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A COMPARISON OF STANDARDIZED METHODS FOR PREDICTING THE HAZARDS OF WHOLE-BODY VIBRATION AND REPEATED SHOCKS

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Methods of measuring, evaluating and assessing whole-body vibration and repeated shock are offered in ISO 2631 (1974, 1985), BS 6841 (1987), and ISO 2631 (1997). This paper presents a comparison of guidance on the health effects of vibration and repeated shock given in these standards. International Standard 2631 (1974, 1985) offered a set of exposure limits. British Standard 6841 (1987) defines a measurement and evaluation procedure (based on frequency weightings and the vibration dose value, *VDV*), gives an action level that can be used to assess vibration severity, and mentions some appropriate actions (consideration of the fitness of exposed persons, design of safety precautions, regular health checks). International Standard 2631 (1997) is unclear in several important areas: which body postures and axes are to be assessed; whether evaluations of multi-axis vibration should be based on the "worst axis" or a combination of the frequency-weighted acceleration in all axes; why a new frequency weighting, W_k, is proposed for vertical vibration when it is almost within the error tolerance of an existing weighting, W_b; why a 1·4 multiplying factor is used to evaluate vibration with respect to health but not with respect to comfort; how to choose between different time-dependencies (overall r.m.s., *VDV*, running r.m.s., and no time-dependency); allowing use of either the maximum value of a running r.m.s. (i.e., *MTVV*) or the *VDV*; allowing different averaging periods when calculating the *MTVV*; using the crest factor to choose between r.m.s. and either the *VDV* or *MTVV* methods; defining two inconsistent criteria for deciding whether to use either the *VDV* or *MTVV* methods; giving no guidance on how *MTVV* values should be assessed; including two very different "health guidance caution zones" (for interpreting r.m.s. and *VDV* measures); providing ambiguous wording for the health guidance caution zones. Very different conclusions can be reached according to what is measured, how the vibration is evaluated and how it is assessed according to ISO 2631 (1997). However, even though it employs a slightly different frequency weighting for vertical vibration, and a 1·4 multiplying factor for horizontal vibration, ISO 2631 (1997) can be interpreted so as to provide evaluations similar to those made according to BS 6841 (1987). It is concluded that the recently revised International Standard for measuring, evaluating and assessing human exposures to vibration and shock will cause unnecessary confusion.

1. INTRODUCTION

Vibration and mechanical shock can damage the human body. However, it is far from obvious what type of damage will occur and what mechanisms are involved in the damage process. It is therefore not possible to state with any precision how the damage depends

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on the physical characteristics of the vibration and shock, the characteristics of the exposed person, or other aspects of the environment.

Notwithstanding the incomplete understanding of the causes and nature of the injuries produced by whole-body vibration, the belief that occupational and leisure exposures to vibration can induce injury has led to a desire to define methods of predicting the conditions which are responsible. This has resulted in various vibration standards.

A standard could define a method of measuring vibration (to obtain a numerical indication of the vibration), or a means of evaluating the vibration (so as to obtain a measure of the vibration severity), or a means of assessing the severity (to predict the likely consequences of exposure). With uncertain knowledge of human responses to vibration, the wording of such a standard requires care: it could offer assistance in the form of clear guidance on methods without implying certainty of knowledge, or it could add to confusion. Perhaps the measurement and evaluation should be precisely defined but the assessment should reflect the uncertainties in knowledge.

Standards do not conform to the principles of published scientific work. For example, their relation to the perceived state of knowledge is not made clear and they are ephemeral, becoming extinct on publication of a revised standard. Consequently, while scientists attempt to evolve a philosophy based on reason and their knowledge of the universe, a standard can exist as an island in which a rule of law is imposed without justification to any pre-existing moral code. This "philosophy" of standardization can be alien to the scientist. Even the availability, referencing and anonymity in the authorship of standards and draft standards is weird: a standardization body may refuse to provide a copy of a standard which has been superseded. This is not the case with scientific work where open access to past work is the norm and authors know that they can forever be identified with their statements.

Increasingly, standards influence important decisions. Very significant multi-national orders for equipment have been won and lost as a result of excessive vibration and shock judged against the guidance for health in a standard. Legal claims by employees against their employers for negligence, or litigation against the manufacturers of machines, involve argument over the interpretation of relevant vibration standards. Manufacturers, employers, and others responsible for the safety of those at work, must decide when it is necessary to apply precautions to prevent injury. The consequences of imprecise formulation and false claims in past standards may have been overlooked; modern standards may be subjected to greater scrutiny in line with their increased impact.

It is the purpose of this paper to compare the three human response to vibration standards of most current interest. The paper seeks to identify the differences between the standards and how the differences affect the measurement, evaluation and assessment of exposures to vibration and shock. The apparent deficiencies in each of the standards are considered. The discussion is restricted to the consideration of the health effects of whole-body vibration and repeated shock.

2. THE HISTORICAL EVOLUTION OF ISO 2631 (1974), BS 6841 (1987) AND ISO 2631 (1997)

2.1. INTERNATIONAL STANDARD 2631: GUIDE FOR THE EVALUATION OF HUMAN EXPOSURE TO WHOLE-BODY VIBRATION

The preparation of International Standard 2631 commenced around 1966, but it was not published until 1974 [1]. The standard was republished in 1978 [2], with "editorial" changes (intended to correct errors in the tables and figures), and a set of amendments was issued in 1982 [3]. The standard was republished in 1985 under a revised title:

"Evaluation of human exposure to whole-body vibration—part 1: general requirements" [4]. All versions of ISO 2631 prior to 1997 were based on r.m.s. 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).

2.2. BRITISH STANDARD 6841 (1987): GUIDE TO MEASUREMENT AND EVALUATION OF HUMAN EXPOSURE TO WHOLE-BODY MECHANICAL VIBRATION AND REPEATED SHOCK

The United Kingdom voted against the publication of ISO 2631 as a full standard in 1974, but published a BSI Draft for Development 32 having a broadly similar content [5]. Between 1979 and 1987, the United Kingdom played an active part in the revision of ISO 2631. By 1984, draft 5 of the revision was sufficiently complete to be used internationally by some transport industries and several publications make reference to this unpublished document. In response to the growing use of the methods defined in draft 5, a new British Standard was evolved and published in 1987 [6]. By 1987 it had become clear that some members of the ISO Sub-Committee would delay the publication of a revision of ISO 2631: it was felt within the UK and elsewhere that the need for a better standard outweighed the advantage of waiting for formal agreement within this international forum. A tabular comparison of the guidance in the old ISO 2631 and BS 6841 (1987) has been provided elsewhere [7].

British Standard 6841 (1987) is philosophically different from ISO 2631 (1974, 1978, 1985). It primarily seeks to define procedures for measuring and evaluating the severity of vibration and shock. It is applicable to all forms of multi-axis, multi-frequency, random, stationary and non-stationary vibration and repeated shock in the frequency range 0·5–80 Hz. In addition, it defines a means of quantifying the severity of vertical oscillatory motion in the frequency range 0·1–0·5 Hz with respect to the probability of motion sickness.

Where the vibration has a low crest factor (the ratio of the peak to the r.m.s. value of the frequency-weighted acceleration), evaluations may be based on root-mean-square measures (except that peak values are used for predicting the perceptibility of vibration). For motions with high crest factors (greater than 6) the vibration dose value must be used. The time-dependency for the effects of vibration on health, for all durations up to 24 h, uses the vibration dose value (i.e., it is a fourth power relation between acceleration and exposure duration).

A series of frequency weightings, labelled W_b to W_g, are defined by both filter equations and by asymptotic approximations to these realisable curves. BS 6841 (1987) and ISO 2631 (1974, 1978, 1985) employ different time dependencies. Unlike the International Standard, BS 6841 defines methods of quantifying rotational vibration and the vibration at the backs and feet of seated persons.

At the time of writing, BS 6841 (1987) has been published for 10 years and seems to have been well-received, with little criticism of its underlying philosophy or its detailed content. However, it is based on incomplete understanding of human responses to vibration and will require revision as understanding advances. The past 10 years of discussion related to standardisation in this area has not been based on any underlying weakness in the basic form of BS 6841 (1987).

2.3. INTERNATIONAL STANDARD 2631 (1997): MECHANICAL VIBRATION AND SHOCK—EVALUATION OF HUMAN EXPOSURE TO WHOLE-BODY VIBRATION—PART 1: GENERAL REQUIREMENTS

Work on the complete revision of ISO 2631 commenced in about 1979 and the new standard was eventually published in 1997 [8]. Revision, rather than amendment, was necessary because the old standard was structured around the provision of vibration limits coupled with an untenable time dependency. It was decided that the frequency weightings in the old standard did not extend over a sufficient frequency range and there were considerable doubts over the accuracy of some of the guidance and the definitions of some terms, such as a limit for the effects of vibration on activities called the "fatigue-decreased proficiency boundary".

It is not easy to summarise the similarities and differences between the "new" ISO 2631 and either the old ISO 2631 or BS 6841: it contains a combination of both philosophies and both methods. Between the late 1980s and the publication of the revised ISO 2631 in 1997, there was little open philosophical deliberation on the role of the standard or systematic discussion of its technical content. Considering the limited opportunity to influence the revised standard, it may be questioned whether it provides a fair reflection of the state of knowledge among the medical, engineering or scientific community at the end of the 20th century.

3. INDEPENDENT VARIABLES

In this section, the manner in which the three main standards (ISO 2631, 1974, 1978, 1985; BS 6841, 1987; ISO 2631, 1997) allow for the physical characteristics of the vibration are compared.

3.1. AXES OF VIBRATION

3.1.1. *ISO* 2631 (1974, 1978, 1982, 1985)

Versions of ISO 2631 prior to 1997 were solely concerned with vibration in the three translational axes centred in the body at the heart as shown in Figure 1. Measurement at this location is neither practical nor useful: the vibration limits defined in the document were always assumed to apply to the point of entry of vibration to the body. The co-ordinate system moves with the body as it changes orientation with respect to gravity so, for example, the longitudinal (z-) axis is only vertical for seated or standing persons. For persons lying on their backs (i.e., supine) the x-axis limits apply to vertical vibration;

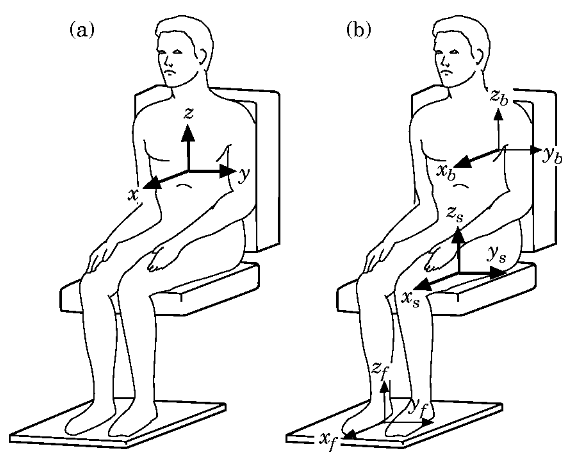

Figure 1. Axes in used for assessing health hazard as in (a) ISO 2631 (1974, 1985) and (b) BS 6861 (1987). (The three axes in ISO 2631 (1974) have a co-ordinate system with an origin at the heart; the four axes in BS 6841 (1987) have co-ordinate systems with origins at the interfaces between the seat and the subject; additional axes used in BS 6841 (1987) to assess discomfort are shown in lighter type).

this implies considerably less sensitivity to intermediate and high frequencies of vibration than was found experimentally. The standard assumed that effects of rotational vibrations could be adequately represented by the translational components they produce away from their centres of rotation. No guidance is given on the evaluation of the vibration on seat backrests or on footrests (see Table 1).

For multi-axis vibration the standard stated that the limits applied separately to the components in each of the three axes (see Table 2). However, the limits given in the standard for x- and y-axis vibration were lower than the limits given for z-axis vibration, so measurements obtained in different axes could not be compared directly with each other, only via the limits given in the standard. The perceptive reader of the standard may have discerned that, when using the frequency weighting method, the limits for x- and y-axis vibration were a factor of 1·4 lower than the limits given for z-axis vibration. Measurements in the different axes could therefore be compared with each other if measurements in the x- and y-axes were raised by a factor of 1·4 (or measurements in the z-axis were lowered by a factor of 1·4). However, the standard did not recommend this and no notation for referring to such values was offered. Published measurements of vibration in different axes obtained according to the old ISO 2631 should not be used to judge the relative severity of the vibration in different axes without allowing for this difference.

