▶ **AS I SEE IT**

Audible Ultrasound ...Revisited

Haeff and Knox[1] writing in *Science* confirmed that humans could hear ultrasound and proposed that a novel ultrasonic hearing instrument might be possible. More than 25 years later, Lenhardt et al.[2] also reported in *Science* the results of the first ultrasonic hearing instrument for those with profound hearing losses. Encouraged by closed-set speech discrimination scores in the 40% range in cases of profound hearing impairment, a license was granted on the supersonic bone conduction hearing and method patent[3] for the purpose of producing a commercial device[4] for the remediation of hearing loss.

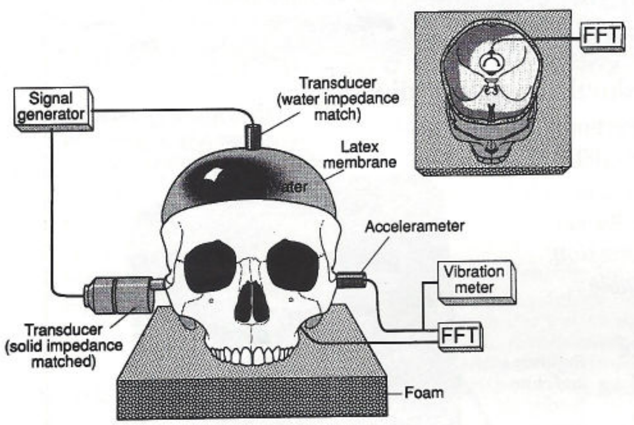

Fig. 1 *Calibration of audible ultrasound is problematic in that only the intensity of the vibration in the path to the ear can be measured. The level of vibration in the inner ear is only estimated. An ultrasonic vibrator will deliver vibrations to either the soft tissue of the head and neck or to bone of the upper torso. A hydrophone in an artificial "brain" (water-filled balloon) is effective in monitoring the vibration near the temporal bone. An accelerometer on the skin of the mastoid is the best mechanism of measuring energy in the clinical setting. Piezoelectric film transducers can also measure the transfer of energy from fluid to bone (and vice versa) when positioned between the "brain" and internal surface of the skull.*

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Name Choice

By standard definition, ultrasound is inaudible. The inventors[3] chose *supersonic* to suggest the ultrasonic sensation is somehow sonic. We also choose to include the term *bone conduction,* because ultrasound was inaudible in air. Each term was unfortunate in that supersonic didn't clearly identify the signal as ultrasound and ultrasound can also be perceived even when the stimulator is in contact with soft tissue in the upper torso and not with bone. Later I coined the terminology, *audible ultrasound*, which is more descriptive. As a play on initials for a recent movement in audiology, I referred to the ultrasonic hearing instrument as the *audible ultrasonic device* (AUD). This term, too, is descriptive since the energy delivered to the head is not amplified speech but rather intense unfocused ultrasound amplitude modulated (multiplied) by speech frequencies. As the name states, this is an ultrasonic device.

Are Humans Really Hearing Ultrasound?

The answer largely depends upon the mechanism postulated for inner ear stimulation. It is generally agreed that, in the normal cochlea, the very basal end is tuned to ultrasonic frequencies from 20,000 to about 100,000 Hz.[5-7] The failure of airborne ultrasound to efficiently stimulate the inner ear is due entirely to the lack of ultrasonic frequency response of the middle ear. Sagalovich et al.[7] modeled the traveling wave maximum displacement for driving frequencies in the audio and ultrasonic frequencies. Each audiofrequency maximum displacement agreed with that of Bekesy[8] and ultrasonic frequencies were found to have peak displacements only in the first few millimeters in the cochlear base. Since the middle ear and the inner ear co-evolved independently, it is not surprising that there is not an exact agreement in frequency response. There are other possibilities for ultrasonic transduction in the cochlea that are not discussed here. In any case, hair cells in the base of the cochlea can not be the sensory area stimulated in the severely hearing-impaired ear.

It has been established that the ultrasonic threshold increases proportionally with the degree of audiofrequency hearing loss.[2] The basilar membrane would be expected to increase its displacement and extend its displacement apically as the ultrasonic intensity increases. As a result, any remaining intact hearing area might be stimulated by ultrasound. In other words, intense ultrasound is an alternative way to stimulate intact apical hair cells in the impaired ear.

Is Intense Ultrasound Safe?

In 1954, Deatherage et al.[6] reported an audible sensation when swimming through a 50,000 Hz beam. An ultrasound loudness judgment experiment performed by Deatherage resulted in intense persistent tinnitus and permanent high frequency hearing loss. It should be remembered that ultrasound is not audible in normal hearing listeners until the stimulation is more than 90 dB above detectability at 8000 Hz. In the case of severe hearing impairment, the ultrasonic threshold may be an additional 25 dB higher.[2] At these levels, the ear and brain are exposed to very intense ultrasound. The effects of sustained intense stimulation on the damaged cochlea may be minimal, yet the safety of intense ultrasound has not been determined. The potential risk versus the benefit of ultrasound-induced audio sensation must be weighed against the risks and benefits of other communicative alternatives.

