Vibration Injury Network

Research Network on Detection and Prevention of Injuries due to Occupational Vibration Exposures

Review of methods for evaluating human exposure to whole – body vibration

Appendix W4A to Final Report

May 2001

EC Biomed II concerted action BMH4-CT98-3291

WORK PACKAGE WP4W REPORT

1. General

In this report the reliability and validity of a few existing methods for the measurement, evaluation and assessment of human exposure to Whole – Body Vibration (WBV) is discussed. Current standard methods are compared with alternative methods. Consideration is given to the completeness, flexibility, possible ambiguities of each method, technical complexity of measurements required, validation of the method by epidemiological data, as well as sensitivity to different objective (mechanical) and subjective (individual) quantities characterizing the system under investigation. The final target of this analysis is to provide elements towards a future improved method for protecting workers against vibration hazards.

Current standard methods, based on acceleration, are reviewed in § 2. An alternative method, based on absorbed power, is discussed in § 3. Finally § 4 includes an agenda for future improvements to the existing methods.

2. Current Standard Methods

Current standard methods include:

- ISO standard 2631 – 1 (1997) “Mechanical vibration and shock – Evaluation of Human Exposure to Whole – Body Vibration. Part 1: General Requirements” [4]
- British Standard 6841 (1987) “Measurement and evaluation of human exposure to whole – body vibration” [1]

In the next two sections the essential elements of each of these two standards are outlined in order to allow a simple comparison. A thoroughful critical review of ISO 2631 – 1 and BS 6841 has recently been published [3], which includes an extensive analysis of merits and weak points of each of these two standards. This paper was originally presented at the 1st International Whole-body Vibration Conference, which was organized by the leader of this research project, The Institute of Sound and Vibration Research (ISVR).

2.1 ISO 2631 - 1

The International Standard ISO 2631 - 1 has emerged as the long – awaited result of an extensive revision process of ISO 2631/1 (1985). Unfortunately, it is not at all clear that it marks any significant improvement over the document which it has superseded.

2.1.1 Axes of vibration

In principle all the translational axes on the surface which supports the subject are included. However, while the possibility of measurements, evaluation and assessment of vibration for standing subjects is mentioned, the actual use of the standard for this purpose is admittedly hampered by the limited experience and the lack of experimental data existing in this field. In practice the standard's field of application appears to be restricted to seated subjects. The measurement of X-axis acceleration on the backrest is encouraged, but not taken into account when assessing vibration severity. The effective set of vibration axes is then limited to the three translational axes between the seat and the ischial tuberosities. The rationale behind this choice was to provide a simple, though approximate, method of evaluation and assessment of the vibration.

2.1.2 Frequency of vibration and weighting curves

Six frequency curves are presented covering the most significant combinations of vibration axes and effects (health, comfort, perception, motion sickness). Three of these curves are used in the evaluation of vibration from the point of view of health effects, but only two in the procedure of assessment of vibration severity (see point 2.1.1. above). The introduction of the new W_k frequency weighting for exposure of seated subjects to vertical vibration appears to be unjustified, given that no compelling scientific evidence has emerged requiring the establishment of a new frequency weighting, and differences with at least one of the pre-existing frequency weighting (W_b in BS 6841) are much smaller than uncertainties currently associated with the definition of a function of this type. Finally, correlations between vibration magnitude and subjective response obtained using W_b and W_k weightings showed no statistically significant difference between each other [10].

2.1.3. Magnitude of vibration

The basic evaluation method makes use of the r.m.s. acceleration a_w. It is unclear if worst axis acceleration or triaxial vector sum has to be used for evaluating the vibration. Because only one set of threshold limit curves is available for severity assessment, this ambiguity may lead to substantial errors. The additional use of two alternative methods is recommended when the vibration crest factor exceeds 9, a criterion the standard itself recognizes as incongruous. The use of the time-integrated fourth power of acceleration, known as Vibration Dose Value (VDV) is regarded as important when the ratio of VDV to ($a_w \times T^{1/4}$) exceeds 1.75. This value is however unjustified and possibly wrong. It is not specified how the total triaxial VDV can be calculated from the axial VDV's. When only r.m.s. measurements of a_w are available, the vibration dose value may be estimated as 1.4 $a_w \times T^{1/4}$ (in which case it is called eVDV). The use of the maximum transient vibration value (MTVV) is regarded as important when the ratio of MTVV to a_w exceeds 1.5. This value is likewise unjustified and possibly wrong. The quantity MTVV is defined in two different ways, potentially providing very different results. There is no indication as to what use should be made of MTVV once it has been calculated, since no limits to be used for comparison with the measured values are provided.

