Chapter 7

Biomedical Ultrasound/Bioresponse to Vibration

By Robin O. Cleveland, Chapter Editor
2004 Committee Chair History Lecture by Donald W. Baker & Janet M. Weisenberger

The Biomedical Ultrasound/Bioresponse to Vibration Technical Committee

Chapter Editor's Introduction

The Biomedical Ultrasound/Bioresponse to Vibration Technical Committee was formed in 1984 as the Bioresponse to Vibration Technical Committee. The early scope of the Technical Committee addressed the effects of vibration on the body and touch as communication sense and the effects of infrasound and ultrasound. The name change, adopted in 1996, reflected the enormous growth in the use of ultrasound in biomedical applications both for therapeutic uses (temporary or permanent alteration of tissue) and for diagnostic imaging inside the body. Currently the primary focus of the technical committee is biomedical ultrasound, however, as Jan Weisenberger notes in her chapter it is possible that the field of Bioresponse to Vibration will "again call the ASA its scientific home."

The BU/BV TC has seen strong growth in the last decade. Attendance at the TC meeting (normally held on Thursday evenings) is between 30 and 40. Over the past few years BU/BV has typically sponsored or cosponsored four special sessions at each meeting. The BU/BV is multi-disciplinary committee and has co-sponsored special sessions numerous other TCs including: Physical Acoustics, Signal Processing, Engineering Acoustics, the Committee on Standards, and Music. An event that the BU/BV TC has implemented, initiated by the immediate past Chair E. Carr Everbach, is the Topical Meeting that is held annually at the Fall ASA Meeting. Topical Meetings are one-day events that focus on a particular topic by bringing numerous experts together (many from outside the Society) to present the state-of-the-art through a series of lectures and panel discussions. These Topical Meetings have provided a wonderful forum for frank debate on the important issues and problems in biomedical ultrasound.

Looking forward, the growth potential of ultrasound in the biomedical field appears to be enormous. There are opportunities and challenges in both imaging and therapy, which are touched on below. Perhaps the most exciting avenue is the combination of ultrasound imaging and ultrasound therapy as an integrated tool for diagnosis and treatment. But as scientific and technological barriers are overcome, as yet undiscovered applications will avail themselves.

In the imaging field, there has been a steady improvement in the quality of diagnostic ultrasound imaging and in the last two years there have been two groundbreaking commercial developments: 1/ the advent of real-time 3D imaging capability and 2/ hand-held ultrasound scanners. Both of these developments will spawn exciting new opportunitites such as ultrasound-guided surgery (surgeons can carry out procedures without requiring optical access), and remote-telemedicine (portable ultrasound scanners can go anywhere even into space). One challenge facing the ultrasound imaging community is that diagnostic ultrasound is not yet able to fully characterize the state of the tissue that it images. For example, ultrasound can detect cysts in many organs but it cannot discriminate between a benign tumour and a malignant tumour. A second example is intravascular ultrasound, which can be used to determine plaque burden in arteries but cannot yet differentiate stable from vulnerable plaque. Although measurements on isolated tissue samples show that acoustic properties (e.g., attenutation and backscatter) do correlate with pathology, implementing algorithms to obtain this information on an clinical scanner is challenging. A second challenge is removing artifacts associated with aberration due to inhomogeneities in the tissue. Despite much research, in many cases clinical images are still fraught with aberration problems and associated artifacts.

The therapeutic use of ultrasound has blossomed in the last 20 years. The earliest work in biomedical ultrasound was the development of early therapeutic devices in 1930s, however, daunting technical challenges sidelined this effort. Technology is now catching up and the promise of using ultrasound as a noninvasive surgical tool has finally come to fruition; this is perhaps the most exciting area in biomedical ultrasound today. Already, shock wave lithotripsy is the predominant surgical option for the treatment of kidney stones. Shock waves also appear to be effective at helping heal broken bones and even reducing pain in joints. Currently, the most exciting developments involve the use of high intensity focused ultrasound (HIFU) to effect focused ultrasound surgery (FUS)– a process where focused ultrasound is used to selective heat or ablate tissue so that cells can be destroyed in a localized region while the nearby cells remain viable. A number of clinical devices, either FDA approved or in the final stages of development, exist for: treating glaucoma, fighting cancer (in many organs), and controlling internal bleeding. New applications are constantly being presented at ASA meetings. Advanced therapies such as puncturing holes in the heart, promoting localized drug delivery, and even carrying out brain surgery through an intact skull appear to be feasible and safe with ultrasound.