Calibration Prodedures

The prudent course of action to minimize any potential damage risk is to keep ultrasonic intensity exposure as low as possible. Calibration must be established for clinical use of audible ultrasound. Difficulties arise because ear stimulation is achieved via vibration in fluid or in bone. Investigators that addressed measured thresholds have referenced ultrasound as sound pressure in water (re: 20 µP). Another calibration option is to measure vibration on the skin over the mastoid bone and reference it to acceleration (re: 1 g rms). These calibration approaches were examined, as well as measuring the displacement of the "brain" (latex water-filled balloon) at the base of the skull using a customized piezoelectric film sensor (Fig. 1). The best calibration for ultrasound delivered to the soft tissue of the neck was a sensor (B&K hydrophone) in the "brain" positioned just above the temporal bone and reported as sound pressure in water (re: µ1 P), obviously impractical in clinical use. Acceleration measured at the mastoid is suggested to be the most reasonable compromise in establishing a calibration for fitting the AUD. Small economical hand-held vibration meters calibrated in acceleration (re: 1 g rms) are readily available for dispensers.

What Then Is Ultrasonic Speech?

When speech is multiplied (amplitude modulated) by an ultrasonic carrier, the result is ultrasound that has the time envelope of the speech. An accelerometer placed on the mastoid would measure the amplitude varying ultrasound and, in turn, the basilar membrane would vibrate resulting in speech envelope demodulation. Normal hearing individuals perceive high pitch speech, whereas, individuals with profound hearing loss detect the speech envelope with their remaining hair cells. The hair cells do not have to be cochlear because intense oscillating ultrasound will result in distention and relaxation of the cochlear windows, which could result in bulk fluid movement in the vestibule that may serve as a saccular stimulant.

Individuals with no measurable hearing and no vestibular function are, therefore, poor candiates for the AUD. The important fact to remember is that, for those with profound hearing loss to hear ultrasonic speech, the intensity must be intense. Deatherage et al. felt no pain with intense ultrasound. The dispenser must be extremely careful in fitting and most importantly monitoring patients fitted with audible ultrasound devices.

Fitting and Training

Ultrasonic speech can be presented in at least three configurations: full amplitude modulation, carrier suppressed modulation or single sideband modulation. We prefer single (upper sideband) modulation (in the 25-40 kHz range),[2] but all three are detectable by hearing-impaired listeners.

The first step in fitting the AUD is to determine the lowest threshold of a range of ultrasonic carrier frequencies. This is often very time-consuming in individuals with profound hearing losses who have little experience with the perception of sound. There is an interaction between the wavelengths of tones in the 25-40 kHz range and the geometry of the head that results in a site (usually the mastoid) that yields the lowest threshold. Finding this "sensitive spot" requires sweeping of the ultrasonic carrier tone until a reliable threshold is obtained. It is important to try various tones, since tuning the carrier to the head will reduce the amount of energy delivered to the ear. The choice of which specific ultrasonic carrier frequency is not critical in that it is the amplitude envelope that conveys speech information to the ear. It has been our custom to present ultrasonic speech at 5 dB sensation level (SL).[2] In the normal ear, ultrasonic noise at 5 dB SL can suppress very high audiofrequency thresholds by as much as 20 dB; therefore, 5 dB SL of ultrasonic energy is not a "faint" sound.

The amount of residual hearing and listening experience often determines the degree of training an audible ultrasound device candidate will require. Hours might be required to obtain reliable detectablity of ultrasonic speech, especially in some children. A training technique has been developed which combines ultrasonic speech with very low frequency modulated envelope speech such that hearing-impaired listeners may simultaneously "feel" and hear words. Speech is modulated on both an ultrasonic carrier and on a 30 Hz carrier. The 30 Hz speech is delivered through a water pillow on which the head is placed. The 30 Hz speech sounds are muffled, but the timing patterns are pronounced. The low frequency vibration provides a prosodic or time cue for the ultrasonic speech. Gradually, the 30 Hz speech is attenuated until only the ultrasound remains.

Conclusions

While conventional hearing instruments and an audible ultrasound device share similar front end processing (microphones, filter, amplifier, etc.), the similarity ends there. The AUD is an ultrasonic device that delivers intense, unfocused speech amplitude modulated energy to the head. Because it allows the delivery of intense energy, most people with profound hearing loss can be helped. Care must be exercised in fitting the instruments to keep ultrasonic exposure as low as possible. I recommend: 1) determining the lowest ultrasonic frequency detectable; 2) tuning the device to that frequency (referencing the threshold in acceleration); and 3) monitoring progress (at both ultrasonic and audio frequencies) for any possible signs of overexposure.

As with so many things in science, a "first" may not really be a first. After years of work on audible ultrasound, I happened upon a letter to the editor in *Nature* in 1993, in which Combridge and Ackroyd[10] described a 1946 visit of Dr. Maass of Bremen who demonstrated not only ultrasonic hearing, but ultrasonic pitch discrimination and ultrasonic hearing in some totally deaf subjects. They further stated that no systematic work on the possiblity of ill effects of ultrasonic vibration had been carried out. This is about the status of the phenomena in 1998. The audible ultrasonic device *does* provide a promising opportunity for a nonsurgical alternative to the remediation of hearing loss. Nonetheless, its clinical effectiveness remains to be documented. ◆

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