significant between 1 and 2 Hz. These horizontal axes contained a multiplying factor for assessment.

Health assessments of WBV used separate analysis for each vibration axis. Vibration severity was determined by energy in each third octave band compared with predetermined limits. An approximation to this method, eliminating the need for spectral analysis was provided. This so named "Weighting Procedure" involved frequency weighting to calculate a single overall RMS acceleration. Guidance for the evaluation of health effects and fatigue-decreased proficiency was provided, although the latter has been deleted in subsequent standards.

British Standard BS 6841 (1987)

Although accepted internationally, the United Kingdom voted against ISO 2631 as a full standard and instead released drafts based on a similar methodology [16] before releasing their own standard in 1987, British Standard BS 6841 (1987).

This standard differs from the earlier International Standards in some areas. A methodology for the measurement and evaluation of vibration containing shocks, called the Vibration Dose Value (VDV), was introduced. This quantity is a single value representing vibration in each axis using frequency weightings, and assessment of the fourth power of acceleration between 0.5 and 80 Hz. Frequency weightings in BS 6841 differ from the early International Standards, and in part were implemented to eliminate the need for multiplying factors in the horizontal axes [16].

Australian Standard AS 2670.1-1990

Australia released a standard relating to WBV in 1990. This standard, AS 2670.1-1990 is identical with and has been reproduced from ISO 2631/1–1985. This standard was first published as part of AS 2670–1983, which was based on ISO 2631-1978.

International Standard ISO 2631-1:1997

Sections of BS 6841 were used in the revision of ISO 2631, released in 1997. This standard includes revised frequency weightings, calculation of a single overall RMS acceleration and the introduction of methods for assessment of WBV containing shocks. ISO 2631-1:1997 contains different methods for the evaluation of WBV, titled the Basic Evaluation method and Additional Evaluation methods, but does not clearly specify when to implement each evaluation method.

The Basic Evaluation method is to be included in vibration reporting in all instances, although at times it will underestimate the effects of vibration containing transients and occasional shocks [1]. The Additional Evaluation methods include the fourth power VDV and a

Running RMS method with one-second time constant. Health guidance is indirectly provided for the VDV. However, no guidance is provided for the Running RMS method. The inclusion of the additional methods was a prelude to recent WBV trends that place strongest emphasis on the peak magnitudes of vibration rather than the average energy of vibration.

Australian Standard AS 2670.1-2001

The current Australian Standard, AS 2670.1-2001 [17], is again identical with the current International Standard, ISO 2631-1:1997.

International Standard ISO 2631-5:2004

ISO 2631-5:2004 provides guidance for the assessment of health effects in the lumbar spine relating to long-term exposure to WBV containing multiple shocks. The fatigue failure of vertebral endplates theory has been developed with practical experiments and theoretical modelling and incorporated into ISO 2631-5 [14]. It is the first time a standard in this field has directly attributed a specific degenerative health effect to WBV and shock. Previous standards generalised the human response as simply adverse health effects consisting mainly of problems in the "lumbar" region.

Research undertaken in forming ISO 2631-5 involved the structuring of a Health Hazard Assessment method. Various stages of this method as implemented in the standard are displayed in Figure 1 [14].

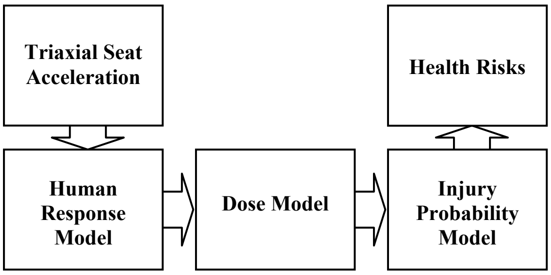

Figure 1: Health Hazard Assessment Flowchart

Triaxial seat acceleration data is converted to spinal accelerations based upon mathematical response models for the human body. The human response model for lateral directions is based on a simple linear system. In the vertical direction, human response to shocks is non-linear, and hence a more sophisticated model based on a recurrent neural network is applied. Only the compressive vertical shocks are included as it is compression of the spine that initiates spinal degeneration [10].