Within the next decade it is inevitable that ultrasound will be packaged as a complete solution to a host of medical conditions. Diagnostic ultrasound will be used to image the body and diagnose problems, therapeutic ultrasound will then be used to treat the problem, with the treatment monitored and controlled using ultrasound imaging, and then diagnostic ultrasound will be used to ensure that the treatment was successful. This will all been done non-invasively and with little or no pain to the patient.

The Acoustical Society of America maintains a strong presence in the field of biomedical ultrasound despite formidable competition from other societies. The Journal has recently appointed a new Associate Editor in the field of ultrasound imaging in response to the increase in submissions in that area. The BU/BV Technical Committee is active and ensures the ASA has a high profile in this field. The TC has enormous potential for further grow as the field of biomedical ultrasound continues its expansion. The TC consists of an energised and enthusiastic group of people with a variety of backgrounds who can facilitate this growth. The Biomedical Ultrasound/Bioresponse to Vibration Technical Committee will serve the Society well in this evolving area that directly impacts greater society.

Robin O. Cleveland
Chair. Technical Committee on Biomedical Ultrasound/
Bioresponse to Vibration

Note: a Seprate lecture on "History of Biomedical Ultrasound in ASA" by Donald W. Baker preceeds this history lecture.

History of Bioresponse to Vibration in the Acoustical Society of America

Janet M. Weisenberger
Ohio State University

The broad definition of "acoustics"

A dictionary definition of the portion of the energy spectrum defined as "acoustic" stimulation includes a range of frequencies audible to the human ear, commonly stipulated to be from 20-20,000 Hz. However, the breadth of technical areas addressed within the Acoustical Society has included work in frequency regions at the lower bounds of this audible range, in regions called "vibration." Similarly, work with stimulation in frequency regions well above the audible range (in fact, in the MHz range), commonly referred to as "ultrasound," has also become a focus of interest within the ASA. The human response to stimulation in these upper and lower regions became the purview of the Technical Committee on Bioresponse to Vibration/Biomedical Ultrasound, which was initially formed in 1984. The goal of this chapter is to provide historical context for scientific contributions made by researchers studying the human response to the lower region, vibration. It is not possible in limited space to provide a truly comprehensive history; rather, this chapter attempts to highlight major developments and focuses on areas in which considerable activity occurred in the Acoustical Society. The first part of this story takes place largely outside the Acoustical Society of America, but is provided as part of the historical context.

Because of the wide range of stimuli to which receptors in the skin responds, including pressure, warmth, cold, and noxious stimulation, there has been considerable debate over the centuries on whether the sense of touch was a single sense, as first espoused by Aristotle, or instead comprised multiple senses. Weber (1826) noted that stimulation of the human skin surface could lead to sensations of location, pressure (or weight), and temperature, suggesting that receptors in the epidermis or dermis conveyed the neural impulses for such sensations (Boring, 1942). Although initial investigations searching for specific receptors to subserve these sensations were not successful, nonetheless von Frey in 1896, extending Müller's doctrine of specific nerve energies, argued for the notion of receptor specificity in tactile sensation. Twentieth-century researchers have provided support for this notion; indeed, it is now believed that there are multiple specialized receptors just for sensations of pressure and vibration, as described below.

The skin is the largest receptor surface in the body, occupying some 1.8 m2 (Sherrick and Cholewiak, 1986). There have been thorough studies of the response to skin indentation, documenting both detection threshold and spatial difference threshold across locations on the body surface (e.g., Weinstein, 1968; Stevens and Choo, 1996), indicating greater sensitivity on the hands and face than on the torso. However, a study by Nafe and Wagoner (1941) illustrates why vibration is an exemplary stimulus for the tactile sense. In their study of adaptation to pressure stimulation, Nafe and Wagoner found that a sensation of pressure is reported upon initial indentation of the skin surface, but that as the skin is further compressed, a point is reached where the skin is fully compressed and the pressure sensation disappears. Nafe and Wagoner referred to this loss of sensation as "stimulus failure," and argued that pressure sensations persist only for the time that the stimulus is actually moving into the skin surface, such that the response is based on the detection of movement velocity. When the velocity drops below some threshold value, the sensation of pressure disappears.

To obtain a more constant sensation of pressure at a particular skin location, what is needed is a stimulus that indents and withdraws repeatedly, such that there is always movement of the skin surface—in other words, vibration. Thus, vibration is a highly appropriate stimulus for the tactile system, and some skin receptors seem to be specialized for its detection. These are reviewed briefly below to provide a foundation for the studies described later in the chapter.