2.1.4 Duration of Vibration

Vibration assessment depends strongly on the duration of exposure. The threshold limit value is not defined below 1 minute. Between 1 and 10 minutes a flat limit for a_w is provided, which is inconsistant with the equal energy principle (implicit in the r.m.s. method). Because no precise statement is provided of what is meant by "period of exposure" (see the Standard's Annex B), the result depends on the method used to subdivide the daily exposure, as well as on the arbitrary inclusion or exclusion of periods of low vibration. Finally, above 10 minutes the allowable acceleration is inversely proportional to the square root of duration ($a \propto t^{-1/2}$). In spite of this law being restricted to durations in excess of 10 minitues, it still allows very large acceleration values because of the relative steepness of the relation between permissible acceleration and exposure time. Annex B of the standard does include a second set of threshold limit curves which follows a more shallow dependance ($a \propto t^{-1/4}$). It is however unclear under which circustances each of the two time dependancies should be used.

2.2 BS 6841

The British Standard BS 6841 was published in 1987 in response to what was perceived in Britain as the failure by ISO standard 2631 (1985) to appropriately address some of the major issues of human exposure to WBV. It appears to have encountered the general appreciation of users, with just a few shortcomings having been identified. Although it might certainly be improved, it may represent a good basis of discussion for the drafting of a future standard on this topic.

2.2.1 Axes of vibration

The standard recommends that measurements are performed on: three translational + three rotational axes between the seat and the ischial tuberosities; three translational axes between the back and the seat backrest; three translational axes beneath the feet. As in the case of ISO 2631-1, assessment of vibration from the viewpoint of implied health risks is based on a limited subset including the three translational axes on the surface supporting the subject + the X-axis acceleration on the backrest (seated subjects only).

2.2.2 Frequency of vibration and weighting curves

Six frequency curves are provided covering most combinations of vibration axes and effects (health, hand control, vision, comfort, perception, motion sickness). Only three curves are used in the evaluation of vibration from the point of view of health effects. The most widely used of these frequency weightings (W_b), which has been designed to mimic human sensitivity to vertical motions, is based mostly on subjective responses with some input provided by transmissibility data. It is unclear to what extent it provides a good representation of human susceptibility to injury.

2.2.3 Magnitude of vibration

The basic recommended method makes use of triaxial r.m.s. acceleration. The use of time-integrated fourth power of triaxial acceleration (VDV) is supported when the crest factor is above 6, a criterion which is at best questionable (see § 2.1.3.). However, when evaluating and assessing vibration for health effects, VDV is the only option given. When only measurements of a_w are available, the vibration dose value may be estimated from a_w (in which case it is called eVDV).

2.2.4 Duration of Vibration

An unique threshold limiting curve is provided, applying to all durations from less than a minute to 24 hours. The final result is therefore independent of the subdivision of the daily exposure.

2.3 Discussion

Both standards assume that acceleration magnitude, frequency spectrum and duration represent the principal exposure variables which account for the potential harmful effects. The acceleration measured at one or more of the points of entry of vibration to the body is used in order to quantify the vibration magnitude.

Because of a combination of tradition and technical difficulties most often this is limited to measuring acceleration on the contact surface between the seat and the ischial tuberosities.

Methods based on acceleration are fast, conceptually simple and technically hassle free, since acceleration is the quantity directly measured by detectors. Signal processing is limited and easily provided by all existing commercial equipment.

On the other hand, the method presented in these standards is insensitive to such quantities as posture and muscle tension which are likely to play a role in coupling the human body to the vibrating surface, and so ultimately in determining the injury risk. This method does not consider the vibration which is actually transmitted (either exchanged or absorbed) to the body.

The basic method advocated by ISO 2631 – 1 (as well as by parts of BS 6841 and by the recently revised proposal of European Union Directive on vibration [2]), makes use of the r.m.s. acceleration a_w. The thresold limit curve is based on the assumed existence of a relation $a \propto t^{-1/2}$, that is $a^2 \times t$ = constant, i.e. the equal energy principle. This appears to be more convenient than realistic. The severe dearth of both epidemiologic and experimental data to establish that such an “energy- equivalent” time dependency provides a good representation of the risk posed by daily exposures of different durations is even more extreme for WBV than it is for HAV.