The 1982 Amendments defined a procedure for combining the "overall weighted vibration values" obtained in three axes, a_{xw}, a_{yw}, and a_{zw}:

$$a = \sqrt{(1{\cdot}4a_{xw})^2 + (1{\cdot}4a_{yw})^2 + (a_{zw})^2}, \qquad (1)$$

The value of a might be considered to be the root-sums-of-squares of the weighted values obtained in each axis, however it was referred to as the "vector sum".

The text of the 1982 Amendment of ISO 2631 was ambiguous as to whether the vector sum (*sic*) should be used when comparing measurements with the exposure limits for health and safety in the standard. The prime purpose was stated as a basis for comparing the vector sums of different motions, but it was stated that " . . . *evaluations for comfort and performance may be made by comparing the vector sum with the overall weighted acceleration value for z-axis vibration* . . . " derived from the tables and figures in the standard. The omission of evaluations for health and safety from this recommendation would appear to allow measurements to be compared with the exposure limits on the basis of the "worst" axis component alone.

3.1.2. *BS* 6841 (1987)

BS 6841 (1987) defined frequency weightings and multiplying factors for the evaluation of vibration in 12 axes for the seated person: three translational and three rotational axes between the seat and the ischial tuberosities, three translational axes between the back and the backrest, and three translational axes beneath the feet (see Figure 1). This allowed the vibration at all principal inputs to the body to be measured and evaluated in a standardised manner. However, the assessment of the health effects of whole-body vibration was restricted to the three translational axes on the supporting surface (of a seat, or the floor for a standing person) and the fore-and-aft axis for vibration on a seat backrest (see Table 1). There is also a tentative recommendation on how to measure and evaluate the vibration exposures of recumbent persons.

The changes to the frequency weightings in this standard compared to ISO 2631 (1985) were partially designed to eliminate the need for multiplying factors for horizontal vibration (see section 3.1.3). This simplifies the evaluation of vibration occurring in the

TABLE 1

The axes and postures in which vibration can be assessed with respect to health in the different standards

ISO 2631 (1974, 1978, 1985):
Section 0: "*Vibrations transmitted to the body as a whole through the supporting surface, namely the feet of a standing man, the buttocks of a seated man or the supporting area of a reclining man*".
Section 0: "*In the case of vibrations applied directly to a reclining or recumbent man, insufficient data are available to make a firm recommendation . . . Provisionally, however, the limits for the standing or seated man may also be used for the reclining or recumbent man*".
Section 1: " . . . *limits are specified in terms of . . . the direction of vibration relative to the torso. This direction is defined according to the recognised anatomical axes of the human body*".
Section 3: "*Rectilinear vibrations transmitted to man should be measured in the appropriate directions of an orthogonal co-ordinate system having its origin at the location of the heart*".
Section 3.1.3: " . . . *separate limits are specified according to whether the vibration is in the (anatomically) longitudinal* ($\pm a_z$) *direction or transverse* ($\pm a_x$ *or* $\pm a_z$) *plane*".
Section 3.2: " . . . *the limits . . . apply to vibration at the point of entry into the human body itself (that is, at the body surface, but not, for example, at the substructure of a resilient seat . . .)*".
Section 4.1: "*Typically, as in most transport situations,* a_z *(longitudinal) vibration will be applied to a sitting or standing person (a situation popularly referred to as "vertical vibration")*".
Section 4.1.2: "*The exposure limit recommended is set at approximately half the level considered to be the threshold of pain (or limit of voluntary tolerance) for healthy human subjects restrained to a vibrating seat*".

BS 6841 (1987):
Section 4.1: "*The guidance is applicable to vibration and repeated shock in the frequency range* 0·5 *to* 80 *Hz which is transmitted to the body as a whole through the supporting surfaces: the buttocks of a seated person or the feat of a standing person. It also applies to fore-and-aft (x-axis) motions of a backrest to a seat*".
Section 4.2.3, Note 1: "*The method of evaluation is applicable to erect standing postures. However, slight bending of the knees can affect the transmission of vibration to standing persons so this application will not always be appropriate*".
Section 4.2.4, Note 2: "*For recumbent postures it is tentatively recommended that weightings* W_b *and* W_d *are used for the vertical and horizontal axes of vibration respectively. It is assumed that the head is never in direct contact with the full vibration magnitude*".

ISO 2631 (1997):
Section 1: "*This part of ISO* 2631 *is applicable to motions transmitted to the human body as a whole through the supporting surfaces: the feet of a standing person, the buttocks, back and feet of a seated person or the supporting area of a recumbent person*".
Section 7.1: "*It applies primarily to seated persons, since effects of vibration on the health of persons standing, reclining or recumbent are not known*".
Section 7.1: "*The guidance is applicable to vibration in the frequency range* 0·5 *Hz to* 80 *Hz which is transmitted to the seated body as a whole through the seat pan*".
Section 7.2.1: "*The weighted r.m.s. acceleration shall be determined for each axis (x, y and z) of translational vibration on the surface which supports the person*".
Section 7.2.2: "*The assessment of the vibration shall be made with respect to the highest frequency-weighted acceleration determined in any axis on the seat pan*".
Section 7.2.3: "*The frequency weightings shall be applied for seated persons . . .* ".
Section 7.2.3, Note: "*Measurements in the x-axis on the backrest . . . are encouraged. However, . . . not included in the assessment of the vibration severity . . .* ".
Section B.1: "*It applies to rectilinear vibration along the x-, y- and z-basicentric axes of the human body*".
Section B.1, Note: "*There is only limited experience in applying this part of ISO* 2631 *for x-, y-axes seating and for all standing, reclining and recumbent positions*".

TABLE 2

Guidance on how to assess multi-axis vibration

ISO 2631 (1974, 1978, 1985)
Section 4.3: "*If vibrations occur in more than one direction simultaneously . . . the corresponding limits apply separately to each vectorial component in the three axes*".
Section 4.3: "*Evaluations for comfort and performance may be made by comparing the vector sum with the overall weighted acceleration value for z-axis vibration*".

BS 6841 (1987)
Section A.5: "*The fourth root of the sum of the fourth powers of the vibration dose values in each axis should be determined . . .* ".

ISO 2631 (1997)
Section 6.5: "*The vibration total value or vector sum have also been proposed for evaluation with respect to health and safety if no dominant axis of vibration exists*".
Section 7.2.2: "*The assessment of the effect of a vibration on health shall be made independently along each axis. The assessment of the vibration shall be made with respect to the highest frequency-weighted acceleration determined in any axis on the seat pan*".
Section 7.2.2, Note: "*When vibration in two or more axes is comparable, the vector sum is sometimes used to estimate health risk*".

three principal axes on a supporting surface and removes the potential confusion when reporting the weighted values.

The evaluation of multi-axis vibration with respect to health recommended in BS 6841 (1987) involves the calculation of the fourth root of the sum of the fourth powers of the vibration dose values in each axis. This means that if two or more axes have similar magnitudes of vibration the overall effect is increased, otherwise the "worst" axis will largely determine the vibration severity.

3.1.3. *ISO* 2631 (1997)

This standard is equivocal on the axes to be assessed, how they may be combined and to which postures the final assessment applies (see Tables 1 and 2). It starts by stating that vibration in each of the three translational axes on the surface which supports the person should be evaluated. Although this might be assumed to apply to seated, standing recumbent persons, the remaining text (and a table) in the body of the standard only mention seated persons. A note in an informative Annex to the standard says that the guidance is mostly based on research with vertical vibration of seated persons: " . . . *there is only limited experience in applying this part of ISO* 2631 *for x-, y-axes seating and for all axes of standing, reclining and recumbent positions*." The phrase "*limited experience*" is open to differing interpretations.

It is stated that the assessment of the effect of a vibration on health in this standard *shall* be made independently along each axis, using the highest frequency-weighted acceleration in any axis on the seat pan. However, a note states that when two or more axes are comparable the vector sum [*sic*] is sometimes used to estimate health risk (see Table 2).

In a note, the standard encourages the measurement of fore-and-aft vibration on a backrest, but this measurement is not included in the assessment of vibration severity.

This standard retains the multiplying factors of 1·4 for vibration in the horizontal axes. Consequently, when weighted values are reported there is a potential ambiguity over

TABLE 3

Application of frequency weightings to the evaluation of whole-body vibration in various axes with respect to health effects

Axis	ISO 2631 (1974, 1978, 1985)†	BS 6841 (1987)	ISO 2631.1 (1997)¶
seated persons:			
x-axis, seat surface	$1.4 \times W_{d(1\text{–}80\ \mathrm{Hz})}$‡	W_d	$1.4 \times W_d$
y-axis, seat surface	$1.4 \times W_{d(1\text{–}80\ \mathrm{Hz})}$‡	W_d	$1.4 \times W_d$
z-axis, seat surface	W_g§	W_b	W_k
x-axis, seat-back	–	$0.8 \times W_c$	$0.8 \times W_c$ (measurement encouraged but not used in assessment)
standing persons:			
x-axis, floor	$1.4 \times W_{d(1\text{–}80\ \mathrm{Hz})}$‡	W_d	††
y-axis, floor	$1.4 \times W_{d(1\text{–}80\ \mathrm{Hz})}$‡	W_d	††
z-axis, floor	W_g§	W_b	††
recumbent persons			
x-axis	$1.4 \times W_{d(1\text{–}80\ \mathrm{Hz})}$‡	–	††
y-axis	$1.4 \times W_{d(1\text{–}80\ \mathrm{Hz})}$‡	–	††
z-axis	W_g§	–	††
horizontal	–	W_d ‖	††
vertical	–	W_b ‖	††

Notes:
† "*frequency range* 1–80 Hz"; ‡ asymptotic frequency weighting with similar form to W_d, but limited to 1–80 Hz; § asymptotic frequency weighting similar to W_g in BS 6841; ‖ "*tentatively recommended*"; ¶ "*limited experience in applying this part of ISO* 2631 *for x*-, *y-axes seating and for all standing*, *reclining and recumbent positions*"; †† weighting and multiplying factor not specified.

whether measures for horizontal axes have been increased by a factor of 1·4 or not. This leads to an error of 40% if the wrong assumption is made.

3.2. FREQUENCY OF VIBRATION

The frequency weightings advocated for the evaluation of vibration in the various axes are listed in Table 3.

3.2.1. *ISO* 2631 (1974, 1985)

This standard was possibly intended to apply to third-octave bands centred at the preferred third-octave centre frequencies from 1–80 Hz: the range of application was therefore 0·89–89·8 Hz. However, it stated that no information given in the standard shall be extrapolated to frequencies outside the range 1–80 Hz. It was not stated how motion outside this range was to be excluded. In the 1982 Amendments it was stated that "*in some applications tentatively constant sensitivity to accelerations has been assumed for the frequency range* 0·63 *to* 1 *Hz*".

Over the 1–80 Hz frequency range, one contour defined limits for z-axis vibration and another defined limits for both x- and y-axis vibration. The z-axis contour indicated greatest sensitivity to vibration acceleration between 4 and 8 Hz; at frequencies above 8 Hz the acceleration limits increased in proportion to frequency. Below 4 Hz, the z-axis acceleration limits increased in inverse proportion to the square root of the frequency. For x- and y-axis vibration, the limits were dependent on acceleration from 1–2 Hz and the acceleration limits increased in proportion to frequency from 2–80 Hz.