Brief overview of mechanoreceptor physiology

Several different pressure-sensitive receptors in the epidermis and dermis, referred to as mechanoreceptors, have been identified. These include the Pacinian corpuscle, a large encapsulated receptor located in the dermis, which responds to vibration across a range of frequencies up to about 1000 Hz; the Meissner corpuscle, a more loosely encapsulated structure at the junction of dermis and epidermis, which is not differentially sensitive to vibration, but which has greater sensitivity than the Pacinian corpuscle to frequencies below 40 Hz; and the Merkel disk, also near the division between epidermis and dermis, which appears to have great spatial sensitivity but which also responds to vibratory inputs (for a review of receptor physiology, see Sherrick and Cholewiak, 1986).

Early work in the psychophysics of vibratory sensitivity

One early behavioral study of vibratory sensitivity was that of Knudsen (1928), who mapped detection thresholds as a function of vibratory frequency, reporting a U-shaped function with best thresholds in the region of about 250 Hz. This function was replicated by other researchers, as reported by Geldard (1941), and was later shown to mirror the sensitivity curve of the Pacinian corpuscle, as measured by a number of researchers in the early 1960s (see, e.g., Sato, 1961). The first comparison of vibrotactile thresholds with the response curve of the Pacinian corpuscle was published by Verrillo (1966). Other important early work was reported by Wilska (1954), who showed that vibration sensitivity was different across body sites, with the finger and facial regions showing greatest sensitivity.

Vibrotactile psychophysics in the ASA

Perhaps because of the overlap in the range of frequencies for vibratory response with that for auditory response, a number of auditory researchers became interested in measuring sensitivity to vibration. Among these was von Bekesy, who published work in vibrotactile psychophysics as early as 1939. In the late 1950s, he used pressure sensitivity on the forearm to model the phenomenon of traveling waves in the cochlea [J. Acoust. Soc. Am., 1955], and became interested in vibrotactile sensitivity of itself as an additional sensory modality that appeared to display his notion of "neural funneling." [J. Acoust. Soc. Am. 1958, 1959]. These papers were among the first in JASA to focus on vibratory sensitivity per se.

Other work soon followed, including that of Verrillo and his colleagues at the Institute for Sensory Research at Syracuse University. Verrillo's contributions to the psychophysics of vibrotaction cannot be overemphasized. His first JASA paper on the subject appeared in 1962. In the early 1960s, Verrillo and colleagues investigated a number of the variables that influenced measurement of the threshold for detection of vibration on the skin, including the size of the contactor, presence or absence of a surround, contact force, etc. These studies established that the tactile system shows spatial and temporal summation of stimulation in defined frequency regions. Threshold was found to be a U-shaped function, as noted above, but the threshold function shifted downward as the size of the contactor increased. This finding held true only for stimulation frequencies above about 40 Hz, however. At lower frequencies, increasing contactor size had no effect on threshold sensitivity. Anomalies such as this led Verrillo in 1968 to propose the "duplex mechanoreceptor hypothesis," in which he posited that there were two distinct classes of mechanoreceptors that governed detection of vibration. One class, which did not show spatial summation and was not differentially sensitive to stimulus frequency, governed detection for frequencies below 40 Hz; the other, which did demonstrate spatial summation, was responsible for detection for frequencies above 40 Hz. At that time, Verrillo asserted that the high-frequency, spatially summating mechanoreceptor was almost certainly the Pacinian corpuscle, but was less definite about the identity of the low-frequency system.

Work on the hypothesis continued, with a paper suggesting that there were actually three systems published in the 1970s, and culminated in the publication in JASA by Bolanowski et al. in 1988 of a now-classic paper that provided evidence for four different classes of mechanoreceptors. Bolanowski et al. brought together findings from mechanoreceptor physiology (response profile), temperature sensitivity, and behavioral studies to conclude that the U-shaped portion of the threshold curve was indeed attributable to the Pacinian corpuscle; he referred to the other three systems as NP (Non-Pacinian) I, II, and III. These mechanoreceptors are most likely the Meissner corpuscle, a small receptive field structure that responds in the range of 10 Hz and above, the Merkel disk, which responds best to lower frequencies (below 10 Hz), and a third, as-yet inconclusively identified receptor, possibly the Ruffini end organ, which responds to high frequencies but does not show the same degree of threshold sensitivity as the Pacinian corpuscle. The general notion of the model is that at threshold, the channel that is most sensitive will govern performance, but at suprathreshold levels, perception is jointly determine by the activity of all of the mechanoreceptors that respond to that frequency. Although considerable work has followed this initial paper in both psychophysics and physiology, the basic findings remain the best theory of mechanoreceptive function.

