Response to "Comments on 'A re-examination of risk estimates from the NIOSH Occupational Noise and Hearing Survey'" [J. Acoust. Soc. Am. 103, 2734 (1998)]

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Concern is raised by Dobie [J. Acoust. Soc. Am. **103**, 2734 (1998)] regarding a recent analysis [Prince *et al.*, J. Acoust. Soc. Am. **101**, 950–963 (1997)] of the NIOSH Occupational Noise and Hearing Survey data. Specifically, issues are raised concerning (1) definition of hearing handicap, (2) the use of frequency-specific articulation index (AI) weights applied to the binaural pure-tone average of 1, 2, 3, and 4 kHz, and (3) conclusions regarding significant excess risk based on this definition. We have reviewed the development of the definitions of hearing handicap and provide additional support for the use of a hearing handicap definition based on the binaural pure-tone average of 1, 2, 3, and 4 kHz and the weighting of specific frequencies. Furthermore, our definition of noise-induced hearing handicap is similar to one of several proposed by the International Standards Organization (ISO-1999, 1990) and the American National Standards Institute (ANSI S3.44, 1996). Additional analyses show that there is significant evidence of excess risk at daily exposure levels below 85 dB using any of the pure-tone average and/or weighting strategies we have examined. Hence we have provided additional support for our conclusions regarding exposure-response curves and we have reaffirmed that our methods are appropriate for the scope of our analysis. [S0001-4966(98)00905-9]

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We are pleased to have the opportunity to clarify our rationale and methodology as it relates to three issues mentioned by Dobie (1998). These include (1) terminology and the use of hearing handicap, (2) use of articulation-based weights applied by frequency for the binaural pure tone average of 1, 2, 3, and 4 kHz, and (3) conclusions regarding significant excess risk based on the weighted and unweighted hearing handicap definition (Prince *et al.*, 1997).

I. DEFINITION OF HEARING HANDICAP

Dobie (1998) states that the choice of outcome variable (Prince *et al.*, 1997) is unusual and believes that it is inappropriate. The rationale for Dobie's statement appears to be that most state and federal workers' compensation programs use either a pure-tone average of 0.5, 1, 2 kHz or a pure-tone average of 0.5, 1, 2, 3 kHz and that "none use the 1, 2, 3, 4 kHz frequency combination recommended by a Task Force of the American Speech and Hearing Association" (ASHA, 1981).

We wish to clarify that this paper and its results were not to be applied nor were the analyses conducted for use by state and federal workers' compensation purposes. Our study was designed to evaluate damage-risk criteria for occupational noise exposure. The analysis focused on characterizing the dose-response relationship between cumulative noise dose and *noise-induced* hearing loss. Therefore its use to infer hearing handicap for compensation purposes is irrelevant to the scope of this analysis. In fact, our analysis specifically focused on "noise-induced hearing handicap" (NIHH) rather than "hearing handicap" which is independent of etiology.

Given this distinction, we believe it was appropriate to use the standard terminology for noise-induced hearing handicap used for this same purpose by international (ISO-1999, 1990) and American national standards (ANSI S3.44, 1996). The reference ISO-1999 and ANSI S3.44-1996 standards have defined hearing handicap as "*a combination of hearing threshold levels at specified frequencies*," whereas "*potential hearing impairment is directly assessed by the noise-induced permanent threshold shift (NIPTS) . . . for the exposure conditions and populations under consideration.*"

To better evaluate concerns regarding terminology, we revisited the literature relevant to the development of the 1959 American Academy of Ophthalmology and Otolaryngology (AAOO) definition which contained three frequencies (0.5, 1, and 2 kHz) and a 27 dB HL threshold for beginning handicap. Even before the adoption of the original AAOO (1958) rule, other rules for calculating percent hearing handicap had been employed, including one issued by the American Medical Association's (AMA) Council on Physical Medicine in 1947 (AMA, 1947). This method, called the Fowler–Sabine scale, used the four frequencies 512, 1024, 2048, and 4096 Hz but gave them weights of 15%, 30%, 40%, and 15%, respectively (Davis, 1978). In fact, Davis (1978) stated that this definition is a "direct ancestor of the AAOO rules, which differ chiefly in their greater simplicity and their rejection of 4000 Hz from the calculation." According to Davis (1973), this method was revised in 1959 because "it was essential to simplify the

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more accurate but complicated Fowler-Sabine scale in order to gain acceptance. Otologists just wouldn't use the complicated table . . . ."

When the Occupational Safety and Health Administration (OSHA) promulgated its amendment for hearing conservation programs in 1981, the AAOO rule was criticized for including only three frequencies and for having a relatively high threshold for beginning handicap. The view at this time was that frequencies above 2 kHz clearly assisted the understanding of speech in noisy situations and this favored the inclusion of 4 kHz or at least 3 kHz in the calculations.