The method of evaluating vibration spectra with respect to the limits involved comparing the vibration in each third-octave band separately with the corresponding limit for the band. Only the band highest with respect to the limits was included in this recommended "*rating procedure*". A permissible approximation, the "*weighting procedure*", was defined so as to simplify measurements where spectral analysis was not required. This method involved frequency-weighting the signal and determining the weighted r.m.s. acceleration. The weighting network had a shape defined by the reciprocal of the vibration limits with zero insertion loss (i.e., unity gain) in the band of maximum sensitivity (see Figure 2). The weighted value was to be compared with the limit for the appropriate axis in the band of maximum sensitivity (i.e., 4–8 Hz for z-axis vibration or 1–2 Hz for x- or y-axis vibration). When comparing (or combining) weighted values in the x- and y-axes with weighted values in the z-axis, a correction factor of 1·4 was required (see section 3.1.1). (In Figure 2 the weightings are shown as straight lines, as illustrated in the standard; a realizable weighting equivalent to this shape for the z-axis weighting was defined in BS 6841 (1987) and designated W_g; in the subsequent text, tables and figures the weighting for z-axis vibration from ISO 2631 (1974, 1985) will be referred to as weighting W_g).

Various difficulties arose with the definition of two very different procedures for assessing complex spectra in the same standard. Some did not accept that the precise shapes of the weighting networks shown in Figure 2 follow correctly from the third-octave limits defined in the standard (e.g., perhaps the corner frequencies should be the cut-off frequencies of the third-octave bands not their centre frequencies). However, the greatest difficulty was that the weighting procedure yielded higher values, since it was influenced by all frequencies while the rating procedure was only influenced by the highest third-octave band. The standard stated that the methods may differ by up to 13 dB (i.e., about 4·5 to 1) and that the weighting method would then be too conservative. In practice, the weighting method was usually used since it was much more convenient, more logical and more consistent with both experimental data and the apparent severity of many stimuli. A band of doubt as much as 4·5 to 1 is very considerable where the range from imperceptible to intolerable can be as little as 100 to 1; further, the time-dependency was such that a 4·5 to 1 change in vibration magnitude corresponded to a 180 to 1 change in allowable exposure time from 1 min to about 3 h (see section 3.3.1).

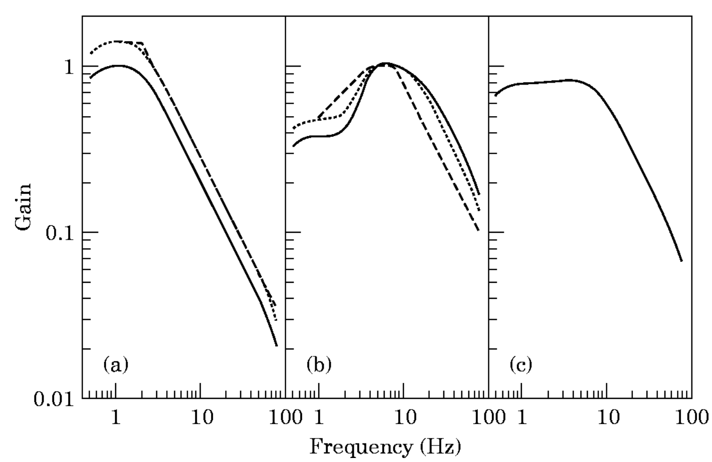

Figure 2. Comparison of the frequency weightings (with multiplying factors) used in the three standards for horizontal and vertical seat vibration and fore-and aft backrest vibration: (a) x- and y-axis seat vibration; (b) z-axis seat vibration; (c) x-axis backrest vibration. Key: –––, ISO 2631 (1985); ——, BS6841 (1987); · · · · , ISO 2631 (1997).

The 1982 Amendments to the standard stated that when a single number is desired to quantify the effects of broad band vibration, the "weighting method" was recommended in preference to the "rating method". However the text suggests that the weighted value should primarily be used for comparison with other weighted values and that the recommendation is based on the results of research on comfort and performance. It said that when making a direct comparison of weighted values with the guidance given in the tables and figures of the standard "*appropriate adjustment of the values may have to be considered*". There was no guidance on the form or extent of the adjustment.

3.2.2. *BS* 6841 (1987)

This standard defines frequency weighting as the procedure for obtaining a single value from multiple frequency or random vibration. It was also the first standard to define the manner in which the frequency weightings were to be implemented (by analogue or digital methods), the first to define the use of band limiting filters, and the first to define tolerances for the response of filters. Asymptotic approximations to the filters (with slopes of $-6{\cdot}0$, $0{\cdot}0$, $+6{\cdot}0$ and $+12{\cdot}0$ dB per octave) were defined to allow easy interpretation of the approximate shapes of the filters.

Four frequency weightings were defined (W_b, W_c, W_d, and W_e) for the general evaluation of vibration in the 12 basicentric axes of the body (three translational and three rotational axes between the seat and the ischial tuberosities, three translational axes between the back and the backrest, and three translational axes beneath the feet). For the assessment of health effects, vibration is evaluated in the three translational axes on a supporting surface (the seat for seated person or the floor for a standing person) and in the fore-and-aft axis for a backrest: W_b is used for vertical vibration on the supporting surface, W_d is used for horizontal vibrations on the supporting surface, and W_c is used for fore-and-aft vibration of a backrest for seated persons.

The frequency weighting W_b differed significantly from the weighting used for vertical seat vibration in ISO 2631 (1974, 1978 and 1985). At low frequencies, the weighting tends to correspond to both biodynamic data (e.g., point apparent mass, transmission to lumbar vertebrae) and subjective responses: there is constant sensitivity to acceleration between 0·5 and 2 Hz and increasing sensitivity from 2–5 Hz. Greatest sensitivity is given between 5 and 8 Hz. At frequencies above 8 Hz, sensitivity reduces slowly up to 16 Hz, and then reduces in inverse proportion to vibration frequency up to 80 Hz. The region from 5–80 Hz reflects greater sensitivity than would be obtained by using solely point apparent mass data (or absorbed energy). This is because studies of the transmission of vibration to the spine do not suggest a rapid reduction in the transmission of vibration above 5 Hz. Furthermore, studies of subjective responses to vertical vibration suggest that sensitivity remains high at frequencies above 5 Hz. Although it was recognised that two frequencies that cause similar discomfort may not present the same health risk, it was considered that there was insufficient data to be confident that there is a difference or, indeed, the direction of any difference. Consequently, in the absence of data to the contrary, it seemed prudent to employ the same frequency weightings for both health and comfort and the availability of suitable data for comfort suggested that this was a reasonable basis for defining the frequency weighting.

Many other factors were considered in the definition of the frequency weighting W_b, including how it affected assessments of vibration in various environments having low frequency and high frequency vibration. Also, it was necessary to define W_b such that it was compatible with the weightings used for horizontal vibration on the supporting seat surface (i.e., W_d) and fore-and-aft vibration on a backrest (i.e., $W_c \times 0{\cdot}8$). It was recognized that the phase response of the filter might have some effect on the evaluations of some stimuli: this was one of the reasons for defining the filter responses in the standard. However, in the absence of data suggesting that the effect was large in the context of the recommended evaluation method, and with no data identifying an appropriate phase, the implementation of the response of weighting W_b, and other filters, was selected on the basis of practical convenience consistent with having a gain conforming to the above considerations of biodynamic responses, subjective responses and consistent with expectations of the relative severity of different vibration environments.

Relative to the weighting for *z*-axis vibration in ISO 2631 (1974, 1978, 1985), the frequency weighting W_b gives greater weighting to vibration at frequencies below 1 Hz (at frequencies where the old International Standard was not normally used). The weighting W_b gives less weight at frequencies between 1 and 5 Hz (61% at 2 Hz) and more weight at higher frequencies (178% at 20 Hz, 200% from 40 to 80 Hz).

In the horizontal axes, the frequency weighting W_d is used without multiplying factors (i.e. the multiplying factor is unity). This results in the gain of the weightings for vertical and horizontal vibration at 3·15 Hz being similar, as in the old ISO 2631.

3.2.3. *ISO* 2631 (1997)

The concept of frequency weighting as the procedure for evaluating multiple frequency and random vibration is similar in ISO 2631.1 (1997) and BS 6841 (1987). With respect to health effects, the principal differences are: (i) the apparent restriction of assessments to seated persons; (ii) the possible restriction to only the vertical vibration of seated persons; (iii) the use of different multiplying factors for horizontal vibration; (iv) the use of frequency weighting W_k in place of W_b for evaluating vertical vibration.

The purpose of frequency weightings is to allow an evaluation of vibration and so make possible, if required, either a relative or an absolute assessment of the vibration severity. It would therefore be reasonable to define frequency weightings for the measurement of vibration in each axis, but restrict any assessment of the vibration severity (e.g., vibration limits) to a lesser number of axes. Table 1 of ISO 2631.1 (1997) defines frequency weightings for the three axes of vibration on a supporting seat surface, and the weighting to be used if measuring fore-and-aft backrest vibration, but it does not identify the weightings for standing or recumbent persons. A reasonable decision of a user of the standard needing to measure and evaluate vibration for these postures would be to apply the weightings advocated for assessing the discomfort caused by vibration in these axes. Although this seems appropriate it is not stated, and readers of the standard will hesitate if they notice that the weightings and the multiplying factors used for assessing discomfort and health for seated persons are *not* the same (see below).

Although it is obviously not the principal problem with ISO 2631 (1997), the prime controversy during the development of the revised standard involved the frequency weighting to be used for the evaluation of vertical vibration. The W_b weighting used in BS 6841 (1987) was the weighting included in the draft revision of ISO 2631 in the mid and late 1980s and the first half of the 1990s. It is not clear why some wanted to change the weighting. For some, the name of the weighting may have been more important than the shape of the weighting, for others there was reluctance to change from the weighting used in the old ISO 2631. It is not possible to provide a technical explanation as to why ISO 2631.1 (1997) has a weighting with the shape of W_k since no evidence was presented as to why W_k was preferred to W_b, or any other shape.

In some respects the difference between W_b and W_k is relatively small: the maximum difference varies from W_b giving 20% less weight than W_k at low frequencies to W_k giving about 25% greater weight than W_b at the highest frequencies (see Figure 3). The differences are much less at other frequencies. Indeed the acceptable tolerance zones for the

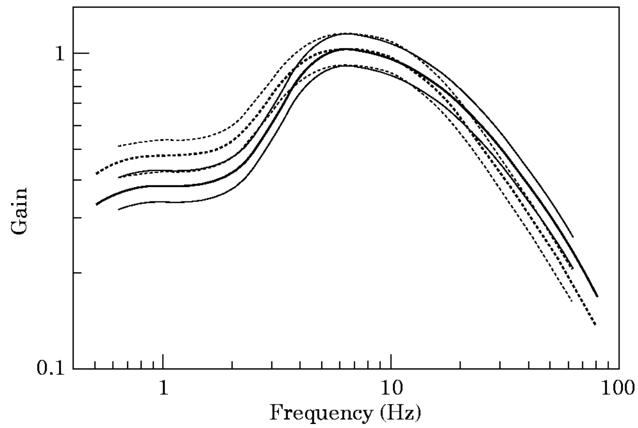

Figure 3. Comparison of frequency weightings W_b and W_k with their specified tolerances. Key: ——, BS 6841 (1987): W_b; · · · ·, ISO 2631 (1997): W_k.

implementation of W_b and W_k either overlap or are adjacent to each other. At any frequency it appears possible that measurements made with instrumentation conforming to either standard could report the same value!

The slightly increased weight given by W_k at low frequencies may appear to raise the importance of vibration in off-road vehicles and, since some of these vehicles are associated with back problems among operators, this may seem appropriate. However this reasoning is superficial: the purpose of the weighting in the evaluation is to define the relative importance of different frequencies, the overall importance of any specific environment depends on the assessment method, which also differs between BS 6841 and ISO 2631. The greater weight given by W_k to vibration below 5 Hz does have an effect on the isolation efficiency of seating (and other suspension mechanisms) which will have resonances in this range. When using BS 6841 (1987), there is a greater incentive to reduce the dominant frequency to as far below 5 Hz as possible, such as by means of a suspension mechanism.

At low frequencies, the 20% reduction in sensitivity when using W_b compared with W_k becomes approximately 100% when it is converted into an acceptable exposure duration using vibration dose values.

The current state of knowledge may be insufficient to state categorically whether W_b or W_k is preferable. At the time of writing, however, it is difficult to see a sufficient justification for introducing a new, slightly different, weighting which inconveniences both those with data collected using the weighting in the old ISO 2631 (equivalent to weighting W_g) and those with data collected using W_b. On balance, the technical arguments seem to be in favour of W_b since it seems to reflect biodynamic and subjective understanding of the frequency-dependence of responses to vertical vibration somewhat better than weighting W_k.