Many studies of vibrotactile perception have looked at standard sensory measures, such as frequency discrimination. Vibratory frequency is not well differentiated across much of the frequency range, as noted by Goff (1967). Although earlier work, going back to the early 1900s, suggested otherwise, these earlier studies did not control for the perceived intensity of sensation. Rothenberg et al. (1977) reported in JASA that frequency discrimination was also not uniform across body sites.

Regarding the perceived intensity, or loudness, of vibration, studies have indicated that there is considerable variation across frequency. Like the "equal loudness contours" reported for auditory stimuli, similar functions have been generated for vibrotactile stimuli by Verrillo et al. (1969). These follow closely the shape of the threshold function at low intensity levels, but are flatter across frequency at high levels, similar to comparable auditory curves. In the tactile case, it has been postulated that the flattening of the curves at high levels may reflect the contribution of additional mechanoreceptive channels to the overall percept.

Other issues of interest have included the response of the tactile system to masking stimulation, both simultaneous (Sherrick, 1964) and non-simultaneous (a series of papers by Gescheider et al., e.g., JASA, 1983, 1985, 1994). In Gescheider's work, temporal masking functions have been generated that follow the general form of those for audition (for detection, more forward than backward masking at the same temporal separation). Still other questions addressed in papers published in JASA have included the nature and time course of vibratory adaptation (Goble and Hollins, 1993, 1994); vibratory localization (Sherrick et al., 1990); and the response of the system to amplitude-modulated stimulation (Weisenberger, 1986).

Over this same period, several other lines of investigation that employed vibrotactile stimulation also appeared in JASA. Most of this work was of a more applied nature. Three specific areas that generated considerable activity in the Acoustical Society are described below.

Applications of vibratory stimulation

1. Assessment of damage from hand-arm vibration

An excellent tutorial paper was published in JASA in 1988 by William Taylor, entitled "Biological effects of the hand-arm vibration syndrome." In this article, Taylor describes the phenomenon originally known as "vibration white finger," or "Raynaud's phenomenon of occupational origin," but now referred to as "hand-arm vibration syndrome." According to Taylor, this syndrome was first described in workers in limestone quarries in Bedford, Indiana in the 1890s. These quarry workers used air hammers for many hours every day for stone cutting. Their symptoms were described as shrunken, whitened fingers, which were nonresponsive to cold, accompanied by numbness and clumsiness in movement. Between attacks, according to the early reports, the fingers were normal in appearance (Hamilton, 1918).

As industrial use of power tools expanded, the number of reported cases of hand-arm vibration syndrome continued to increase. By the 1960s, cases were reported in epidemiological surveys in North America, Japan, Europe, Korea, and Canada. Particularly susceptible occupations included riveters, grinders, and pneumatic drill operators, as well as chainsaw operators in the timber industry.

Clinical symptoms reported by patients in the early stages of hand-arm vibration syndrome include numbness and tingling of one or more fingers. In more advanced cases, periodic blanching of the fingers occurs with exposure to cold, and the damage extends from the fingertips down to the roots of the fingers. Continued vibration exposure leads to involvement of all of the fingers. Following an attack, the fingers often return to a brighter than normal red coloration, accompanied by pain. Eventually, these attacks can occur in both cold and warm temperatures. Other subjectively-reported symptoms include weakness in the affected hand, loss of manual dexterity, and in the most advanced cases, to tissue necrosis and gangrene.

In some respects these symptoms are not different from primary Raynaud's disease, which produces symmetric finger blanching and numbness in cold conditions. This phenomenon occurs primarily in women and is not associated with exposure to excessive levels of vibration. The emergence of symptoms after extended exposure to high vibration levels is an example of secondary Raynaud's phenomenon, as are symptoms arising from a variety of medical causes, including scleroderma, arteriosclerosis, other connective tissue diseases, and peripheral neuropathy from diseases such as diabetes.

The exact physiological causes of the phenomenon are not known, but it is assumed that peripheral vasoconstriction is a primary determinant of some of the symptoms, and likely related to neuropathy in mechanoreceptive pathways. This neuropathy, and attendant loss of acuity in mechanoreceptive sensitivity, has been the focus of some activity in the ASA. Work by Brammer and Piercy and colleagues reported at the ASA investigated the epidemiology of mechanoreceptive loss in HAVS (e.g., Brammer & Verrillo, 1988). Their findings indicated elevations in vibrotactile thresholds that are temporary in the beginning stages of the syndrome, but eventually become permanent. Measurements suggest losses both in the Pacinian channel, as evidenced by elevated high-frequency vibratory thresholds, and in slowly-adapting channels, as evidenced by loss of spatial acuity in the two-point aesthiometry test. Some evidence of reduced neural conduction velocity has also been reported. Further, tests of manual dexterity, such as the Purdue Pegboard Test, and of grip force are also part of the standard test battery and often indicate loss of sensorimotor fine control.