The relative significance of vibration at different frequencies from the viewpoint of health risks is accounted for by means of frequency weightings. All frequency weightings (including W_b and W_k) are based on a combination of data on transmission of vibration along the spine and subjective judgement. The latter is of course a good indicator of comfort / discomfort, but may not be as good an indicator of the existence and magnitude of health or injury risks.

3. Alternative Methods

3.1 Absorbed Power

The possibility of using the power absorbed (P_{ABS}) by the human body when exposed to seat – transmitted vibration, in order to evaluate and assess the vibration, was first explored by a group of US Army engineers in the mid-60’s. The main results of their investigation were summarized in a paper [5] which was strongly critical of the philosophy underlining the (then underway) drafting of the first version of ISO 2631, which has to a large extent been carried over to the latest version of 1997. Work on this issue was then discontinued, and the technique has been left dormant until it has been recently revived [8] by one of the partners of this research project, the Swedish National Institute for Working Life (NIWL) following the promising results collected in the last 10 years in the field of Hand-Transmitted Vibration.

The power absorbed by the subject exposed to vibration is calculated from the simultaneous measurement of force, acceleration and their relative phase. In this method the coupling between the vibrating structure and the body is automatically accounted for, so that the result is sensitive to both working posture and seat contact dynamic forces, and might be a better measure of the physical stress imposed on the body.

3.1.1. Axes of vibration

This method can be used to independently measure the power absorbed as a consequence of vibration along any given axis. However, since power is a scalar quantity, it is easy to calculate the effect of exposure to all three components of vibration. The novel approach of absorbed power includes the quantities to be measured as well as the subsequent signal processing, but it does not include the measurement locations, whose choice is still left to the experimenter's expertise. Consideration has only been given to vibration of seated subjects, but there is no difficulty of principle in extending the analysis to standing or recumbent subjects.

3.1.2. Frequency of vibration

The differing injury potential of different frequencies is already accounted for in the calculated value of the power. No frequency weighting is therefore necessary if the hypothesis is made that absorbed power is directly linked to health effects. The measurement of absorbed power can lead to an assessment of vibration severity if combined with the duration time of vibration, giving the time - integrated absorbed energy.

3.1.3. Magnitude of vibration

It is quantified by the absorbed power. There is a tight linear relation between power and acceleration squared. Non linearity shows up mostly for vertical vibration at frequencies close to resonance (around 5 Hz), where P_{ABS} increases more quickly than a^2 [9], possibly requiring higher order ter.m.s. such as $P \propto a^4$. This makes a direct conversion of acceleration spectra to power spectra very complicated. On the other hand, frequency – integrated power is to a very good approximation linear with a^2 [7], [9], suggesting that it can be modeled as a "redistribution" in frequency of human sensitivity.

If the assumption is made that equal values of P_{ABS} imply equal injury risk, then a weigthing curve can be calculated, which can be used to weight acceleration data. The appropriate weighting is given by the square root of the power absorbed by a subject exposed to a flat acceleration power spectrum. When compared to the W_k and W_b weightings of ISO 2631-1 and BS 6841 this weighting curve shows good overall agreement below 5 Hz, but indicates lower sensitivity at frequencies above 5 Hz [7], [9]. This is at variance with the current trend towards higher sensitivity values, in recognition of an existing underestimate of the discomforting potential of vibration in this frequency range. Any significant use of absorbed power for the prediction of comfort can almost certainly be ruled out.

It must be stressed however that since both W_k and W_b reflect subjective reactions (discomfort) more than actual sensitivity to health risks, departures from these curves do not necessarily imply inadequacy in the evaluation of vibration for the prediction of health effects. What can be said is that, given the present absence of evidence in favour of differences between human subjective response and human sensitivity to injury, there is no reason to claim that the weighting based on absorbed power is superior to W_k and W_b. No proof can however be given that this weighting is inferior either.

No validation of this method using epidemiological studies exists. A final statement on the validity, let alone superiority, of this method in the evaluation of vibration in ter.m.s. of possible health effects cannot yet be made.