The dose model consists of two stages. The first stage involves the calculation of the spinal response acceleration dose, which considers the sixth power summation of all spinal acceleration peaks. This approach models fatigue properties of the spine. The second stage involves calculation of an equivalent static compressive stress, S_e, able to cause the same degree of fatigue as that seen by the spine of the subject for the vibration data.

The injury risk model is a cumulative probability distribution devised using data obtained from cadavers, so that population variance is accounted for [14]. Health risks can be determined using guidance in the standard.

Overview of WBV Standards

WBV standards specify a measurement and analysis method for operator WBV based upon triaxial accelerations typically at the operator seat, but provide guidance rather than criteria for the assessment of the severity of WBV. The most recent standard, ISO 2631-5 is specific to spine related health effects and is most detailed, requiring dynamic analysis to model mechanical stress of vertebral endplates. Health guidance in the standards defines action and limit levels for daily exposure indicating proposed safe and unsafe long-term exposures as well as a significant range of uncertainty between these values. The exposure limits are not epidemiologically verified. Nevertheless, when specifying levels of acceptability, authorities often use the guidance provided in the standards.

The strength of the standards is that they are internationally recognised and applied and will classify very high and low WBV with certainty. However, as already stated, many industrial WBV exposures will fall into a caution zone between categories, providing uncertainty to the user, which is a weakness. Other weaknesses of the standards are the absence of a single measurement and assessment methodology and the ambiguities in the current methods. Possible improvements include definition of acceptable short-term exposures and guidelines outlining acceptable measurement durations and data certainty. Some of these are not possible based on current knowledge.

Issues for the Assessor

An assessor is typically faced with the task of evaluating WBV exposure and any corresponding long-term health implications. Sequential steps to achieve this consist of, representative measurement of seat vibration, calculation of the severity of vibration according to methods contained within applicable standards, determination of the average exposure duration of the human subject and the selection of the criterion to be applied. Assessors require understanding of the operation of machinery causing WBV, the WBV standards and assumptions that must be made in their application.

Representative Measurement of Vibration

The assessor must determine average vibration severity that is relevant. ISO 2631-1 states *"it generally takes several years for health changes caused by whole-body vibration to occur. It is therefore important that exposure measurements are representative of the whole exposure period"* [1]. As measurement of vibration exposure over years is impractical, short-term measurements are used to determine long-term average exposures. A short-term measurement must incorporate all types of regular activity of the machine in the correct ratio of durations. An accurate representation of vibration is critical as it applies to long-term exposure.

For equipment with operating conditions that cause vibration to vary little from day to day, it is sufficient to measure typical conditions to achieve reliable results. This can be the case for mining haul trucks, when conducting regular load-haul-dump cycles over similar distances every day. Here, measurement of a small number of complete cycles results in acceptable assessment of the long-term vibration severity.

For equipment with operating conditions that cause vibration to vary significantly from day to day, measurements must incorporate the full range of conditions in order to determine vibration that is representative. This situation occurs often, for instance with excavation equipment where digging conditions vary, or for dozers where the operating mode and hence ride roughness can vary. For such cases, vibration measurements must be planned using advice from the equipment operator. Individual assessments can be made of each activity and combined using representative durations.

The measurement duration must be sufficient to define the character of vibration for the analysis method used. For RMS vibration, it is enough for the duration to include several repetitions of machine behaviour. However, for VDV and S_e evaluations, which are dramatically affected by vibration shocks, the measurement duration must include repeated similar maximum amplitude shocks. If not, there is uncertainty regarding the frequency of occurrence of the measured once-off maximum shock, which is critical when determining long-term exposure. The assessor can only determine whether the measurement duration was sufficient after processing the data. Furthermore, it must be accepted that irregular, say once per day or more, maximum shocks will not be accurately considered during short-term measurements. Figures 2 and 3 show measured vertical spinal acceleration using ISO 2631-5. Values above $5ms^{-2}$ can be considered significant. Figure 2 shows repeated shocks of equivalent magnitude and can be considered a better sample than Figure 3 having one very large shock, which may be a rare occurrence.

Another factor that can affect WBV results considerably is the condition and set-up of the operator seat suspension. This can vary long-term because of deterioration and also because of improper adjustment for operator mass. An assessment of seat dynamic performance is useful when conducting WBV assessments.