In addition, interactions between basic science and more applied vibrotaction researchers in the ASA led to the development of practical and in some cases portable methods for measuring receptor-specific vibrotactile perception thresholds, the tactile equivalent of audiometry. These methods have recently been codified into an ISO standard (ISO 13091-1).

In the 1980s and 1990s, clinical concerns of an "epidemic" of HAVS among manual workers in the manufacturing and forestry industries in Europe and North America drove the focus of activities in this field into occupational health journals. However, efforts within the Acoustical Society to link this clinical focus with more basic work in vibrotaction led to some significant advances. Perhaps most notable was the development of a model for predicting the onset of vibration-induced white finger in persons occupationally exposed to vibration (Brammer, 1986), initially presented in ASA special sessions. The model has served as the basis for vibration exposure guidelines in national and international standards, and led to enaction of exposure limits in several countries and the European Union.

Recent attempts to monitor HAVS proactively have met with some success. In a manner similar to that used for monitoring noise-exposure hearing loss, workers are now tested periodically to provide early warning of possible HAVS symptoms. In addition, the development of better protective wear and restrictions on duration of use of vibrating tools in the workplace should reduce the incidence of HAVS in the future.

2. Whole body vibration

Another area of focus by researchers in the ASA has been the effects of whole-body vibration. Perhaps the name in the Acoustical Society most often associated with whole-body vibration is that of Henning von Gierke, whose more than 50 years of activity in this area encompassed both original research and standards development. The negative effects of whole-body vibration are dependent on the species and the magnitude and duration of the exposure, and can range from mild discomfort to death. Vibrations in the range of .5-80Hz seem to have the greatest impact, with resonances in the 2.5-5Hz range affecting neck and lumbar regions, 4-6 Hz affecting the trunk, and 20-30Hz the head and shoulders. Internal injuries are typically the immediate cause of death in such intense exposures (Griffin, 1990), and include heart and lung damage and gastrointestinal bleeding. The damage patterns suggest a resonance motion of organs in the range of 3-8 Hz. For less intense exposures, particularly of a chronic nature, back pain from prolapsed or herniated disks is often reported; such complaints can come from crane operators, tractor drivers, and truckers. When a smaller contact area is involved, often the damage is related to the elastic and tensile limits of tissue (von Gierke & Brammer, 2002).

Brammer and Peterson's (2003) chapter nicely summarizes the state of knowledge in this area. They divide the harmful effects of whole-body exposure by the direction of impact. Vertical impacts (e.g., through the seat of a vehicle) produce an upward acceleration, followed by a downward acceleration when the mass of the torso returns to the seat. Horizontal shocks are more often encountered in vehicle crashes, in which rapid deceleration can lead to injuries to head, neck, torso, and abdomen.

Measurements of whole-body vibration can be made using laser vibrometers to gauge tissue vibration in conjunction with accelerometers mounted to the interface that contacts the human (e.g., the seat of the vehicle). These measurements are typically made in the context of a biodynamic coordinate system. The results of tissue measurements have led to the development of models of human tissue as a passive, linear mechanical system, and include measurements of density, viscosity, sound transmission velocity, impedance, and tensile, compressive, and shear strength (see von Gierke and Brammer, 2002). These relatively simple lumped biodynamic models provide a good approximation for the purposes of predicting damage from shock and vibration. More recently, finite element modeling has been employed to provide a more detailed and realistic description of individual body parts. These models are also used in the development of anthropomorphic models for simulations of harmful impacts (e.g., crash test dummies). Such manikins are actually better simulation devices than are cadavers, which lack the appropriate tissue and muscle tension properties.

Work in the area of whole-body vibration has led to the development of estimated health effect and injury criteria that can be used to determine the potential harmful effects of exposure in particular occupations, and thus dictate the use of appropriate countermeasures in the work environment. Such countermeasures include vibration isolation by means of low-pass mechanical filters in suspension systems, tool redesign, and active control vibration reduction systems (Brammer & Peterson, 2003). In addition, these criteria are used in the design and implementation of restraint and protection systems, such as seat belts, airbags, and helmets. A concerted effort within the ASA standards community, led by Henning von Gierke, focused on the codifying the measurement and assessment of human exposure to whole body, hand, and arm vibration. The results of this effort are a family of ANSI standards, now serving as the basis for implementing the European Union Health Directive on exposure to vibration.