4. Suggestions for Future Documents

4.1 Classical methods

British standard BS 6841 may represent a good base for a future document. Here is a short set of suggestions which may lead to improvements and removal of some of the existing weak points:

- Contrariwise to what happens for health effects, vibration assessment for comfort, perception, etc. depends on the crest factor exceeding a threshold value. It would be desirable to have a single method of vibration assessment. Additionally, VDV might also be cast in ter.m.s. of a mean acceleration (termed r.m.q.) representing the formal equivalent of r.m.s. acceleration.
- It must be recognized that measurements of a_w are presently much more widespread than VDV measurements. The need for a conversion mechanism from a_w to VDV is real. The algorithm provided by ISO 2631 - 1 and BS 6841 is very simple, possibly too much. Better results can be found by fitting data (e.g [6]) originating from experiments where a_w and VDV have been measured simultaneously.
- Health effects are presumably associated to long-term exposures. No estimate is currently provided of the injury probability at the threshold limit curves. Nor is it indicated how those threshold limits would change if exposure were erratic or continuous, over very long or short timescales. Following the existing standards on exposures to noise and to HAV, an effort should be made to find predicting algorithms for the fraction of impaired subjects as a function of some estimate of cumulative dose (e.g VDV $\times$ D), or at least a 10% threshold limit such as the one shown in ISO 5349 for HAV. Although we recognize that this task is especially difficult given the absence of pathologies with high

specificity, it should nonetheless have high priority if a reliable quantitative prediction of the involved risks is desired.

- Some deeper understanding of the link between the exact time evolution of exposure, and the incidence of relevant pathologies is needed, so that the effect of recovery periods is adequately taken into account.

4.2 Alternative methods

Acceleration measured at the seat – body interface is certainly one of few quantities lying at the roots of the process eventually leading to injury occurrence, and it might well be the single most important one. However it is oversimplistic to try and correlate directly the exposures based on acceleration values with the results of epidemiological surveys. The resulting relationship is necessarily poor.

Injury or health risks are much more likely to be related to quantities describing local alterations or departures from healthy conditions. It is among quantities of this kind (local forces, strain, temperature, absorbed energy, fluctuating energy, ….) that the best descriptor must be searched. A theoretical approach evaluating vibration – related loads on the lumbar spines has been recently developed for risk assessment [11]. This is a very attractive but equally sophisticated procedure, whose practical application is presently impossible. This and other studies also indicate that the significance of biological factors such as age, posture and anthropometric data is probably as important as the exposure magnitude itself.

Absorbed power is also a step forward in the right direction, although it will surely have to be supplemented by other descriptors.

- No information is currently available on the location of energy deposition in the body. A better understanding of this issue is of critical importance because larger structures may be able to absorb larger amounts of energy with little or no damage.
- Fluctuating energy has not yet been taken into accont. Although this component does not contribute to energy deposition in the body, it is associated with extensive and compressive movements, interfering with blood circulation and nutrition. This might also cause tissue stress eventually contributing to the insurgence of problems.

5. References

1. British Standards Institution **BS 6841. Measurement and evaluation of human exposure to whole – body mechanical vibration.** London, 1987.

2. Council of the European Union, **Amended proposal for a Council Directive on the minimum Health and Safety requirements regarding the exposure of workers to the risks arising from physical agents (Vibration)** - Individual Directive within the meaning of Article 16 of the Directive 89/391/EEC, 1999

3. Griffin M.J., **A comparison of standardized methods for predicting the hazards of whole body vibration and repeated shock**, Journal of Sound and Vibration 1998, 215: 883 - 914.

4. International Organization for Standardization **ISO 2631-1. Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole – Body Vibration. Part 1: General Requirements.** Geneva, 1997.

5. Lee R.A., Pradko F.1968, **Analytical Analysis of Human Vibration**, SAE paper 680091

6. Lewis C.H., Griffin M.J., **A comparison of evaluations and assessments obtained using alternative standards for predicting the hazards of whole-body vibration and repeated shock**, Journal of Sound and Vibration 1998, 215: 915 - 926.

7. Lundström R., Holmlund P., **Absorption of energy during whole-body vibration exposure**, Journal of Sound and Vibration 1998, 215: 801 - 812.

8. Lundström R., Holmlund P., Lindberg L., **Absorption of energy during exposure to whole-body vibration**, UK Informal Group Meeting on Human Response to Vibration, 1995.

9. Mansfield N.J., Griffin M.J., **Effect of magnitude of vertical whole-body vibration on absorbed power for the seated human body**, Journal of Sound and Vibration 1998, 215, 813 - 825.

10. Mansfield N.J., Holmlund P., Lundström R., **Comparison of subjective responses to vibration and shock with standard analysis methods and absorbed power,** submitted for publication, 1999

11. Seidel H, Blüthner R., Hinz B., Schust M., **On the health risk of the lumbar spine due to whole-body vibration – theoretical approach, experimental data and evaluation of whole-body vibration,** Journal of Sound and Vibration 1998, 215, 723 - 741.