TOWARD ACOUSTIC STANDARDS FOR POWERED ASSIST DEVICES

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ABSTRACT

A study of sound and its effect on human beings is reported. This study reviews the theoretical basis for sound measurement and abatement, and establishes a rational approach for setting standards as well as for achieving these specifications in prosthetic appliances. This study revealed that 50 decibels represent both a reasonable current standard and a maximum acceptable noise level for powered assist devices. Since the noise that is associated with currently available prosthetic devices commonly exceeds this noise level, its is recommended that component manufacturers be encouraged to begin immediately to achieve operational noise levels below 50 decibels and that the Committee on Prosthetics Research and Development (CPRD) establish 50 decibels as a standard by 1975, since such noise abatement can be obtained by standard design techniques which eliminate or muffle the noise sources. References to these techniques are given. By 1980, a standard of about 30 decibels should be feasible and should be adopted; this revised standard will provide adequate auditory feedback until synthetic, non-auditory feedback methods are developed which will permit the adoption of more stringent noise standards.

INTRODUCTION

Externally powered prosthetic devices in current use are unacceptably noisy. In moving toward noise abatement, efforts to define acceptable noise level standards must proceed concurrently with efforts to actually reduce noise. The objectives of this paper are: 1. to move toward a rational basis for setting these standards, 2. to distinguish between short-term goals and longer range standards for noise levels, and 3. to identify conventional techniques and methods for reducing or eliminating such noise. In order to accomplish these objectives and to provide a concise reference for manufacturers, a brief review of the theory of sound is also presented.

PHYSICAL AND PHYSIOLOGICAL CHARACTERISTICS OF SOUND

Sound can be defined as those pressure variations which can produce a physiological effect. These pressure variations travel through any medium, such as air, with a velocity dependent on the density of that medium. For normal sound-pressure levels, this wave velocity, c, in m/sec, can be approximated very well by an isotropic process model [1][a], which for air gives

$$c \approx 20\sqrt{T} \tag{1}$$

where T is the absolute temperature in degrees Kelvin.

Sound can be quantified in many ways. A sequential description of local instantaneous pressure amplitudes is perhaps the most straightforward technique in principle, but a less cumbersome technique for describing sound utilizes the fact that any complex wave can be duplicated by properly adding together a number of simpler waves. This important property was first described by Fourier; he used sinusoidal waves as the simple waves. An example of a sinusoidal motion, which is a useful concept for fixing ideas, is the undamped oscillation of a mass on the end of a spring. Any complex sound waveform can be completely characterized by describing each of the sinusoidal waves making up this waveform. And each sinusoidal wave can be completely described by three parameters, the frequency, the phase, and the amplitude. For example, a *pure tone* consists of only one sinusoidal wave and can thus be completely described by specifying the single frequency, phase, and amplitude characterizing the wave.

The *frequency* in hertz (Hz) is a measure of the rate of vibration (1 Hz = 1 cycle per second). If the oscillating mass described above is moving up and down 50 times per second, its frequency of oscillation is 50 Hz. The frequency of a sound is commonly perceived as the *pitch* of the sound. The key middle "C" on a properly tuned piano produces a frequency of vibration of 440 Hz. Moving up the scale *one* octave to "C"

[a] Numbers in square brackets refer to references at the end of this article.

above middle "C" corresponds to doubling the frequency to 880 Hz. The maximum range of *audible frequencies* is highly variable from one individual to another, but generally is contained in the range from 20 Hz to 20,000 Hz.

The *phase* parameter is a measure of the time of occurrence of a particular event at a specific location or conversely, a measure of the location of an occurrence at a specific time. Implied in this definition is the ability to measure time or position relative to a fixed standard. Therefore, a reference system in the form of a second oscillating mass, with the same frequency of oscillation must be added to the oscillating mass example. These masses can then oscillate together, in which case they are said to be "in phase."