3. Tactile aids for speech perception by hearing-impaired persons

A final area that has been addressed by ASA researchers is the use of tactile aids for speech perception. The idea that the tactile system had sufficient information-processing capacity to serve as a substitute sensory system for an impaired auditory system, particularly for the reception of speech input, has a rather long history. Methods for the tactile reception of speech, such as Tadoma, indicate that cues transmitted to the fingers of a receiver are sufficient for the transmission of speech (Alcorn, 1932). Tadoma was developed for use by deaf-blind individuals to take advantage of articulatory cues in the talker's speech. In the Tadoma method, the receiver places the fingers and thumb of one hand on the face of the talker, such that the little finger, on the throat, detects laryngeal vibration, the ring and middle fingers detect jaw and cheek muscle movement and tension, the index finger detects nasal resonance, and the thumb detects lip movement and airflow changes. Trained users of Tadoma are able to receive speech at rates that are only slightly lower than normal speech rates, about 70 words per minute (wpm). This finding has been cited as an "existence proof" that the sense of touch has sufficient capacity to process the complex cues in the speech signal. Empirical evaluations of the Tadoma method were conducted by Reed and her coworkers at the Massachusetts Institute of Technology [e.g., Reed et al., JASA 1985].

However, the Tadoma method requires considerable training, measured in years, for proficient use, and also requires direct contact between the talker and receiver, which might be awkward or impossible in many situations. For this reason, researchers became interested in the development and evaluation of vibrotactile and electrotactile devices that convert input acoustic speech waveforms into patterns of tactile stimulation. The first record of such a device was that designed by Gault (1924). Gault's original notion was that the skin could pick up vibrations just as the ear could, but required greater intensity of stimulation. Thus, his first device was based on simply amplifying speech presented via a bone vibrator to the hand of the receiver. When this device did not prove successful, Gault went on to design a device that stimulated the fingers of one hand. He reported some success in training with this latter device. Similarly, Lindner (1937) described the "teletactor," a device that provided electrotactile stimulation to two fingers, one channel delivering stimulation to code speech inputs below 1500 Hz, and the other devoted to speech inputs above 1500 Hz.

The development of the vocoder at Bell Laboratories in the late 1930s stimulated further efforts in designing tactile speech aids (Dudley, 1939). A tactile vocoder was described by Wiener and Weisner in 1951, but widespread interest in tactile aids was not rekindled until the early 1970s, when Jacob Kirman published a review of these devices (Kirman, 1973). A number of researchers in the 1970s attempted to train tactile speech perception with new devices, some based on the vocoder concept (e.g., Engelman and Rosov, 1975). Sparks et al. (JASA 1979), reinvestigated the idea of using electrotactile arrays. However, the greatest success with vocoder-style devices was that reported for the Queen's University tactile vocoder by Brooks and colleagues (e.g., JASA 1986). This device, which delivers vibrotactile stimulation to 16 magnetic solenoids in a linear array on the forearm, has been shown to provide effective cues for consonant manner and voicing, and for vowel formants. Users of this device successfully acquired large tactile-only vocabularies of single words. In addition, this device produced considerable benefits when used in conjunction with speechreading in connected speech tasks, such as connected discourse tracking (e.g., Weisenberger et al., JASA 1989).

Encouraging results with such laboratory based devices supported the development of wearable tactile aids. Beginning with relatively simple, single-actuator devices that could be worn with a suspender-like harness on the sternum, wearable tactile aids have also been shown to provide benefit to hearing-impaired wearers. Proctor and Goldstein (1983; see also Geers, 1986) reported results for one profoundly hearing-impaired child, whose vocabulary development showed rapid acceleration after she was fitted with the Tactaid, a device that transmitted amplitude envelope information via a fixed-frequency vibration delivered to a bone-conduction vibrator. More sophisticated wearable devices have employed multiple channels of stimulation, and include the Tactaid VII, and the Tickle Talker, an electrotactile device worn as rings on the fingers of one hand (Blamey & Clark, JASA 1985; Cowan et al., JASA 1990).

These wearable devices have shown considerable promise, particularly for users who might not be appropriate candidates for cochlear implantation, such as patients whose auditory nerve fiber survival in the cochlea is compromised, or patients with retrocochlear losses. Improvements in transducer design and in signal extraction algorithms for speech encoding should lead to further progress in the development of the next generation of tactile aids.

Future considerations

The Technical Committee on Bioresponse to Vibration in the Acoustical Society, was first formed in 1984. As the first new technical committee added in more than 20 years after the original formation of technical committees in the Society, it paved the way for the addition of technical committees for other new areas of research focus, including Acoustical Oceanography, Animal Bioacoustics, and Signal Processing in Acoustics. Shortly after its inception, the group welcomed researchers in the area of biomedical ultrasound, who also sought a more representative technical committee. The nature of research and the associations and societies that house it is necessarily fluid; the founding of new organizations and journals, as well as reorganizations of existing groups and journals, are part of the process of science. At present, most of the areas of research reported in this chapter are pursued outside the confines of the Acoustical Society, and the primary focus of the technical committee has been in biomedical ultrasonics. However, work in the areas outlined in this chapter proceeds with vigor in other associations and societies, and it is not outside the realm of possibility that such work will once again call the ASA its scientific home.