In the horizontal directions on a seat, ISO 2631 (1997) advocates the use of frequency weighting W_d (as in BS 6841) but with a 1·4 multiplying factor. This will raise all evaluations of vibration in these axes, so again tending to increase the reported magnitudes of vibration in off-road vehicles. This also increases the chance that horizontal vibration will be judged as more severe than vertical vibration. The difference caused by replacing W_b with W_k is obviously much smaller than the difference caused by the re-introduction of the 1·4 multiplying factor for horizontal vibration. The 1·4 multiplying factor should mean that frequency-weighted evaluations of vibration reported according to the health guidance in ISO 2631-1 (1997) are exactly 40% greater than those reported according to

BS 6841. However, some prefer to report frequency-weighted accelerations without including the effect of multiplying factors. This is very likely for x- and y-axis seat vibration because evaluations according to the comfort guidance in the ISO 2631 (1997) do not include the 1·4 multiplying factor.

The conflicting guidance given within ISO 2631 (1997) for evaluating vibration with respect to comfort and health arises partly from the 1·4 multiplying factor and partly from the recognition that W_b can be an acceptable frequency weighting for evaluating vibration with respect to comfort (although in the same paragraph of Annex C of the standard, W_b is wrongly defined). The standard specifically mentions the use of the W_b weighting for rail vehicles, but it is also very extensively used in many parts of the international automobile industry. The different guidance for comfort and health in ISO 2631 (1997) means that some modifications made by vehicle designers to improve the comfort of their vehicles will increase the health risks to drivers and passengers, at least according to this standard!

ISO 2631 (1997) suggests that fore-and-aft backrest vibration should be evaluated using a multiplying factor of 0·8. This value was copied from earlier drafts (or from BS 6841) without considering that the relative importance of the backrest vibration (and therefore this multiplying factor) will be affected by the re-introduction of the 1·4 multiplying factor for fore-aft seat vibration. Similarly, when defining the weightings and multiplying factors for evaluating vibration with respect to comfort, W_k has been substituted for W_b without consideration of the effect that this has on the relative importance of the vibration occurring at the backrest and the feet in various axes.

The standard was published twice in 1997 with the W_b weighting defined incorrectly in both versions.

3.3. MAGNITUDE AND DURATION OF VIBRATION

The quantification of vibration severity must involve the definition of the relative importance of vibration magnitude and exposure duration within the vibration evaluation method: it is over-simplistic to define a method of measuring the average magnitude of vibration and then compare this average magnitude with a limit drawn on a graph of acceleration magnitude versus exposure duration. Vibration exposures are usually time-varying (containing periods at different magnitudes, transients and shocks) so the evaluation method must define how exposures to different magnitudes, transients and shocks are to be quantified.

The ISO approach shows a strong affinity for the use of r.m.s. averaging of the vibration magnitude and the separate definition of a vibration limit against which the r.m.s. values are compared. This approach allows two time-dependencies: the implied relation between acceleration and time in r.m.s. averaging (i.e., $at^{1/2}$ = constant) and the time-dependent limit presented in graphical or tabular form in the standard.

3.3.1. *ISO* 2631 (1974, 1978, 1985)

The old International Standard advocated the use of r.m.s. acceleration and included a time-dependency with the very complex form shown in Figure 4. (The 1974 and 1978 versions differ at durations of 16 and 24 h—the 1978 version is illustrated.) The standard implied that the effects of vibration are independent of duration from 1 min to at least 4 min and then increase so that the acceleration limit for 24 h is 1/20th of the limit for a 1 min exposure. A method for assessing intermittent and other time-varying vibration conditions was offered but was impractical and rarely used.

The standard required that vibration magnitudes should normally be expressed in ms^{-2} r.m.s. It stated that for "*the adequate description of vibration which is markedly*

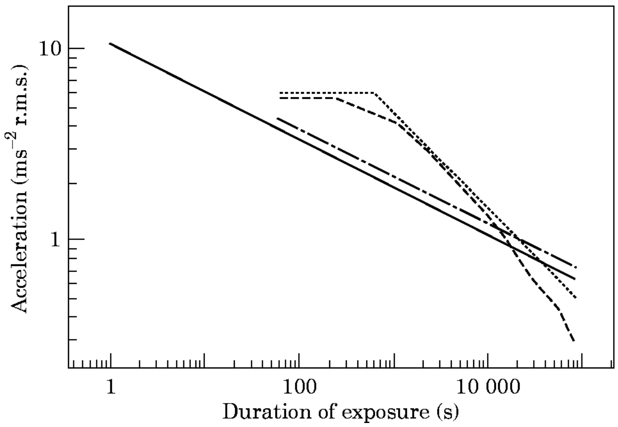

Figure 4. The four time-dependencies: exposure limits in ISO 2631 (1974, 1985); the 15 *VDV* "action level" in BS 6841, the upper "r.m.s. limit" and the 17 *VDV* limit in ISO 2631 (1997). Key: ——, ISO 2631 (1974, 1978, 1985): exposure limit; ——, BS 6841 (1987): 15 *VDV*; · · · ·, ISO 2631 (1997): boundary for "health risks are likely"; –·–·–, ISO 2631 (1997): 17 *VDV*.

non-sinusoidal, *random or broad-band*, *the crest factor* (*ratio of maximum peak to r.m.s. value*) *of the time function must be determined or estimated*: *the limits given in this International Standard should be regarded as very tentative in the case of vibrations having high crest factors* (*that is*, *greater than* 3, . . .)". Most reasonable interpretations of this sentence resulted in almost all applications being "tentative" since most real environments have crest factors in excess of 3.

The unrealistic crest factor restriction in the original standard was raised to 6 in the 1982 Amendments, which also provided a less ambiguous definition of the crest factor. The Amendments also state: " . . . *it is clear that the importance of some motions which contain occasional extremely high peak values may be underestimated by the recommended evaluation method* . . . " and " . . . *when the crest-factor is greater than about six*, *the recommended vibration evaluation method may underestimate the effect of the motion*".

The basis of the complex time-dependency in ISO 2631 (1974, 1978, 1985) was never defined. The chairman of the ISO Sub-Committee has stated that the curves were influenced by short time physiological tolerance data, the need for 24 h comfort limits to be close to the threshold of perception of vibration in buildings, and reports suggesting that subjective tolerance, fatigue and comfort change with exposure duration [9]. Considerations of the time-dependent characteristics of human responses have not confirmed the form of this time-dependency for either short or long durations.

It does not require experimental or epidemiological study to conclude that the limits in ISO 2631 were not well-founded. In contrast to the standard, common experience suggests that human responses are dependent on duration of exposure below 4 mins. Furthermore, measurements of vibration show that vehicle vibration does not normally approach the extremely severe 1–4 min "exposure limit" (5·6 ms^{-2} r.m.s. for the z-axis), and occupational exposures would be considered to produce unacceptable discomfort at much lower magnitudes. Similarly, the vibration magnitudes in transport exceed the 24 h exposure limit (0·224 or 0·280 ms^{-2} r.m.s. in the z-axis, depending on which version of the old standard is consulted) yet produce no evidence of being the prime cause of any injury.

The 1982 Amendments of ISO 2631 defined what is called "*a more convenient method of approximating the manner in which the tolerable acceleration levels decrease with increasing exposure duration up to* 8 *h*". This method involves assuming no time-dependent change in the limit between 1 min and 10 min exposures, and a reduction in the tolerable acceleration which is inversely proportional to the exposure duration between 10 min and 480 min. If a_1 is the tolerable level for a one minute exposure given in the standard and t_0 is 10 min, then the tolerable level for an exposure of t min is a_t, where

$$a_t = a_1, \qquad t \leqslant 10\ \text{min},$$

$$a_t = a_1\sqrt{(t_0/t)} \qquad 10\ \text{min} < t < 480\ \text{min}.$$

The amendment notes that the approximation might be tentatively extended up to 24 h if it is incorporated into instrumentation. This amendment provided (for the first time) a mathematical definition of the time-dependency, but its form seems unsupported by evidence or by reasonable expectations of responses to either durations below 10 min or longer durations.

A possible interpretation of ISO 2631 (1974, 1978, 1985) is that the $at^{1/2}$ time-dependency in r.m.s. averaging should be employed for durations below 1 min and the complex time-dependency shown between 1 min and 24 h should be used for longer durations. This, however, allows unrealistically high magnitudes at short durations.

In ISO 2631 (1974, 1978) it is stated that "*When peak values are measured, these must be converted as appropriate to r.m.s. values before reference to the limits given in this International Standard* . . . ". It would appear that peak values could only be converted to r.m.s. values if the crest factor is known, but the r.m.s. value would be required to determine the crest factor! A value between $\sqrt{2}$ and 3·0 might have been assumed, but it became clear later that this sentence was included without having an understanding of the crest factors and being aware that in most environments the crest factors are greater than 3·0.

3.3.2. *BS* 6841 (1987)

British Standard 6841 (1987) states that the primary quantity for expressing vibration magnitude is the weighted root-mean-square acceleration. However, it indicates that r.m.s. magnitudes will underestimate some motions which are intermittent or contain occasional high peak values. For the evaluation of vibration with respect to health, it says: "*When either the crest factors exceed* 6·0, *or the vibration has variable magnitude*, *or the motion contains occasional peaks*, *or the motion is intermittent*, *the vibration dose value procedure . . . should be used*".

A preferred method of calculating the vibration dose value is defined as

$$VDV = \left[\int_{t=0}^{t=T} a^4(t)\,\mathrm{d}t\right]^{1/4}, \tag{2}$$

where VDV is the vibration dose value ($\text{ms}^{-1\cdot 75}$), $a(t)$ is the frequency-weighted acceleration, and T is the total period of the day (in s) during which vibration may occur.

Alternatively, the vibration dose value might be calculated from the r.m.s. acceleration using the "estimated vibration dose value", $eVDV$,

$$eVDV = [(1{\cdot}4 \times a_{rms})^4 \times t]^{1/4}, \tag{3}$$

where a_{rms} is the frequency-weighted r.m.s. value, and t is the duration (in s). The estimated vibration dose value assists the comparison of r.m.s. values with exposure guidelines proposed for vibration dose values. The empirically determined correction factor of 1·4 is said to be obtained from typical vibration environments having low crest factors (below about 6·0) but, of course, will not work when the crest factor is high (or very low). The standard says that where there is any doubt or difference between true and estimated vibration dose values the true values according to equation (2) should be used.

The evaluation of intermittent vibration is performed by using the fourth root of the sums of the fourth powers of the vibration dose values determined during each period:

$$VDV = \left[\sum_{n=1}^{n=N} VDV_n^4 \right]^{1/4}. \tag{4}$$

This means that the same value is obtained as would be obtained if the vibration had been determined from one measurement starting at the beginning of the first exposure and ending at the end of the last exposure. Hence, unlike the various versions of ISO 2631 (1974, 1985 and 1997), the value obtained cannot be significantly changed by dividing the exposures into different periods.

The vibration dose value overcomes several of the problems inherent in the use of the r.m.s. acceleration and the time-dependent limits in the old ISO 2631: (i) it gives a single simple equation for the time-dependency; (ii) the same relation between acceleration and time is used in the method of evaluation as in the assessment; (iii) the method is used for all durations (including less than 1 min) and therefore is also applied to transients and shocks; (iv) unlike the ISO time-dependency (or r.m.s. methods), vibration dose values do not result in apparently excessive magnitudes at short durations or apparently unreasonably low magnitudes at long durations.

The concept behind the vibration dose value is that the weighting for duration, from the shortest relevant shock to a full days exposure, can be adequately approximated by a two-fold reduction in vibration magnitude for a sixteen-fold increase in duration. (This corresponds to a 1·5 dB reduction per doubling of exposure duration compared to a 3 dB reduction per doubling of exposure for an "energy-based" time-dependency.) This duration weighting can be applied to r.m.s. measures of continuous vibration in the same manner as the ISO 2631 duration weighting. Because the vibration dose value calculation performs the duration weightings as it is accumulated, it automatically incorporates a method of giving greater weight to occasional peaks in the motion. It would be naïve to assume that human responses really depend precisely according to this fourth power relationship, but with the current state of knowledge it seems a reasonable simple basis for comparing exposures and gaining more experience. Since the publication of BS 6841 in 1987 the vibration dose value has been used to assess the acceptability of a very large number of widely differing exposures with reasonable conclusions. In the fullness of time, however, some refinements may be possible. Figure 4 compares the shapes of the old ISO 2631 and the vibration dose value time-dependencies.