When the phase parameter is applied to sound, it is measured with respect to an easily identifiable event associated with the pressure wave, such as the peak pressure. The exact timing or absolute phase of such events is not important. However, the relative timing, or relative phase of sound components can be very important. For example, if two signals of the same frequency and amplitude are maximally out of phase, the two waves cancel, leaving no resulting wave. Similarly, changes in the relative phases of different frequency components can drastically alter the character of the combined wave. However, presently there exists only a qualitative understanding of how relative phase shifts affect perceived sound. The fact that there is a mechanism for perceiving relative phase can be appreciated by anyone who has listened to a high-fidelity recording using stereo headphones which were not in phase when a phase reversal to one earphone occurred. The most common perception of phase probably occurs in the binaural perception of the direction of a sound source. This capability is most often attributed to a perception of the relative time of arrival of the sound, or phase shift, to each ear.

The third parameter, *amplitude,* is a measure of the magnitude of the wave. For the oscillating mass analog, the amplitude is a measure of the maximum displacement of the weight. The amplitude of pressure variations can be measured using a number of different systems of units, each based on a force per unit area. One of the more common units used to measure sound pressure is the *microbar,* a pressure of one dyne per square centimeter. While an absolute measure of sound pressure in microbars is possible, a measure of relative pressure is more useful. A commonly used reference value for *sound-pressure variation* is the value 2.0×10^{-4} microbars, which is roughly the pressure variation associated with the weakest sound that can be heard by a person with "very good" hearing in an "extremely quiet" location [2]. The term *acoustic intensity* is sometimes used to quantify sound and is defined as the average rate of flow of energy through a unit area normal to the direction of propagation; a nominal reference value for acoustic intensity is 10^{-12} watt/cm.^{2}

If the energy flux in one sound is ten times that in another, the ratio of intensities is said to be one *bel*. Thus, an intensity scale, N_i, in bels, is a logarthmic scale of relative energy fluxes, or

$$N_i = log_{10}\frac{I}{I_o}\,(bels) \tag{2}$$

where I is the intensity of one signal and I_o is the intensity of a reference, or standard signal. Since the bel represents large differences in intensity, a smaller unit, the *decibel* (dB) has been introduced, which is equal to one-tenth of a bel, or

$$N_i = 10\,log_{10}\frac{I}{I_o}\,(dB)\,. \tag{3}$$

This scale is convenient since an individual's perception of sound is logarithmic in nature. For example, a tone of given frequency with an "intensity" of 40 dB sounds about twice as loud as another tone of the same frequency but with a 20 dB "intensity," even though the actual ratio of intensities is 100:1. The range of acoustic intensities that are of interest in sound measurement correponds approximately to an energy flux ratio of 10^{18}:1, hence it is convenient to relate these intensities on the logarithmic decibel scale.

If I is measured in watt/cm², and the quantity $I=10^{-12}$ watt/cm² is chosen as a reference level, the intensity scale is given by

$$N_i = 10\,log_{10}\frac{I\,(w/cm^2)}{10^{-12}}\,dB. \tag{4}$$

In determining the physiological and psychological effect of sounds on individuals, however, the intensity alone is not an adequate parameter to describe these effects. To a listener, the apparent loudness of any given sound varies both with the actual intensity and with the frequency. Although sounds with frequencies varying over a large band can be heard, the auditory response is not constant over the band, as frequency is varied. Therefore, at the present time there is no way in which one can analytically predict the physiological response to a given signal *a priori*.

Many psychoacoustical experiments have been conducted in which listeners were asked to rate the loudness of a sound. As a result of these experiments, involving many types of sounds in various arrangements, much has been learned about the concept of "loudness." One step toward rating the loudness of a sound has been to determine the *sound-pressure levels* of simple tones at various frequencies that are perceived to be as loud as a 1000 Hz tone of a given sound-pressure level. The results of this determination by Robinson and Dodson [3] are given as equal-loudness contours in Figure 1. The number on each curve is the sound-pressure level of the 1000 Hz tone used for comparison for that curve and the sound pressures are referenced to 0 dB at 0.0002 microbar. The *mini-*