In light of mounting evidence that the higher frequencies were important for speech discrimination in nonideal conditions (distorted or with competing noise), the AAO (formerly AAOO) amended its formula to include 3 kHz (AAO, 1979). Later studies confirmed that hearing sensitivity above 2 kHz is critical for speech communication (Suter, 1985; Smoorenburg, 1992). A study by Phaneuf *et al.* (1985) confirmed that hearing sensitivity above 2 kHz was required to predict hearing disability and handicap. The study also reported that the highest precision in predicting "judged hearing disability" was obtained with a pure tone average of 1, 2, 3, and 4 kHz in the worse ear.

Terminology: Hearing impairment versus hearing handicap

In the original manuscript submitted to the journal, we used the term *hearing impairment* in a manner consistent with its use in the 1972 NIOSH criteria document (NIOSH, 1972) and with OSHA's definition of *material impairment of hearing* (46 Fed. Reg. 4082, 1981).[1] However, journal reviewers strongly recommended substituting *hearing handicap* to be consistent with the ISO-1999 (1990) and ANSI S3.44 (1996) standards. This seemed appropriate since additional analyses were included to compare the new NIOSH excess risk estimates to models used in these standards.

In our use of the term *hearing handicap*, the ears were given equal weighting and the frequency-specific pure-tone average was used to dichotomize the population into groups with and without hearing loss (as defined by OSHA and NIOSH). The proportions of workers with and without hearing loss were then compared to a reference value (based on "control group" pure-tone averages), a strategy consistent with recommendations of ISO-1999 (1990) and ANSI S3.44 (1996). Hence our definition of hearing handicap does not appear to be particularly unusual or inappropriate.

Our statements in the paper appear to be misinterpreted with regard to variation of excess risk estimates by definition of hearing handicap. To place the statements in their proper context, we discussed why the dose-response curves for NIHH may vary. We stated (Prince *et al.*, 1997) that:

"Hearing damage at 3 and 4 kHz is expected to occur sooner than loss at lower frequencies (0.5, 1, and 2 kHz). Definitions [of NIHH] that exclude the higher frequencies tend to be less sensitive to noise damage and may require longer durations of exposure to a given sound level to see significant excess risks in the population. Figures 4A and B suggest that the most suitable definition of hearing handicap may depend on the population characteristics, such as age, exposure duration, and degree of hearing handicap already accrued . . . ."

There appears to be confusion regarding the concept of standard threshold shift and a criterion to prevent noise-induced hearing loss, for which OSHA and NIOSH ordinarily use the term "material impairment of hearing." Dobie suggested that "these comments would be very appropriate if *hearing handicap* was replaced by *standard threshold shift*." The purpose of *hearing handicap* (as meant here to represent material impairment of hearing), is quite different from that of *standard threshold shift*. While *hearing handicap* is used in the development of damage-risk criteria, a *standard threshold shift* refers to a change in hearing for an individual relative to a previous test and is used in the context of a hearing conservation program. The NIOSH Occupational Noise and Hearing Survey, a cross-sectional study, did not collect data on individual changes in hearing over time.

To further his arguments regarding our choice of frequencies, Dobie makes an analogy to the use of a single frequency (8 kHz). Dobie's comment that "we wouldn't call these changes [at 8 kHz] 'HH' [hearing handicap] because isolated threshold shifts at 8 kHz do not affect everyday speech communication" is specious. We never implied that 8 kHz or any single frequency is important for everyday speech communication. However, there is evidence that 3 kHz and 4 kHz are indeed important for speech recognition as are 1 kHz and 2 kHz. The fact that 3 kHz and 4 kHz are earliest and most severely affected by noise should not exclude them from our selection of a prevention criterion, but argue in their favor. Therefore, we consider it accurate to state that "the addition of the most sensitive frequencies to a hearing handicap definition is a valid option if the goal is to have a measure that addresses both prevention and identification of noise-induced hearing handicap."

II. USE OF ARTICULATION-BASED WEIGHTS FOR BINAURAL PURE-TONE AVERAGE

As mentioned previously, the idea of frequency-specific weighting is not a new concept (AMA, 1947). In our paper, the idea was conceived as an alternative that would balance the need to take into account both hearing sensitivity to noise-induced damage at 3 and 4 kHz and speech understanding. Since the frequencies do not contribute equally to speech recognition, as demonstrated by the research of French and Steinberg (1947) and others (Kalikow *et al.*, 1977; Suter, 1985; Quiggle *et al.*, 1959), a decision was made to weight the frequencies for the pure tone average with weights using the articulation index (ANSI S3.5-1969).

The articulation weights from Table 5 of ANSI S3.5-1969 were used as a relative guide to weighting the frequencies we chose to include in our definition of noise-induced hearing handicap. Given the importance of these four frequencies (1, 2, 3, and 4 kHz) in predicting noise-induced hearing handicap, we wanted to make some allowance for the relative contribution of each frequency. We were not using these data to represent 1/3 octave bands and do not have audiometric data corresponding to the 20 octave bands used in the calculation of the AI, or for each of the 15 1/3-

TABLE I. Excess risk percent by exposure level, age, duration exposed, and hearing handicap definition.