3.3.3. *ISO* 2631 (1997)

International Standard 2631 offers a somewhat confusing combination of evaluation methods (r.m.s. and *VDV*) and the time-dependencies from ISO 2631 (1985) and BS 6841 (1987). The standard does not clearly reflect the need to define an evaluation procedure which is consistent with, yet can be used separately from, the assessment of vibration severity.

The standard refers to a "basic evaluation method" (the calculation of the r.m.s. value) and says that for vibration with crest factors below or equal to 9, the basic evaluation method is normally sufficient. For some motions this is obviously untrue. For example, a 10 s sinusoidal motion with a peak value of 1·0 ms^{-2} has an r.m.s. value of 0·7071 and a crest factor of 1·4142. However, the standard would appear to allow the measurement period to be extended to 162 s (if one assumes fairly low magnitudes of vibration for the other 152 s) such that the crest factor rises to 9·0, while the r.m.s. value falls to 0·1111 ms^{-2}. In this case, it would be permissible to report any value between 0·1111 and 0·7071 ms^{-2} r.m.s. for the vibration magnitude. Although this is an extreme example and the range of reported values will not normally reach 6·4:1, the method allows evaluations to be artificially reduced by extending the period of measurement to include periods with low magnitudes of vibration. When evaluating time-varying motions this will be inevitable.

The standard defines "*additional*" or "*alternative*" methods where "*the basic evaluation method may underestimate the effects of vibration* (*high crest factors*, *occasional shocks*, *transient vibration*)". These methods are called "*the running r.m.s. method*" and the "*fourth power vibration dose method*".

The running r.m.s. method is defined in two alternative ways, by using either linear averaging,

$$a_w(t_0) = \left\{ \frac{1}{\tau} \int_{t_0 - \tau}^{t_0} [a_w(t)]^2 \, \mathrm{d}t \right\}^{1/2}, \tag{5}$$

where $a_w(t)$ is the instantaneous frequency-weighted acceleration, τ is the integration time for the running average, t is the time and t_0 is the instantaneous time, or by exponential averaging,

$$a_w(t_0) = \left\{ \frac{1}{\tau} \int_{-\infty}^{t_0} [a_w(t)]^2 \exp\left[\frac{t - t_0}{\tau} \right] \mathrm{d}t \right\}^{1/2}. \tag{6}$$

It is stated that the difference between the two methods may be "*up to* 30%" for some motions. This will correspond to greater differences in acceptable exposure durations (up to 69% or 186% when using the r.m.s. or *VDV* time-dependencies, respectively). Somewhat uncertainly, the standard recommends the use of 1 s as the integration time when calculating the running r.m.s. values; very different values can be obtained if other integration times are used [10]. A quantity called the "*maximum transient vibration value*, *MTVV*" is defined as the highest magnitude of the running r.m.s. obtained during the measurement period. The standard appears to give no indication as to what to do with the *MTVV* after it has been calculated: it does not seem reasonable to compare this value with either the r.m.s. caution zone or the *VDV* caution zone given in the standard (see section 4.3).

The "fourth power vibration dose method" in ISO 2631 (1997) is the same as the vibration dose value defined in BS 6841 (1987). A note in an Annex also defines the estimated vibration dose value.

It is surprising that the *MTVV* method should be advocated for evaluating the severity of exposures to vibration and repeated shock. The "*maximum transient vibration value*" will be determined by the worst one second during an exposure, and so will be unaffected by the motion occurring at all other times. The *MTVV* will rate an exposure to one shock as having the same severity as an exposure to many shocks; it will rate the severity of one isolated shock as being of the same severity as an exposure to the same shock occurring within an exposure to vibration. The *MTVV* will not indicate the relative contribution of exposures to vibration and bumps: this is needed when optimising suspensions of vehicles and seats. Figure 5 illustrates how the *MTVV* and *VDV* change during an exposure to a vibration containing occasional shocks: after the highest shock the *MTVV* will no longer increase, but the *VDV* will continue to increase in a manner dictated by the magnitude and the duration of exposure.

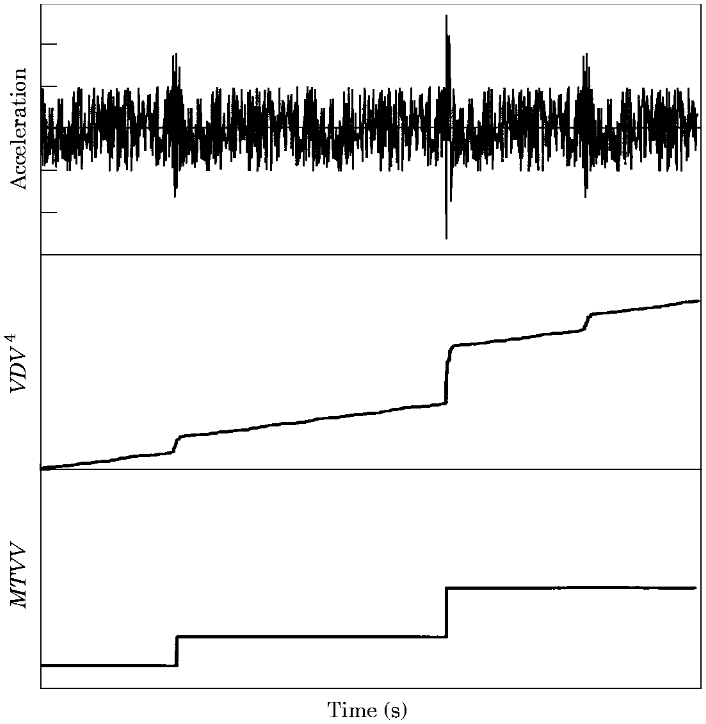

Figure 5. Illustration of the formation of a vibration dose value, *VDV*, and a maximum transient vibration value, *MTVV*, for a vibration containing occasional shocks.

With a promising opening, section 6.3.3 of the standard states: "*Experience suggests that the use of the additional methods will be important for the judgement of the effects of vibration on human beings when the following ratios are exceeded* (*depending on which additional method is being used*) *for evaluating* [sic] *health or comfort*:

$$MTVV/a_w = 1{\cdot}5, \qquad VDV/a_w T^{1/4} = 1{\cdot}75. \tag{7, 8}$$

The basic evaluation method shall be used for the evaluation of the vibration. In cases where one of the additional methods is also used, both the basic evaluation value and the additional value shall be reported". Sadly, the first sentence is hollow rhetoric: the origin of the ratios is unknown and they do not seem reasonable.

With the *MTVV*, the standard appears to state that the overall weighted r.m.s. acceleration, a_w, can be used unless the 1 s running r.m.s. value is 50% greater than the overall r.m.s. value. At the point of changing from using the r.m.s. to the *MTVV* a 50% difference, or error, arises. In practice, the value of 1·5 will probably be exceeded in most environments where an evaluation is considered necessary [10].

With the *VDV*, the estimated vibration dose value can be substituted into the equation, giving

$$VDV/eVDV = 1{\cdot}25. \tag{9}$$

The standard is therefore saying that the r.m.s. value can be used unless the vibration dose value is 25% greater than the estimated vibration dose value (obtained from the r.m.s. value). Hence allowing a 25% error at the transition.

Although the transition from r.m.s. to *MTVV* allows twice the "error" allowed for the transition from r.m.s. to *VDV* (50% compared with 25%), the criterion for using the

MTVV is more likely to arise than the criterion for using the *VDV*. This is because the *MTVV* is sensitive only to the highest short period that ever occurs in the motion, whereas the *VDV* weights all magnitudes in the waveform according to the duration for which they occur. The 25% error allowed for the *VDV* would seem unnecessarily excessive.

Obviously, the *MTVV* in the form defined in the standard cannot be an acceptable general method of evaluating exposures to time varying vibration: it is based on only the worst 1 s of the motion and totally insensitive to what happens to the vibration at any other time.

A note in the standard suggests that for statistical reasons the minimum measurement duration will be 227 s (assuming a lower limiting frequency of 0·5 Hz), but that in practice the measurement duration will be much longer such that it is representative of the vibration exposure. This seems to misapply statistical concepts of signal processing: an exposure to vibration or shock can cause injury whether or not it can be considered representative of any other possible exposure: a few short shocks or a transient lasting much less than 227 s can be hazardous. The standard should have identified how to measure and evaluate all possible exposures, either: (i) from a measurement over the full period of exposure (however short), or, (ii) by calculating a value using one or more measurements obtained over shorter periods.

The standard defines two separate sets of time-dependent limits (see section 4.3, below). One is based on vibration dose values, which can be compared with measurements of the *VDV*, calculations of the *eVDV*, or measurements of overall r.m.s. values. The other has a similar shape to that defined in the 1982 amendments to ISO 2631: constant acceleration from 1–10 min and, from 10 min–24 h, the acceleration falling in inverse proportion to the square root of exposure duration. The time-dependent limits give no guidance on the assessment of exposures lasting less than 1 min.

Apart from the use of vibration dose values, ISO 2631 (1997) does not identify a viable method of evaluating vibration severity if exposures are intermittent or occur at different magnitudes. For those not wishing to use vibration dose values, there is an equation suggesting that such exposures could be combined on an r.m.s. basis. However, this allows the severity of high magnitudes of short durations to be apparently lessened by the addition of long periods of lower magnitudes. Further, since the time-dependency in the standard does not have the form $at^{1/2}$ = constant for durations below 10 min, this would result in an internal inconsistency: the answer obtained would depend on the durations over which it is chosen to evaluate the motions. This is a consequence of defining a vibration limit for use with r.m.s. acceleration measurements which does not have, for all exposure durations, the same time-dependency as that inherent in r.m.s. averaging: the time-dependencies in evaluation and assessment methods should be compatible.

International Standard 2631 (1997) allows the use of an "energy-equivalent vibration magnitude" when evaluating the severity of exposures to two or more periods of exposure to different magnitudes and durations. If the periods are all greater than 10 min, this will give the same value as that obtained using an a^2t time-dependency (inherent in r.m.s. averaging) and the value will be consistent with the r.m.s. time-dependency in the standard from 10 min–24 h. However, if the periods are less than 10 mins, high magnitudes occurring for short durations will be under-evaluated. For example, if a 10 min exposure is subdivided into 10 1-minute periods, one of these periods could have a magnitude as high as 18·97 ms^{-2} r.m.s. before an energy-equivalent value of 6·0 ms^{-2} r.m.s. is certain to be obtained for the "energy-equivalent vibration magnitude" over the 10 min period. Although this is internally inconsistent with other guidance in the standard, it is not prevented and, on a smaller scale, may be used to artificially reduce measured values. The standard allows an alternative method (the fourth root of the sum of vibration dose values) for which this problem does not arise.

4. DEPENDENT VARIABLES

In the context of the health effects of whole-body vibration, the dependent variable could be the probability or severity of a specified disorder, or the cumulative exposure duration before the occurrence of a specified disorder in a specified percentage of the exposed population. With the limited knowledge of the health effects of whole-body vibration, the standards do not offer speculative procedures for predicting such effects. In different ways, the three standards offer guidance on what might be unacceptable vibration exposures.

4.1. ISO 2631 (1974, 1978, 1985)

This standard defined an "*exposure limit*" for the "*preservation of health or safety*" (see Table 4). The exposure limit was said to be set at approximately half of the "*threshold of pain* (*or limit of voluntary tolerance*) *for healthy human subjects*". It was stated that exceeding the exposure limit was "*not recommended without special justification and precautions*", although there was no guidance on necessary justifications or appropriate precautions.