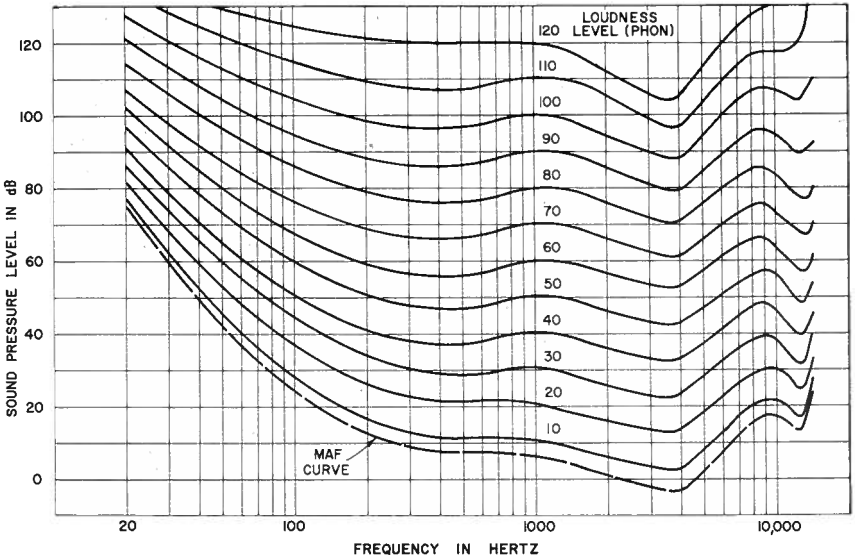

FIGURE 1.—Equal loudness contours for pure tones compared to a 1000 Hz signal (0 dB at 0.0002 microbar).

mum audible frequency (MAF) curve indicates the minimum sound-pressure level which is audible at that frequency.

To use the contours for determining the "equally loud" levels at other frequencies, find the point on the curve corresponding to the desired frequency and read off the corresponding sound-pressure level as the ordinate. For example, the 60 dB contour shows that a 67 dB level at 100 Hz is "just as loud" as a 60 dB 1000 Hz tone. It is also noteworthy that a 4000 Hz pure tone can be heard quite easily at a sound-pressure level of 10 dB, but a 50 Hz, 0 dB tone cannot be detected by a person with normal hearing.

The loudness level in *phons* of a particular sound, specified in intensity and frequency, is numerically the same as that dB level of a 1000 Hz source which subjectively appears to be just as loud as the original sound.

A set of equal-loudness contours [4] for bands of random noise is shown in Figure 2. Steady-state random noise is a common type of noise that occurs in ventilating systems, jets, blowers, combustion chambers, powered assist devices, etc. It does not have a well-defined pitch, such as characterizes a tone with the energy concentrated in components of definite frequencies; rather, random noise has energy distributed over a band of frequencies. The contours shown in Figure 2 are for relatively narrow bands of noise, such that 11 bands cover the range from 60 to 5800 Hz. The reference level for this case is again a 1000 Hz pure tone 0 dB at 0.0002 microbar.

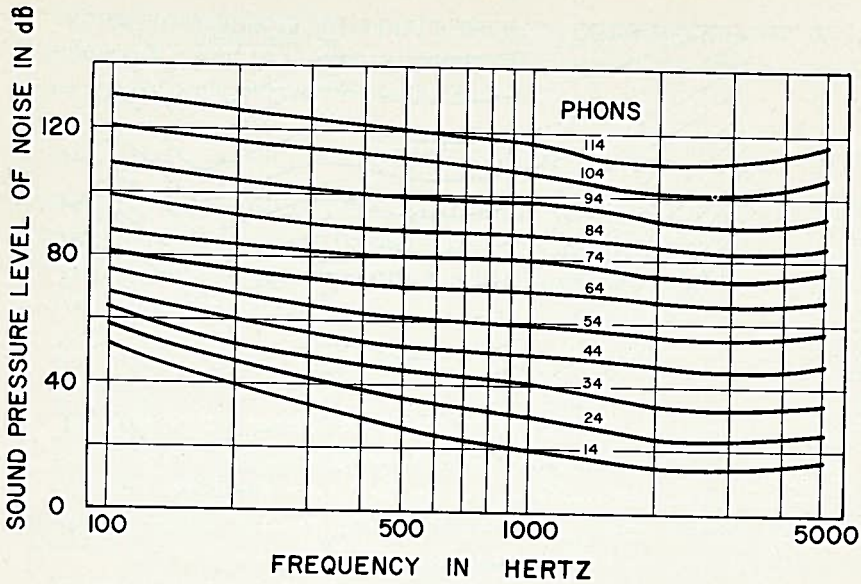

FIGURE 2.—Equal loudness contours for narrow-band noise compared to a 1000 Hz signal (0 dB at 0.0002 microbar).