Daily exposure level (dB)	Hearing handicap definition: 1–4 kHz	1–4 kHz, AI weight[a]	1–4 kHz (alternate weighting scheme)[b]	1–3 kHz	0.5–2 kHz. (*AAOO definition*)	0.5–2 kHz. (*AAOO definition*)	0.5, 1, 2, 4 kHz (Fowler–Sabine weights)[c]
			Age 30, duration 2–4 years				
80	0.2	0.1	0.4	0.4	0.4	0.3	2.0
85	0.9	0.9	1.1	1.1	1.0	0.9	0.6
90	3.3	3.3	2.9	2.7	2.5	2.3	1.9
95	10.2	10.3	7.9	7.3	6.8	6.5	6.1
100	30.1	30.2	24.0	21.6	20.6	20.4	23.1
			Age 45, duration 5–10 years				
80	0.6	0.5	1.8	2.3	2.0	1.7	0.9
85	3.5	3.3	5.0	6.4	5.3	4.8	3.0
90	12.4	12.2	13.3	17.3	13.6	13.5	9.2
95	34.6	34.0	34.0	43.8	34.4	36.7	28.2
100	65.8	65.1	68.8	78.1	69.6	74.1	68.8
			Age 60, duration >10 years				
80	1.5	1.2	4.9	5.8	4.3	4.8	2.9
85	8.4	7.9	13.2	15.1	10.5	13.2	9.1
90	25.5	24.7	30.2	33.4	22.8	31.3	24.7
95	46.4	45.6	53.4	56.8	43.0	56.9	51.5
100	54.2	53.8	66.5	69.0	63.3	70.2	67.8

[a]AI-based were approximately 20%, 32%, 28%, and 20% for 1, 2, 3, and 4 kHz, respectively.
[b]Weights are 44%, 26%, 17%, and 13% for 1, 2, 3, and 4 kHz, respectively (Dobie, 1998).
[c]Weights are 15%, 30%, 40%, and 15% for 0.5, 1, 2, and 4 kHz, respectively (Davis, 1978).

octave bands. As calculated in Eq. (1) (Prince *et al.*, 1997), the hearing threshold level for the frequencies 1, 2, 3, and 4 kHz were given weights of approximately 20%, 32%, 28%, and 20%, respectively. In comparison to the unweighted binaural pure-tone average of 1–4 kHz, the AI-weighted version produced only minor changes in excess risks. These nominal changes in excess risk suggest that the unweighted binaural 1–4 kHz definition would also be adequate in describing the dose-response relationship. Most importantly, we have observed that nearly every other combination of frequencies and weightings examined results in the same or greater degree of excess risk.

III. CONCLUSIONS REGARDING SIGNIFICANT EXCESS RISK

Dobie appears to minimize the significance of our sensitivity analyses. Such analyses are important in exploring whether the inferences made from the data are consistent under different conditions or assumptions. The sensitivity analysis was a systematic method for evaluating modeling assumptions and decisions regarding the choice of definitions and use of frequency-specific weights.

Dobie states that in our analysis, excess risk estimates vary by choice of frequencies used, but that our primary conclusion, that "there is excess risk of hearing handicap at time-weighted average exposure levels both above 85 dB and also between 80–84 dB," is based on the binaural AI-weighted pure-tone average of 1–4 AI definition, which he believes to be inappropriate. However, additional age-specific stratified analyses show that regardless of the definition of noise-induced hearing handicap (including the AAOO definition) used, our primary conclusions are supported. Table I shows additional analyses using several other definitions of noise-induced hearing handicap, all producing excess risk estimates that are higher than the binaural 1–4 kHz AI definition, particularly at daily exposure levels below 90 dB.

IV. SUMMARY

Based on the review of the literature and supporting data analyses, we conclude that Dobie's criticisms are tenuous. Further, we wish to reiterate that the results presented in our paper (Prince *et al.*, 1997) were not proposed as a basis of calculating hearing handicap for workers compensation purposes. Rather, our calculations were similar to those used by ANSI S3.44 (1996) and ISO-1999 (1990) in which the percentage of exposed workers with hearing handicap was based on a dichotomization of a binaural pure-tone average (i.e., average HTL $\geq$ 25 dB for selected frequencies) and compared to an appropriate control data base. These results may be used as a guide for developing occupational health standards for the protection of workers' hearing. The frequency-specific weighting was employed only as a relative guide to associate the pure-tone average with speech intelligibility and was not specifically advocated for use by state and federal compensation boards. Our analyses indicate that irrespective of the binaural pure-tone average definition or the frequency weighting used, excess risk estimates were similar or greater than the binaural 1–4 kHz AI definition of hearing handicap (Prince *et al.*, 1997).

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[1]NIOSH (1972) used the term "hearing impairment" to define its criteria for maximum acceptable hearing loss, and OSHA later used a slightly modified term "material impairment of hearing" to define the same criteria (46 Fed. Reg. 4082, 1981). In this context, a worker was considered to have a material impairment of hearing when his or her binaural pure-tone average at the audiometric frequencies 1000, 2000, and 3000 Hz exceed 25 dB.

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