The vibration limit for preserving health depends, ultimately, upon the degree of allowable risk. This standard did not offer any guidance on what percentage of persons will be adversely affected at the level of the exposure limit and gave no indication of what may happen to any person exposed to excessive vibration. The standard stated that the limits applied when the exposure was repeated daily over many years and that higher limits might apply when the exposure is less frequently experienced. Raising the 24 hour limits appears appropriate, but few who have experienced vibration approaching the 1–4 min "exposure limit" can have any doubt that it should not be raised, but lowered. Those responsible for the welfare of exposed persons and the operation of their systems must weigh the relevant factors to arrive at a decision on acceptable exposures: ISO 2631 (1974,

TABLE 4

Guidance on assessment of whole-body vibration with respect to health given in ISO 2631 (1974, 1985)

Section 4.1.2: "*maximum safe exposure*".
Section 4.1.2: "*Exceeding the exposure limit is not recommended without special justification and precautions, even if no task is to be performed by the exposed individual*".
Section 4.1.2: "*The exposure limit recommended is set at approximately half the level considered to be the threshold of pain (limit of voluntary tolerance) for healthy human subjects restrained to a vibrating seat*".
Section 4.4.1: "*These limits apply when the exposure is continuous for the period stated, and when the exposure is repeated daily over many years, for example for an industrial worker in a vibrating environment or for a transport driver. For exposure which is much less frequently experienced, for example by the causal traveller, the acceptable exposure, i.e., the tolerable combination of acceleration and time, may well be higher.*"
Section 4.4.1: "*In the case of an interrupted daily exposure, or division of the exposure into several intervals, the effects of vibration on man may be mitigated by some degree of recovery, which, if it occurred, would allow prolongation of the tolerable total exposures indicated . . .* ".
Section 4.4.4: " *. . . in computing an equivalent total exposure time, the period over which individual exposure shall be integrated is limited to 24 h*".

TABLE 5

Guidance on assessment of whole-body vibration with respect to health given in BS 6841 (1987)

Section 2.2: "*Any part of the body may be injured by exposure to a sufficient magnitude of vibration*".
Section 2.2: "*The probabilities and extents of particular health effects from prolonged exposures to whole-body vibration have not been established. There is a shortage of conclusive evidence relating specific injuries to definite causes. Therefore, it is not yet possible to provide a definitive dose-effect relationship between whole-body vibration and injury or health damage*".
Section 2.2: "*Epidemiological studies suggest that back complaints are associated with exposure to prolonged periods of vibration and repeated shock but there are currently inadequate data to define a precise dose-effect relationship. Similarly, it is not yet possible to provide a definitive dose-effect relationship between whole-body vibration and any other injury*".
Section 4.1: "*The guidance provided is therefore a consensus of current opinion on the likely relative importance of physical factors associated with the conditions that might cause injury or disease. The guidance takes into account knowledge of the magnitudes of vibration that occur in different occupations, the biodynamic response of the body and the severity of sensations that occur during exposure to vibration*".
Section A.2: "*It may reasonably be assumed that increased exposure to vibration causes an increased risk of tissue damage and that periods of rest without vibration may lessen this risk. However there are no conclusive data showing how this risk is affected by exposure duration*".
Section A.6: "*Sufficiently high vibration dose values will cause severe discomfort, pain and injury. Vibration dose values also indicate, in a general way, the severity of the vibration exposure which caused them. However, there is currently no consensus of opinion on the precise relation between vibration dose values and the risk of injury. It is known that vibration magnitudes and durations which produce vibration dose values in the region of* 15 $ms^{-1.75}$ *will usually cause severe discomfort. It is reasonable to assume that increased exposure to vibration will be accompanied by increased risk of injury*".
Section A.6: "*At high vibration dose values prior consideration of the fitness of the exposed persons and the design of adequate safety precautions may be required. The need for regular checks on the health of routinely exposed persons may also be considered*".

1978, 1985) specified numerical limits which usurped this responsibility yet gave no satisfactory basis for the limits or explanation of their meaning.

4.2. BS 6841 (1987)

British Standard 6841 (1987) offers an interpretation of vibration dose values which amounts to the definition of an action level: "*Sufficiently high vibration dose values will cause severe discomfort, pain and injury. . . . vibration dose values in the region of* 15 $ms^{-1.75}$ *will usually cause severe discomfort . . . increased exposure to vibration will be accompanied by increased risk of injury. At high vibration dose values prior consideration of the fitness of the exposed persons and the design of adequate safety precautions may be required. The need for regular checks on the health of routinely exposed persons may also be considered*." (see Table 5).

Although the guidance in British Standard 6841 (1987) is expressed in terms of vibration dose values, an "estimated vibration dose value" can be expressed as an r.m.s. value which reduces in inverse proportion to the fourth power of the exposure duration. The r.m.s. values corresponding to 15 $\mathrm{ms}^{-1.75}$ are shown in Figure 6.

The text of the standard states that "*it is not possible to specify with any precision either the type or the probability of any injury that may occur due to excessive vibration exposures*". However, a note states that epidemiological studies suggest that back complaints are associated with exposure to prolonged periods of vibration and repeated shock. The standard states that the value of 15 $\mathrm{ms}^{-1.75}$ is not a limit but a consensus of opinion on methods of assessing vibration and shock which was influenced by biodynamic and

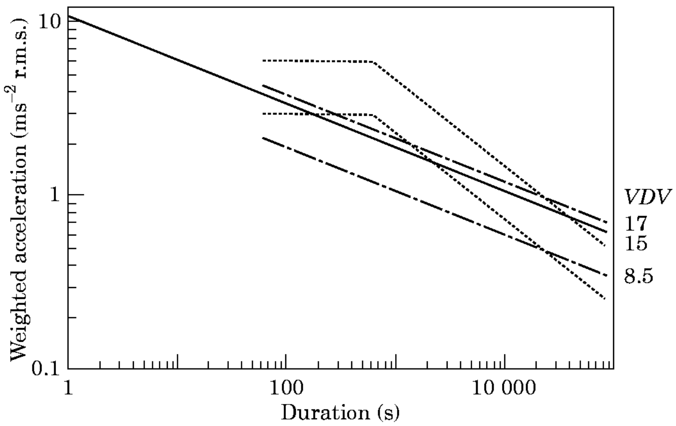

Figure 6. The 15 *VDV* action level given in BS 6841 (1987) and the two "health guidance caution zones" given in ISO 2631 (1997). Above zone, "health risks are likely"; within zone, "caution with respect to potential health risks"; below zone, "health effects not documented".

subjective data obtained in laboratories and by data from field studies. It states that body positions and seating conditions may be particularly important in determining the hazardous effects of vertical vibration. The standard does not identify whether the value of 15 ms$^{-1.75}$ should be raised or lowered if exposures occur on only one occasion or throughout a lifetime. It must be assumed that the cumulative exposure during each 24 h period is considered separately, with no special allowance for rest periods.

4.3. ISO 2631 (1997)

It is difficult to use ISO 2631 (1997) to reach a conclusion as to whether an exposure is acceptable: apart from the doubts arising from the alternatives and ambiguities specified in sections 2 and 3 above, Annex B to the standard offers two very different "*health guidance caution zones*", as shown in Figure 6, and does not specify how the zones should be interpreted.

A "*VDV* health guidance caution zone" is simply defined by vibration dose values of 8·5 and 17 ms$^{-1.75}$; the corresponding r.m.s. accelerations have been calculated by using the "estimated vibration dose value" (see equation (3)) and are shown in a figure. An alternative health guidance caution zone, consisting of constant acceleration from 1–10 min and then acceleration falling in inverse proportion to the square root of exposure duration from 10 min–24 h is shown in the same figure, but there is no mathematical definition. The figure is poorly drawn, such that no confidence can be given to the values illustrated. It may be assumed that this "r.m.s. health guidance caution zone" also covers a 2:1 range of vibration magnitudes, although this is not confirmed by the figure and the precise values of the upper and lower boundaries of the zone cannot be discerned from the standard. It might be assumed that the upper boundary of the r.m.s. caution zone coincides with the "exposure limit" in the old ISO 2631 [10]. This would place the vibration magnitude at 5·6 ms^{-2} r.m.s. for exposures between 1 and 10 mins. The lower boundary of the r.m.s. caution zone would then approximately correspond to the so-called "fatigue-decreased proficiency limit" in the old ISO 2631 at 2·8 ms^{-2} r.m.s. for exposures between 1 and 10 min. The r.m.s. caution zone would then represent acknowledgement that the exposure limits in the old ISO 2631 were insufficiently cautious. However, inspection of the figure presented in the standard indicates that the lower boundary is certainly greater than 2·8 ms^{-2} r.m.s. and the upper boundary of the r.m.s. health guidance caution zone is possibly not at 5·6 ms^{-2} r.m.s. but at 6·0 ms^{-2} r.m.s., representing a surprising increase in the "allowable" exposure to vibration. (In this paper it is assumed that the lower boundary is at 3·0 ms^{-2} r.m.s. and the upper boundary is at 6·0 ms^{-2} r.m.s.: this primarily affects only the position of two lines in Figure 6).

The two caution zones are not named in the standard, so it is difficult for users to identify which zone they are using. The terms "*VDV* health guidance caution zone" and "r.m.s. health guidance caution zone" are used here for convenience. For a 10 min exposure to continuous vibration, the standard allows the choice of an upper boundary to the health guidance caution zone at either 2·45 ms^{-2} r.m.s. (when using the fourth power method) or 6·0 ms^{-2} r.m.s. (when using the r.m.s. method). If it is uncertain whether the upper or lower boundary of a zone is applicable, the range of uncertainty for 10 min exposures extends from 1·23 ms^{-2} r.m.s. to 6 ms^{-2} r.m.s. For a 10 min exposure, the r.m.s. health guidance caution zone indicates that at magnitudes less than 3·0 ms^{-2} r.m.s., health effects have not been documented or observed, whereas the *VDV* health guidance caution zone indicates that at magnitudes greater than 2·45 ms^{-2} r.m.s. health effects are likely! There is no guidance on how to interpret this internal inconsistency in the standard.

ISO 2631 (1997) does not indicate what measures should be compared against the "r.m.s. health guidance caution zone". Users might use either of the two caution zones to assess the significance of overall r.m.s. measures. Vibration dose values will normally be compared with the vibration dose value caution zone. It is not clear how *MTVV* values can be compared with either health guidance caution zone without yielding unlikely conclusions.

Referring to a health guidance caution zone, the standard says: "*For exposures below the zone, health effects have not been clearly documented and/or objectively observed; in the zone, caution with respect to potential health risks is indicated and above the zone health risks are likely*". None of these definitions appear well-worded, for example, it is not clear how a risk can be likely. Since, for some durations, the upper boundary of the vibration dose value caution zone is below the lower boundary of the r.m.s. caution zone, the reader will not be surprised that the definition of the zones is not supported by any specific evidence.

The standard says that the recommendations with regard to the health guidance caution zone based on r.m.s. acceleration are mainly based on exposures in the range 4–8 h and appears to suggest that at shorter durations the zone should be treated with extreme caution. This arises because the $at^{1/2}$ (or r.m.s.) time-dependency gives unreasonably high acceleration values at short durations. It may be questioned whether it is responsible to publish a standard which can be interpreted as suggesting that the high magnitudes shown for this zone at some durations below 4 h might be safe.

The standard does not identify whether a caution zone should be raised or lowered if exposures occur on only one occasion or throughout a lifetime, but it is specified that they apply to people who are "*regularly exposed*". There is no mention of any special allowance for rest periods, although it is stated that periods of rest can reduce the risk.

An informative annex states that mainly the lumbar spine and the connected nervous system may be affected by vibration (see Table 6). It is stated that there are not sufficient data to show a quantitative relationship between vibration exposure and risk of health effects and that it is therefore not possible to assess whole-body vibration in terms of the probability of risk at various magnitudes and durations. This conflicts with the statement that health risks are "*likely*" above the caution zone, or at least it may be construed as meaning that it is not possible to quantify what "*likely*" means: it may mean that a problem is more likely than not to arise for an individual or it may merely mean that there is a greater than chance increase in a specific disorder in such an exposed population.