MEASUREMENT OF SOUND LEVELS

Direct measurement of acoustic intensity is not possible with existing instrumentation; however, since acoustic intensity is approximately proportional to the square of the magnitude of the pressure variation, a *sound-pressure* scale N_p can be defined as:

$$N_p = 20 \log_{10} \frac{P\,(Mbar)}{.0002}\, dB, \qquad (5)$$

where P is the effective (r.m.s.) sound pressure in microbars, which can be easily measured. Since several reference levels are used for sound-pressure scales, the reference level should be specified along with N_p, i.e., N_p dB re 0 dB at 2.0 x 10^{-4} microbar for the scale given by equation (5).

Although it may be necessary to combine sound intensity data (obtained utilizing r.m.s. sound-pressure measurements) to correct a sound-level reading for existing background noise, decibel levels are never algebraically additive. However, decibel levels can be converted to relative intensities by using the following expression,

$$I \approx 10\ (N_p\ (dB)\ /20-12)\ w/cm^2, \qquad (6)$$

and since energies are algebraically additive, the energy levels can be combined and then converted back to the required decibel scale using equation (4), since $N_p \approx N_i$.

The techniques described thus far provide a relatively sensitive and accurate estimation of incident sound-field intensity. However, if sound-level meters were built to correspond exactly to these characteristics, with a uniform response regardless of frequency, the instruments would not accurately reflect the physiologically perceived sound levels, since the human auditory response is not uniform with frequency, as is pointed out in Figures 1 and 2. Thus, some provision must be made for the frequency-dependent effects of sound.

The effects of frequency on the *loudness level* of a sound can be taken into account by including electrical weighting networks in instruments designed to measure sound-pressure levels. In order to establish reasonable uniformity among the different sound-level meters, the American Standards Association, in collaboration with scientific and engineering societies, has established a set of sound-level meter standards. The current USA Standard for Sound-Level Meter [5] requires three frequency-response characteristics be provided in each instrument. These responses, as shown in Figure 3, indicate the deviation from the true decibel reading at any frequency; for example, at a frequency of 50 Hz, the meter set to response curve "A" with a signal which was actually 40 dB re 0 dB at 4×10^{-4} microbar would read (40–32) or 8 dB. These three responses are obtained by internal electronic weighting networks which provide the desired equal-loudness characteristics (Fig. 1). It is customary to use

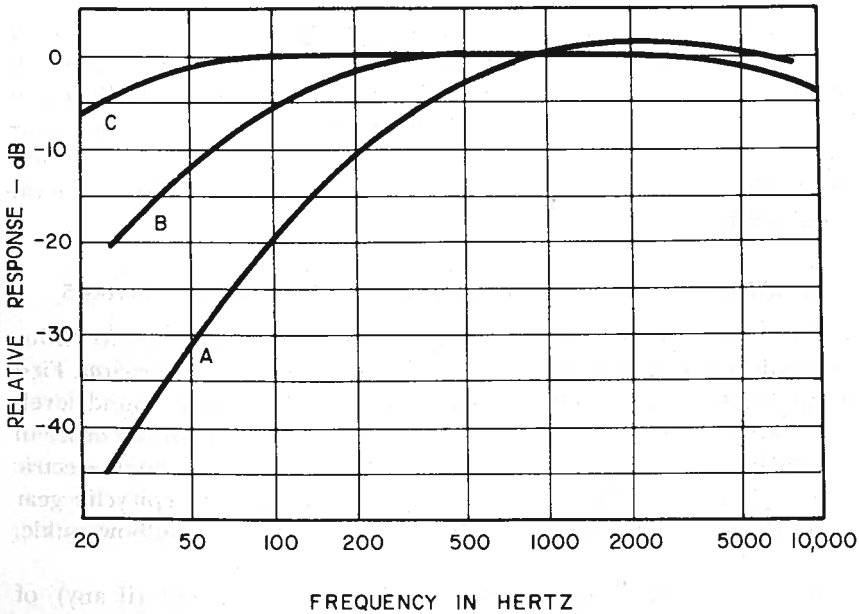

FIGURE 3.—Electrical frequency response for the ASA weighting characteristics for standard sound-level meters.

response A for sound levels below 55 dB, response B for levels between 55 and 85 dB, and response C for all levels above 85 dB [6, 7].