Vibration Severity (Standards Methodology)

The severity of measured vibration is calculated by the analysis methodology applied by the practitioner. Typically, vibration will be defined by RMS acceleration, VDV or S_e as described in the standards, each providing different descriptions of the measure, or severity, of the vibration. As highlighted earlier, the methods differ in the power of acceleration, frequency weighting of acceleration and treatment of vibration directions.

When applying ISO 2631-1, Annex B states, *"health disorders are currently understood to be influenced by peak values and are possibly underestimated by methods involving RMS averaging alone"* [1]. The fourth power VDV evaluation method therefore seems more applicable than RMS acceleration in characterising the effects of vibration on long-term health effects. However, the standard does not require compulsory use of the VDV. The assessor must decide which evaluation method and criteria to implement; hence assessments of similar vibration exposure performed by different assessors can result in varying recommended exposure limits. Introduction of ISO 2631-5 adds another option, and based on latest health research regarding spinal degeneration due to WBV; it appears to be the most applicable. A conservative analysis approach is to apply the worst case of three methods.

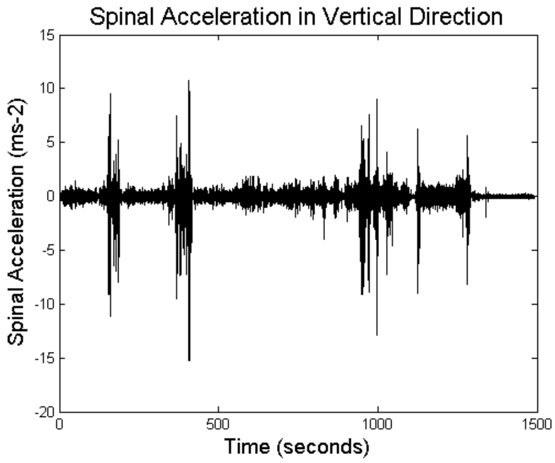

Figure 2: Spinal Acceleration A [ISO 2631-5]

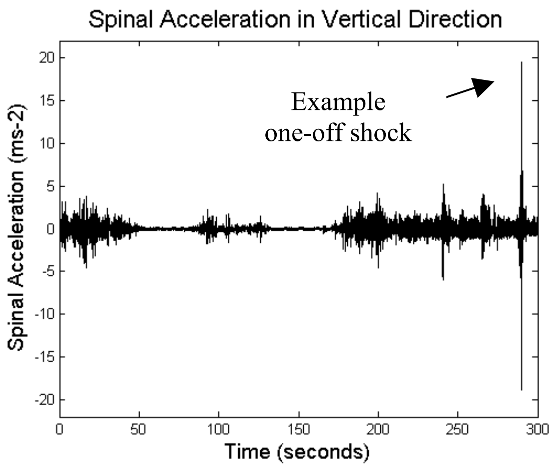

Figure 3: Spinal Acceleration B [ISO 2631-5]

The assessor should be aware that sometimes the measurement of VDV or S_e would not be valid for long-term prediction. The assessor is advised to review measurement data to determine whether the VDV and S_e results are dominated by a single vibration event, in which case the measurement is not suitable for long-term prediction.

It must be added that the Basic Evaluation method of ISO 2631-1 is ambiguous regarding vibration measured in more than one direction. ISO 2631-1 states *"[t]he assessment of the effect of a vibration on health shall be made independently along each axis"* [1]. However, in a note following this statement, it is indicated, *"the vector sum is sometimes used to estimate health risk"* [1]. Adding further uncertainty, the Additional Evaluation method of ISO 2631-1 does not indicate whether the VDV of multiple axes should be evaluated separately or combined. The current British Standard indicates that the combination is to be used.

Table 1 compares different WBV assessments for the data of Figures 2 and 3. The weighted RMS acceleration is similar resulting in ISO 2631-1 Basic Evaluations that are similar (a limit of approximately 13 hours per day). The VDV and S_{ed} results show dramatic differences between the measurements. The VDV for Figure 2 is greater, having more large impacts per unit time, resulting in a limit of 4.1 hours of exposure per day. The S_{ed} for Figure 3 is greater, having one extremely large impact per unit time, resulting in a limit of 0.4 hours per day. These results illustrate the different outcomes that can result from a single measurement depending upon the analysis method used and the extreme (perhaps incorrect) results that can occur when extrapolating data containing a single shock result when implementing ISO 2631-5.