Table 6

Guidance on assessment of whole-body vibration with respect to health given in ISO 2631 (1997)

Section 7.1: " . . . *concerns the effects of periodic, random and transient vibration on the health of persons in normal health . . . applies primarily to seated persons*".
Section 7.1: "*The relevant literature on the effects of long-term high-intensity whole-body vibration indicates an increased health risk to the lumbar spine and the connected nervous system of the segments affected. This may be due to the biodynamic behaviour of the spine: horizontal displacement and torsion of the segments of the vertebral column. Excessive mechanical stress and/or disturbances of nutrition of and diffusion to the disc tissue may contribute to degenerative processes in the lumbar segments (spondylosis deformans, osteochondrosis intervertebralis, arthrosis deformans). Whole-body vibration exposure may worsen certain endogenous pathologic disturbances of the spine. Although a dose-effect relationship is generally assumed, there is at present no quantitative relationship available.*"
Section 7.1: "*With a lower probability, the digestive system, the genital/urinary system, and the female reproductive organs are also assumed to be affected*".
Section 7.1: "*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*".
Section B.1: " . . . *applies to people in normal health who are regularly exposed to vibration.*"
Section B.2: "*Biodynamic research as well as epidemiological studies have given evidence for an elevated risk of health impairment due to long-term exposure with high-intensity whole-body vibration. Mainly the lumbar spine and the connected nervous system may be affected. Metabolic and other factors originating from within may have an additional effect on the degeneration. It is sometimes assumed that environmental factors such as body posture, low temperature, and draught can contribute to muscle pain. However, it is unknown if these factors can contribute to the degeneration of discs and vertebrae*".
Section B.2: "*Increased duration (within the working day or daily over years) and increased vibration intensity mean increased vibration dose and are assumed to increase the risk, while periods of rest can reduce the risk*".
Section B.2: "*There are not sufficient data to show a quantitative relationship between vibration exposure and risk of health effects. Hence, it is not possible to assess whole-body vibration in terms of the probability of risks at various exposure magnitudes and durations*".
Section B.3.1: "*For exposures below the (health guidance caution) zone, health effects have not been clearly documented and/or objectively observed; in the zone, caution with respect to potential health risks is indicated and above the zone health risks are likely. This recommendation is mainly based on exposures in the range* 4 *h to* 8 *h . . . . Shorter durations should be treated with extreme caution*".
Section B.3.2: "*health disorders are currently understood to be influenced by peak values and are possibly underestimated by methods involving r.m.s. averaging alone*".

It is not clear how the caution zone should be used. Possibly, the author thought of conditions above the upper boundary of a zone as a definite health risk and conditions below the lower boundary of a zone as carrying no risk. However, there is no indication of the extent to which the risk changes from the bottom to the top of the zone, or the factors (e.g., irregularity of exposure) that could allow exposures high in a zone without them becoming unacceptable. It must therefore be concluded that, according to this standard, to prevent a foreseeable risk of injury from vibration, the conditions should be below the health guidance caution zone. It will be a matter of differing opinion as to when exposures up to the top of a health guidance caution zone can be considered acceptable. Perhaps the standard should have mentioned the need for precautions (not just caution) when conditions are within the zone and specified what actions might be considered appropriate. With this interpretation, conditions below the zone are always acceptable, conditions within the zone would require precautions (to be specified) for them to be acceptable, and conditions above the zone would always be unacceptable.

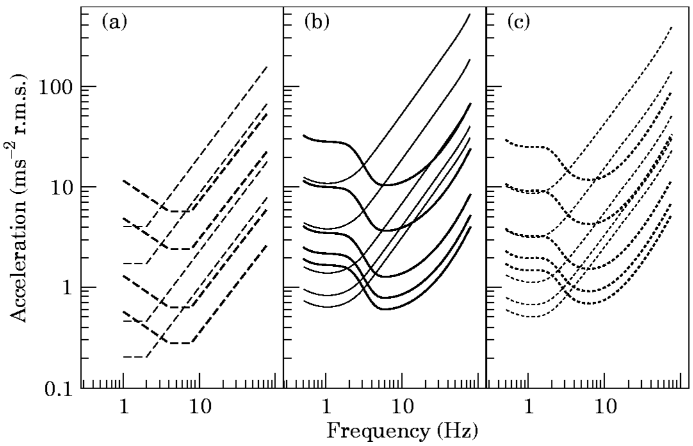

Figure 7. Comparison of horizontal and vertical vibration limits as a function of frequency for (a) ISO 2631 (1974, 1985)—1 min, 1 h, 8 h, 24 h; (b) BS 6841 (1987)—1 s, 1 min, 1 h, 8 h, 24 h; (c) ISO 2631 (1997)—1 s, 1 min, 1 h, 8 h, 24 h. (Thinner lines for horizontal vibration, thicker lines for vertical vibration).

4.4. COMPARISON OF THE GUIDANCE GIVEN IN THE ISO 2631 (1974, 1978, 1985), BS 6841 (1987), AND ISO 2631 (1997)

The Appendix offers a tabular summary of some of the principal problems with each of the three standards. It will be realised that the various doubts and ambiguities in the standards make it difficult to provide a wholly satisfactory comparison between the "limits", action level or health guidance caution zones that they offer. Nevertheless some comparison remains useful.

Figure 7 shows horizontal and vertical vibration guidance as a function of frequency, using the exposure limits from the old ISO 2631, the 15 $ms^{-1.75}$ action level from BS 6841 and the 17 $ms^{-1.75}$ upper boundary from the health guidance caution zone from the new ISO 2631. In each case, the appropriate frequency weighting is used.

Figures 8 and 9 allow the guidance in each of the standards to be compared with the guidance in the other two standards. It may be seen that for horizontal vibration, the

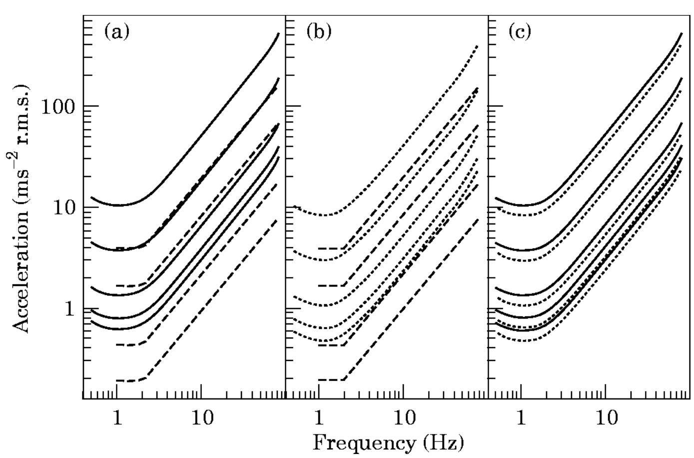

Figure 8. Comparison of horizontal vibration limits as a function of frequency for (a) ISO 2631 (1974, 1985) versus BS 6841 (1987); (b) ISO 2631 (1974) versus ISO 2631 (1997); (c) BS 6841 (1987) versus ISO 2631 (1997). (Values shown for 1 s, 1 min, 1 h, 8 h, 24 h; no values for 1 s for ISO 2631, 1974, 1985). Key as for Figure 2.

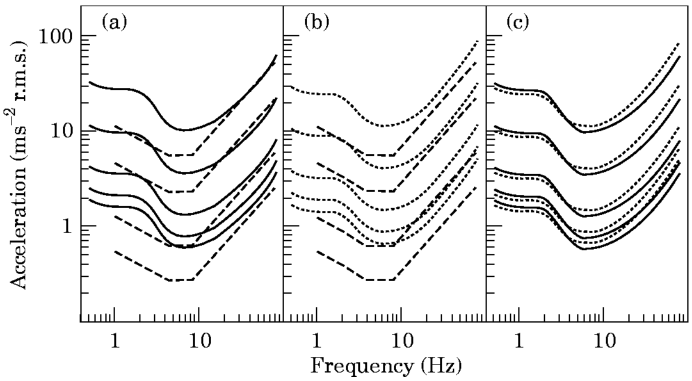

Figure 9. Comparison of vertical vibration limits as a function of frequency for (a) ISO 2631 (1974, 1985) versus BS 6841 (1987); (b) ISO 2631 (1974) versus ISO 2631 (1997); (c) BS 6841 (1987) versus ISO 2631 (1997). (Values shown for 1 s, 1 min, 1 h, 8 h, 24 h; no values for 1 s for ISO 2631, 1974, 1985). Key as for Figure 2.

vibration dose value guidance in BS 6841 (1987) and ISO 2631 (1997) is fairly similar, since the rise in vibration dose values from 15 to 17 is partially offset by the use of the 1·4 multiplying factor in ISO 2631. In the vertical direction, BS 6841 (1987) allows slightly greater magnitudes than ISO 2631 (1997) at frequencies up to 4 Hz: the rise in vibration dose values from 15 to 17 in ISO 2631 is offset by the increase in the frequency weighting at low frequencies. At 5 Hz and higher frequencies, BS 6841 suggests greater caution than suggested by ISO 2631 (1997).

It seems strange that so much energy should have been spent between 1987 and 1997 only to produce very similar guidance which is more difficult to use. It would have been expected that the state of knowledge would have increased between 1987 and 1997, but the only obvious increase has been the degree of confusion.

6. DISCUSSION

The measurement of human exposures to vibration is not without error. The evaluation of vibration can also introduce errors. Table 7 attempts to identify a possible error budget for ISO 2631 (1997). It may be seen that the frequency weightings are not the prime areas of uncertainty: doubts associated with evaluating multiple axis vibration, the use of the 1·4 multiplying factor, and the method of evaluating time-varying vibration introduce large differences. Large variations are also caused by uncertainty over the selection of the alternative assessment method: which caution zone and whether the lower or upper boundary of a caution zone is appropriate. The "acceptable exposure durations" vary much more than the reported measure of vibration magnitude: the error is raised to the second power (i.e., squared) when using the r.m.s. time-dependency and raised to the fourth power when using the vibration dose value. The evaluation and assessment method defined in BS 6841 (1987) appears to only have errors associated with the tolerances on the frequency weighting (i.e., the first three rows in Table 7).

Figure 10 shows the measurement, evaluation and assessment method defined in BS 6841 (1987). This contrasts with the potentially more complex procedure for ISO 2631 (1997) as shown in Figure 11.

After referring to ISO 2631 (1997), different people will decide to quantify the vibration in different axes when measuring vibration with respect to health. When evaluating the same recorded waveforms according to ISO 2631 (1997), two people can decide to use different methods of analysis and report widely different values without specifying what

TABLE 7

Maximum possible errors and differences associated with tolerances or different interpretations in ISO 2631 (1997)

Source of error	% change in magnitude	Effect on acceptable exposure duration (from 1 min–24 h) (%) r.m.s. (>10 min)	*VDV* (%)
10% measurement error (example)	10	21	46
frequency weighting tolerance (+1 dB)	12	25	57
frequency weighting tolerance (+2 dB)	26	59	152
W_k versus W_b (<40 Hz)	20	44	107
1·4 multiplying factor	40	96	284
dominant axis versus root-sums-of-squares	73	200	800
dominant axis versus ΣVDV	32	73	200
evaluation of intermittent motion: 1–10 min	216	900	9900
crest factor (between $\sqrt{2}$ and 9·0)	536	3950	163 925
criterion for using r.m.s. or *MTVV*	50	125	406
criterion for using *eVDV* or *VDV*	25	56	144
linear or exponential running r.m.s.	30	69	186
width of health guidance caution zone	100	300	1500
VDV versus r.m.s. "health guidance caution zone"	144	498	3477

method of evaluation they have used; unfortunately, the standard does not define methods of reporting which method has been used. Even if they decided to use the same measurement and evaluation methods, and therefore obtained almost the same value, after referring to the guidance in the standard they could disagree on whether a specified vibration exposure was acceptable or unacceptable.