A better indication of the frequency distribution of a sound can be obtained using an *octave band analyzer*. This instrument operates directly from the output of a microphone or sound-level meter to provide a measure of the energy in each octave band of sound. The analyzer consists of a set of band-pass filters, selected by means of a rotary switch, followed by an attenuator and an amplifier, which drives both an indicating meter and a monitoring output.

While the frequency, phase, and amplitude distributions are all individually important in characterizing sound, currently employed sound-measurement techniques use a combination of these three parameters. The sound-level meter output is a single quantity obtained from the logarithmically scaled amplitude sum of the input frequency distribution. Since the full effects of phase in human hearing are ill-defined, the control of the phase of a noise signal is highly impractical, and the single parameter derived from the sound-level meter represents a reasonable estimate of the integrated noise signal as it is actually perceived by an individual, it is not profitable to use phase information. It is currently appropriate to use the one parameter as a measure of the noise output of prosthetic devices.

CHARACTERISTIC ENVIRONMENTAL SOUND LEVELS

Typical environmental levels measured with a standard sound-level meter include 4–6 dB for normal respiration, 10 dB for a safety pin falling on a hard surface, 15–20 dB for the rustle of leaves, 55–60 dB for an average factory, 85–90 dB inside an unmuffled truck, 100–110 dB for some discotheques, and up to 165–180 dB for a turbo-jet engine with afterburner [6, 8]. (Appendix I gives a more complete list of such typical sound levels.)

FACTORS IN THE DETERMINATION OF ACOUSTIC STANDARDS

There are a number of factors to consider in an attempt to define standards for acceptable noise levels produced by prosthetic devices. First of all the source and source strength must be considered. Sound levels generated by externally powered prostheses are presently of the order of 60–80 dB [9]. The primary sources of this noise are the small electric motors (which operate in excess of 10,000 r.p.m.), the epicyclic gear trains, the clutch mechanisms, and areas of sliding contact (elbow, ankle, and knee joints, e.g.).

However, consideration must be given to which portion (if any) of prosthetically produced sound might be desirable. Currently, some of the generated sounds can be used to provide feedback in normal back-

ground noise situations. Such acoustic feedback is highly desirable for efficient operation since the operator is made aware of the load, motor malfunction, etc., through such cues as frequency and volume changes in the output sound of the device. With current output levels of 60–80 dB, however, the problem is not one of providing adequate feedback but rather one of reducing the sound level to an acceptable level.

Excessively high levels of sound (i.e., noise) produce a number of undesirable effects. If the noise level is high enough, damage to a person's hearing can occur. Sustained noise levels as low as 85–90 dB can cause irreversible changes in the ear. Also, such energy densities can cause damage at the point of attachment to the wearer.

At somewhat lower levels, noise can be troublesome by disrupting conversation. The *speech-interference* level, which is roughly the maximum permissible level of impinging sound for which satisfactory intelligibility of moderately difficult speech material is realized, can be used to derive a realistic upper bound on allowable noise. Speech-interference levels for men with average voice strengths are given in Table 1 as a function of the distance separating the conversing parties [6].

TABLE 1.—*Voice Level (dB)*

Distance feet	Normal	Raised	Very loud	Shouting
0.5	71	77	83	89
1	65	71	77	83
2	59	65	71	77
3	55	61	67	73
4	53	59	65	71
5	51	57	63	69
6	49	55	61	67
12	43	49	55	61
24	37	43	49	55

Adverse effects are possible at even lower levels in the form of annoyance or embarrassment to the user. However, measurement of the annoyance level and the *embarrassment level* is quite subjective in that these "parameters" vary greatly depending on the task the wearer is trying to perform at any specific instant, on previous conditioning, and on the emotional stability of the wearer. In addition, the exact character of the noise greatly influences the amount of annoyance caused; harsh, strident sounds characterized by a large proportion of high-frequency energy, particularly sounds above 2000 Hz, tend to be very annoying.