Table 1: Comparison of Evaluation Methods

	Vibration Level	*Action Hours*	*Limit Hours*
ISO 2631-1	0.60[a]	5.5	14.1
RMS (ms^{-2})	**0.64[b]**	**4.9**	**12.6**
ISO 2631-1	20.1	0.3	4.1
VDV8hr ($ms^{-1.75}$)	**16.4**	**0.6**	**9.2**
ISO 2631-5	0.74	0.7	12.5
S_{ed} (MPa)[c]	**1.32**	**0.02**	**0.4**

[a] Italic type – Analysis of data presented in Figure 2
[b] Bold type – Analysis of data presented in Figure 3
[c] S_{ed} – *Daily* equivalent static stress using ISO 2631-5

Vibration Exposure Duration

The duration of vibration exposure is fundamental to the risk of health effects from WBV. Determination of the average daily duration of WBV exposure for the operator is difficult without detailed observations and is most often estimation based upon best available information or judgement, which can be erroneous. Vibration exposure depends upon machine utilisation and staff rotations as well as variables such as length of working shifts and number of working days per annum. Guidance in current WBV standards for calculation of the risk of adverse health effects is based on an 8-hour working day, and about 240 working days per annum. For typical 12-hour shift rosters, equivalent exposure can be related to around 170 working days per annum. The effects of longer working days but also longer recuperation periods with this type of roster are not considered in the methods of the standards. However, ISO 2631-1 notes that increasing the duration of exposure, whether over a day or daily over years, will lead to an increase in vibration dose which is assumed to increase the risk. It is also stated that periods of rest can reduce the risk [1].

Health Criterion

Despite standards providing health limits for guidance only, they are usually applied to provide assessments. Two criteria are described in the standards, an action level and a limit level. These levels can either be acceptable number of hours exposure for the vibration profiles measured, or else acceptable vibration severity for the number of hours of exposure. An interpretation is, the limit level warrants immediate action as health effects are likely, whereas the action level describes preferable action, as health protection is not assured.

Although WBV Standards do not formally provide health limits, Directive 2002/44/EC of the European Parliament and of the Council [18] provides exposure limit values and action values for WBV based upon ISO 2631-1 that differ in some instances from the guidance of ISO 2631-1 itself.

It is the authors' opinion that a starting point for the maximum line of acceptability is half way between the action and limit criteria. This represents a target that is likely to be achievable with current technologies, and according to interpretation of existing standards, a criterion that represents a 10% to 20% risk of long-term health effects.

Future

The developing nature of WBV understanding indicates that future progress is imminent. Future standards will likely address some of the following aspects. Definition of proven methodologies and health limits is eagerly awaited, although it is most likely that the definition will be in terms of risk probability, rather than an absolute value. Furthermore, it is possible that different standards will be defined for different health symptoms, each standard characterising the vibration contributing to a specific health ailment, just as ISO 2631-5 refers to degeneration of vertebral endplates. However, until epidemiological data becomes available, the assessor must determine whether health limits will be based upon those provided within Standards, the directive of the European Parliament, or otherwise.

If a proven cause-effect relationship cannot be established, limits of acceptability are predicted to become conservative, equaling the action values indicated in the standards.

It is arguable that daily or other short-term vibration exposure limits exist for which acceptable limits must be defined. These are anticipated in the future and are expected to be relevant to modern day work practice where contractors may conduct bursts of high intensity labour. Furthermore, given the dependence of recent trends upon peak values, techniques to determine whether measurement data is acceptable for long-term predictions will be required.

Conclusions

Guidelines in WBV measurement standards permit a broad level of assessment that will identify clearly acceptable or clearly unacceptable vibration. However, many industrial applications fall within an intermediate caution zone. Several methods of analysis and assessment are available, as a recognised dose-response relationship is not established. International Standard ISO 2631-5:2004 is the most recent and seemingly advanced standard for assessing spinal degeneration health effects. WBV health assessments require understanding of the operation of machinery causing WBV, the WBV standards and assumptions that must be made in their application. Therefore, assessors require skills not imparted by the standards.

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