Origins and evolution of the developments which led to echo-Doppler duplex color flow diagnostic methodology

Donald W. Baker, University of Washington

Research efforts to develop instrumentation for animal physiologic research to better characterize the cardiovascular system in engineering ultimately evolved for application on man and led to the Pacific Northwest becoming the current foci of the medical ultrasound industry. This presentation will trace the events from my being a student in Electrical Engineering to heading the Cardiovascular Instrument Development Program originally begun by Dr. Robert Rushmer in 1957. This narrative will range from early instruments for measurements on research animals to their development for noninvasive use on man. The instruments covered will be the transit time flow-meter, CW Doppler, pulsed Doppler, duplex scanner, and color flow mapping. The role of collaboration in both engineering many specialties of medicine will be demonstrated. Many of the original instruments have been in the Smithsonian Museum of American History and will in the near future be on permanent exhibit there.

References

Alcorn, S. (1932). "The Tadoma method," Volta Rev. 34, 195-198.

Bekesy, G. von (1939). "Über die Vibrationsempfindung," Akustische Zeitschrift 4, 316-334.

Bekesy, G. von (1955). "Human skin perception of traveling waves similar to those on the cochlea," J. Acoust. Soc. Am. 27, 830-841.

Bekesy, G. von (1958). "Funneling in the nervous system and its role in loudness and sensation intensity in the skin," J. Acoust. Soc. Am. 30, 399-412.

Bekesy, G. von (1959). "Neural funneling along the skin and between the inner and outer hair cells of the cochlea," J. Acoust. Soc. Am. 31, 1236-1249.

Bolanowski, S.J., Jr., Gescheider, G.A., Verrillo, R.T., & Checkosky, C.M. (1988). "Four channels mediate the mechanical aspects of touch," J. Acoust. Soc. Am. 84, 1680-1694.

Boring, E.G. (1942). Sensation and perception in the history of experimental psychology, Appleton-Century (New York).

Brammer, A.J. (1986). "Dose-response relationships for hand-transmitted vibration," Scand. J. Work Environ. Health 12, 284-288,

Brammer, A.J., & Peterson, D.R. (2003). "Vibration, mechanical shock, and impact," in Handbook of biomedical engineering (edited by M. Kutz). McGraw-Hill (New York).

Brammer, A.J. & Verrillo, R.T. (1988). "Tactile sensory changes in hands occupationally exposed to vibration," J. Acoust. Soc. Am. 84, 1940-1941.

Blamey, P.J. & Clark, G.M. (1985). "A wearable multiple-electrode electrotactile speech processor for the profoundly deaf,"

J. Acoust. Soc. Am. 77, 1619-1620.

Brooks, P.L., Frost, B.J., Mason, J.L., & Chung, K. (1985). “Acquisition of a 250-word vocabulary through a tactile vocoder. J. Acoust. Soc. Am. 77, 1576-1579.

Cowan, R.S.C., Blamey, P.J., Galvin, K.L., Sarant, J.Z., Alcantara, J.I., & Clark, G.M. (1990). “Perception of sentences, words, and speech features by profoundly hearing-impaired children using a multichannel electrotactile speech processor,” J. Acoust. Soc. Am. 88, 1374-1384.

Dudley, H. (1939). “The vocoder,” Bell Labs. Rec., 17, 122-126

Engelmann, S. & Rosov, R. (1975). “Tactual hearing experiment with deaf and hearing subjects,” Exceptional Children 41, 243-253.

Frey, M. von (1896). “Untersuchungen über die Sinnesfunctionen der menschlichen Haut, Erste Abhandlung: Druckempfindung und Schmerz,” Abhandlungen der Mathematisch-Physischen Klasse der Königlich-Sächsischen Gesellschaft der Wissenschaften 23, 175-266.

Gault, R.H. (1924). “Progress in experiments on tactual interpretation of oral speech,” J. Abnorm. Soc. Psychol. 19, 155-159.

Geers, A.E. (1986). “Vibrotactile stimulation: Case study with a profoundly deaf child,” J. Rehab. Res. Dev. 23, 111-117.

Geldard, F.A. (1940). “The perception of mechanical vibration III: The frequency function,” J. Gen. Psychol. 22, 281-289.