IMMEDIATE NOISE REDUCTION GOALS

From this discussion, it is clear that current noise levels produced in prostheses are unacceptably close to dangerous levels. Thus, a reduction

in maximum output levels is desirable. As an immediate goal, the noise should be reduced to about 50 dB as measured using the "A" characteristic on a sound-level meter to allow relatively normal conversation at close range. In addition, care should be taken to eliminate or reduce noise in the spectrum above 2000 Hz. These measures would provide freedom from serious physiological effects and would reduce speech interference problems.

FUTURE STANDARDS FOR PROSTHETIC NOISE LEVELS

Future standards should require more stringent control of noise. However, until better feedback methods are devised, the standards should reflect the need for adequate auditory feedback. One possible procedure which could be utilized in defining such a standard would be to set maximum permissible levels for a number of frequency bands with an octave band analyzer. If sound-level meters with the proper characteristic were available, the specification could be more easily set and progressively changed with time. One such characteristic analogous to those in Figure 1, would be a curve, which is flat at 0 dB from 20 Hz to 1000 Hz and which increases to +30 dB at 10,000 Hz, then decreases rapidly to a cut-off of −10 dB at 20,000 Hz. This curve, combined with the average auditory-response characteristic, would effectively insure very little high-frequency noise, and could be incorporated as curve "D" in standard sound-level meters. Calibration of such a device would be done at 1000 Hz in the same manner as the other curves are calibrated. A standard of 30 dB maximum sound level as measured with the "D" scale on such a meter should be attainable by 1980, and could therefore be set as a standard by that time.

TECHNIQUES FOR NOISE ABATEMENT

The noise output of any device such as a prosthetic elbow can be reduced in two principal ways: 1. elimination of the noise sources by design or 2. isolation and/or muffling. Currently employed noise-control techniques include the use of precisely fitted, alternate steel and non-resilient plastic helical-spur gears for high-speed gear reducers (epicyclic trains), the sealing of moving parts in grease housings, and the isolation of vibrating devices from potential sounding boards; e.g., motors should be placed on rubber mounts to decrease transmission of motor vibrations to the remainder of the structure. Entire operating units should be enclosed in air-tight shells if possible, to absorb and reflect airborne sound [10, 11, 12]. It should be noted that designs which decrease noise levels are not necessarily associated with increased total costs to the consumer since the reduction in wear may offset increased initial costs by decreasing maintenance and replacement costs.

It is conceivable that more direct methods of attaching and controlling prostheses will be developed, perhaps including direct skeletal attachment with direct neural control. When direct neural control is achieved, neural feedback will be possible. At that time no auditory feedback will be needed and it will be desirable to reduce noise as far as possible at all frequencies. Since audible noise is the most undesirable, acceptance tests can then be based on the "A" scale of standard sound-level meters with a maximum acceptable noise-level output standard of 20 to 25 dB for prosthetic devices.

CONCLUSIONS

To accomplish the desired noise reduction, it is recommended that prosthetic component manufacturers take immediate steps to reduce the sound levels produced by prosthetic devices to below the 50 dB level. Furthermore, it is recommended that the Committee on Prosthetics Research and Development draft a standard of 50 dB to be used as an acceptance criterion for prosthetic devices beginning in 1975.

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APPENDIX I

Typical Sound Levels [6, 8]

Decibels (re 0.0002 microbar)	*Event*
0	
5	Threshold of audibility (500–800 Hz)
10	Pin dropping in quiet room
15	Whisper
20	Rustle of leaves
25	Quiet conversation
30	Average auditorium
35	Quiet home or auditorium
40	Quiet radio
45	Average conversation
50	Average office
55	Noisy home
60	Average factory
65	Average radio
70	Average street noise
75	Noisy office
80	Police whistle
85	Truck (unmuffled)
90	Noisy factory
95	Loud street noise
100	Boiler factory
105	Train
110	Nearby riveter
115	Thunder, artillery
120	Threshold of feeling
125	Boiler shop (maximum level)
130	Hydraulic press
135	50-hp. siren (at 100′)