The production of an International Standard may involve reaching a compromise between differing opinions. However, when opinion is based on evidence and experience, and discussion seeks to locate areas of agreement rather than conflict, a satisfying outcome is likely. ISO 2631 (1997) reflects muddle and absence of agreement. With uncertain

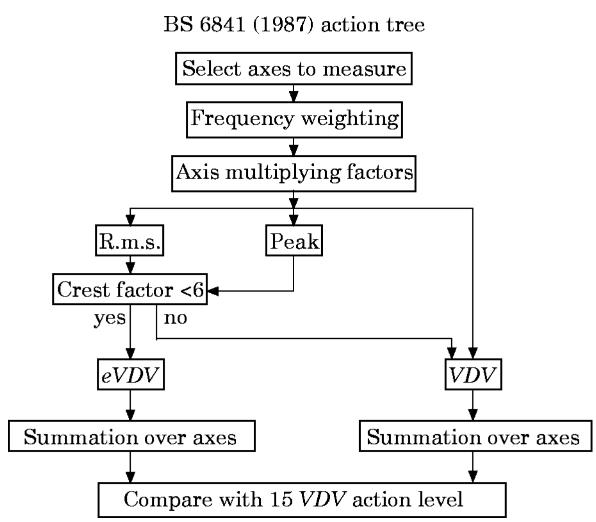

Figure 10. Method of evaluation and assessment defined in BS 6841 (1987).

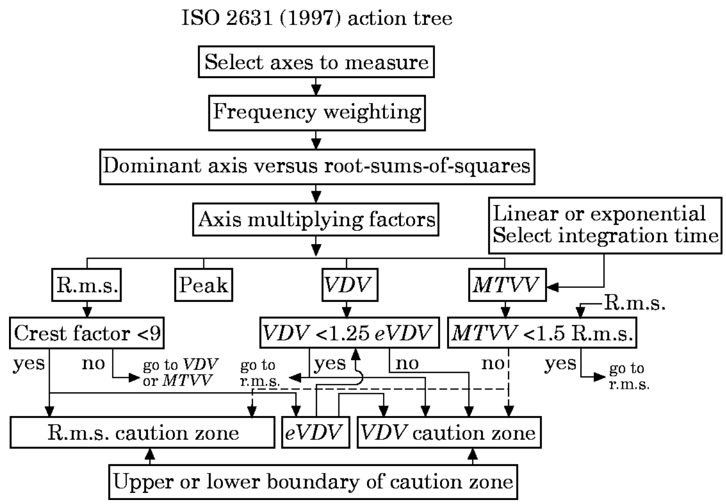

Figure 11. Methods of evaluation and assessment defined in ISO 2631 (1997). (The summation over axes is performed after the calculation of the r.m.s., *VDV* or *MTVV*, but is shown earlier for clarity).

knowledge, it is possible that alternative methods (or a different importance for different quantities) may need to be defined. However, the methods should be clear (and, if possible, simple): a failure to agree should not lead to unclear expression of what is required. This International Standard is virtually unusable without a guide to its interpretation.

It would be hoped that any measurement, evaluation or assessment method promulgated in an International Standard would have been tried and tested. Clearly this is not the case. The process of formulating such standards has tended to be open loop (i.e., what can be agreed among those most influential in the work) rather than that which has been most used and found most useful or most appropriate. Feedback from users is not a necessary part of the standardisation process, which lacks quality control: many countries approve new standards without reading them, let alone having tried and tested the procedures they contain.

Standardization can become a self-serving game to those involved who may be unaware of how insensitive and out-of-touch with the experience of industry and the state of medical, engineering and scientific knowledge their standards have become. It remains to be seen how the world will respond to the current human vibration standards, but experts in industry and elsewhere with their own experience and reasoned opinions will often need to interpret, and improve upon, the information in standards which are inherently ephemeral.

Users of standards frequently have no way of knowing the basis of a standard. An indication of whether they are based on arbitrary consensus, current practice, logical reasoning, or scientific knowledge would be of interest to those considering whether they are suitable. All too often it is necessary to choose between standards because of their apparent status rather than evidence that they are based on any relevant information. Even the committee responsible for a standard will not have information on why a standard has a particular form: there is nobody capable of withstanding a cross-examination on the technical justification of ISO 2631 (1997). If it were required that the source of the information in standards was traceable it might assist intelligent users of standards and impede a sloppy approach to the drafting of standards.

A standard which is confused, internally inconsistent, and contains errors should not reach publication. The problems are not confined to the drafting of standards and the membership of committees: it must be questioned whether the representatives of member countries of the ISO who voted for the standard had read and understood its content. Additionally, standards organisations should consider whether their standards can be unduly influenced by minorities and whether they have arranged adequate quality control mechanisms.

It is desirable to express clearly that whole-body vibration can cause injury and that the measurement and evaluation of vibration exposures according to current methods will usually form a significant and useful part of a preventative programme. However, it is also desirable to identify areas in which current measurement, evaluation and assessment procedures are capable of improvement.

6. CONCLUSIONS

It requires no consideration of the epidemiological or experimental evidence of injuries caused by whole-body vibration to conclude that the text of ISO 2631 (1997) is confusing. For users of BS 6841 (1987) and ISO 2631 (1997), the positive conclusion from this review is that it is possible to interpret ISO 2631 (1997) as being consistent with BS 6841 (1987). However other interpretations are also possible. The British Standard has the advantage of giving (a) a simpler, clearer and an internally consistent evaluation method, (b) the same evaluation method for comfort and health, and (c) a set of apparently reasonable actions associated with severe exposures to vibration or repeated shock. An improved International Standard for measuring, evaluating and assessing human exposures to vibration and shock is required.

REFERENCES

1. INTERNATIONAL ORGANIZATION FOR STANDARDIZATION 1974 *ISO* 2631. Guide for the evaluation of human exposure to whole-body vibration.
2. INTERNATIONAL ORGANIZATION FOR STANDARDIZATION 1978 *ISO* 2631. Guide to the evaluation of human exposure to whole-body mechanical vibration and shock.
3. INTERNATIONAL ORGANIZATION FOR STANDARDIZATION 1982 *ISO* 2631-1978/*Amendment* 1. Guide for the evaluation of human exposure to whole-body vibration.
4. INTERNATIONAL ORGANIZATION FOR STANDARDIZATION 1985 *ISO* 2631/1. Evaluation of human exposure to whole-body vibration—part 1: general requirements.
5. BRITISH STANDARDS INSTITUTION 1974 *British Standard*, *DD*32. *Draft for development*. Guide to the evaluation of human exposure to whole-body vibration.
6. BRITISH STANDARDS INSTITUTION 1987 *BS* 6841. Measurement and evaluation of human exposure to whole-body mechanical vibration.
7. M. J. GRIFFIN 1988 *Proceedings of joint French-British Meeting*, *Groupe Francais des Etudes des Effets des Vibrations sur l'homme and UK Informal Group on Human Response to Vibration*, *INRS*, *Vandoeuvre*, *France*, *September* 26–28. International Standard 2631 and British Standard 6841: a comparison of two guides to the measurement and evaluation of human exposure to whole-body vibration and repeated shock.
8. INTERNATIONAL ORGANIZATION FOR STANDARDIZATION 1997 *ISO* 2631-1. Mechanical vibration and shock—evaluation of human exposure to whole-body vibration—part 1: general requirements.
9. H. E. VON GIERKE 1975 *Society of Automotive Engineers*, *Truck Meeting*, *Philadelphia*, 10–13 *November*, *SAE Paper* 751009. The ISO Standard Guide for the evaluation of human exposure to whole-body vibration.
10. C. H. LEWIS and M. J. GRIFFIN 1998 *Journal of Sound and Vibration* **215**, 915–926. Evaluations and assessments obtained using alternative standards for predicting the risk of injury from whole-body vibration.

APPENDIX: TABULAR SUMMARY OF SOME PRINCIPAL PROBLEMS WITH THE THREE STANDARDS

TABLE A1

A summary of some problems with International Standard 2631 (1985) *in respect of health guidance*

Defined vibration limits irrespective of context or consequences.
Does not distinguish between measurement, evaluation and assessment: based on a set of limits.
Limited to three translational axes supporting a seated, standing or recumbent person.
Unclear whether assessments of multi-axis vibration should be based on "worst axis" or r.s.s. of all axes.
Frequency range limited to 1–80 Hz, with no proper definition of weighting or band-pass filters until the publication of ISO 8041 in 1990.
Inappropriate frequency weightings advocated for recumbent postures.
Unclear whether "frequency weighting" or the "rating" method should be used to assess random and multi-frequency motions.
Weighted values reported for x- and y-axis vibration may, or may not, include 1·4 multiplying factor.
Frequency weighting (W_g) appears to be an inappropriate shape at high and low frequencies.
Unknown effect of filter phase on peak values used to determine crest factors.
Time-dependency not defined for exposure durations <1 min.
Time-dependency appears to define excessively high vibration limits for short duration exposures.
Time-dependency appears to define excessively low vibration limits for long duration exposures.
Difficult to evaluate time-varying and intermittent exposures.
Not possible to use the standard to quantify the severity of daily exposures by a single value.
No guidance on population cover or probability of injury or disease when exposure limits are exceeded.

TABLE A2

A summary of some problems with British Standard 6841 (1987) *in respect of health guidance*

Limited to three translational axes supporting a seated, standing or recumbent person, and fore-aft back vibration.
Weighted values reported for backrest vibration may or may not include 0·8 multiplying factor.†
Phase response of filters is defined without knowledge of importance to human response, may sometimes affect vibration dose values.
The actions appropriate to exposures above and below the 15 *VDV* "action level" could be more clearly specified by an appropriate body.
Unclear whether the 15 *VDV* "action level" applies to single daily exposures and lifetime exposures in addition to those who are "routinely exposed".
Any influence of rest periods not specified.
No indication of the percentage cover provided by the 15 *VDV* "action level".

† This is a typographical error in the standard: 0·8 multiplying factor should be used.

TABLE A3

A summary of some problems with International Standard 2631 (1997) *in respect of health guidance*

Standard offers too many ambiguous alternatives to be used as a standardised method of evaluating and assessing vibration with respect to health.
Unclear which axes should be assessed, possibly three axes on surface supporting seated persons.
Difficult to extend evaluation and assessment to other axes since method for evaluating vibration in other axes with respect to comfort uses different axis multiplying factors.
Unclear whether assessments of multi-axis vibration must be based on "worst axis" or whether "vector sum" of all axes is also appropriate.
Unclear how to determine the "vector sum" when using vibration dose values.
Weighted values reported for x- and y-axis vibration may or may not include a 1·4 multiplying factor.
Phase response of filters is defined without knowledge of importance to human response; may sometimes affect peak values and vibration dose values.
Frequency weighting W_b defined incorrectly.
The origin and justification for frequency weighting W_k not known.
Difficult to understand the need for introducing W_k which is almost within the error tolerance of existing weighting W_b.
The use of a different evaluation method for comfort gives unjustified inconsistency between evaluations within respect to comfort and health.
The 0·8 multiplying factor for fore-and-aft backrest vibration does not take account of the increased multiplying factor (to 1·4) for fore-and-aft seat vibration.
Time-dependency of health guidance caution zones not defined for exposure durations <1 min.
When using "energy-equivalent vibration magnitude", artificially low values may be obtained by using the method defined for exposures to different magnitudes and durations.
Confused combination of different time-dependencies offered: r.m.s., *VDV*, *MTVV* and none (1–10 min).
Excessive crest factor limit of 9·0 for deciding whether r.m.s. evaluations are sufficient.
Two alternative definitions of running r.m.s.
Unclear whether *MTVV* should only be used with 1 s integration time.
No stated use of *MTVV* values after they have been calculated.
Criterion for using *MTVV* is such that use of *MTVV* will usually be indicated in preference to overall r.m.s.
At the limiting criterion for using *MTVV* or r.m.s. the error obtained by choosing one or the other is 50%.
At the limiting criterion for using *VDV* or r.m.s. the error obtained by choosing one or the other is 25%.
Health guidance caution zones shown in Figure B.1 are drawn incorrectly.
The two health guidance caution zones are in dramatic conflict.
The "r.m.s. health guidance caution zone" allows very excessive magnitudes for short duration exposures.

(*Continued on next page*)

TABLE A3—*continued*

Health "r.m.s. health guidance caution zone" is not defined mathematically.
The wording of the health guidance caution zones is ambiguous.
Unclear whether a health guidance caution zone applies to single daily exposures and lifetime exposures in addition to those who are "regularly exposed".
Influence of rest periods not clear.
No indication of the percentage cover provided by the health guidance caution zones.