Gescheider, G.A., O’Malley, M.J., & Verrillo, R.T. (1983). “Vibrotactile forward masking: Evidence for channel independence,” J. Acoust. Soc. Am. 74, 474-485.

Gescheider, G.A., Sklar, B.F., Van Doren, C.L., & Verrillo, R.T. (1985). “Vibrotactile forward masking: Psychophysical evidence for a triplex theory of cutaneous mechanoreception,” J. Acoust. Soc. Am. 74, 534-543.

Gescheider, G.A. (1995). “Some temporal parameters in vibrotactile forward masking,” J. Acoust. Soc. Am 98, 3195-3199.

Goble, A. & Hollins, M. (1993). “Vibrotactile adaptation enhances amplitude discrimination,” J. Acoust. Soc. Am. 93, 418-424.

Goble, A. & Hollins, M. (1994). “Vibrotactile adaptation enhances frequency discrimination,” J. Acoust. Soc. Am. 96, 771-780.

Goff, G.D. (1967). “Differential discrimination of frequency of cutaneous mechanical vibration,” J. Exptl. Psychol. 74, 294-299.

Griffin, M.J. (1990). Handbook of human vibration, Academic Press (London).

Hamilton, A. (1918). “A study of spastic anaemia in the hands of stonecutters,” U.S. Bureau of Labor Stat. No 236, 19, 53.

ISO 12091-1 (2001). “Mechaincal vibration—Vibrotactile perception thresholds for the assessment of nerve dysfunction – Part 1: Methods of measurement at the fingertips,” International Organization for Standardization, Geneva.

Kirman, J.H. (1973). “Tactile communication of speech: A review and an analysis,” Psychol. Bull. 80, 54-74.

Knudsen, V.O. (1928). “Hearing with the sense of touch,” J. Gen. Psychol. 1, 320-352.

Lindner, R. (1937). “The physiological fundamentals of the electrical speech feeling and their application in the training of deaf mutes,” Z. Sinnesphysiol. 67, 114-144.

Nafe, J.P. & Wagoner, K.S. (1941). “The nature of pressure adaptation,” J. Gen. Psychol. 25, 323-351.

Proctor, A., & Goldstein, M.H. Jr. (1983). “Development of lexical comprehension in a profoundly deaf child using a wearable vibrotactile communication aid. Lang., Spch. and Hear. Serv. Schools 14, 138-149.

Reed, C.M., Rabinowitz, W.M., Durlach, N.I., Braida, L.D., Conway-Fithian, S., & Schultz, M.C. (1985). “Research on the Tadoma method of communication,” J. Acoust. Soc. Am. 86, 981-988.

Rothenberg, M., Verrillo, R.T., Zahorian, S.A., Brachman, M.L., & Bolanowski, S.J., Jr. (1977). “Vibrotactile frequency for encoding a speech parameter,” J. Acoust. Soc. Am. 62, 1003-1012.

Sato, M. (1961). “Response of Pacinian corpuscles to sinusoidal vibration,” J. Physiol. 159, 391-409.

Sherrick, C.E. (1964). “Effects of double simultaneous stimulation of the skin,” Am. J. Psychol. 77, 42-53.

Sherrick, C.E., Cholewiak, R.W., & Collins, A.A. (1990). “The localization of low and high frequency vibrotactile stimuli,” J. Acoust. Soc. Am. 88, 169-179.

Sherrick, C.E. & Cholewiak, R.W. (1986). “Cutaneous sensitivity,” in Handbook of perception and human performance I, K.R. Boff, L. Kaufman, & J.P Thomas, eds., Wiley (New York).

Sparks, D.W., Kuhl, P.K., Edmonds, A.E., & Gray, G.P. (1979). Investigating the MESA: The transmission of connected discourse,” J. Acoust. Soc. Am. 65, 810-815.

Stevens, J.C. & Choo, K.K. (1996). “Spatial acuity of the body surface over the life span,” Somat. Motor. Res. 13, 153-166.

Taylor, W. (1988). “Biological effects of the hand-arm syndrome: Historical perspective and current research,” J. Acoust. Soc. Am. 83, 415-422.

Verrillo, R.T. (1962). “Investigation of some parameters of the cutaneous threshold for vibration,” J. Acoust. Soc. Am. 34, 1768.

Verrillo, R.T. (1963). “Effect of contactor area on the vibrotactile threshold,” J. Acoust. Soc. Am. 35, 1962.

Verrillo, R.T. (1966). “Vibrotactile sensitivity and the frequency response of the Pacinian corpuscle,” Psychonom. Sci. 4, 135-136.

Verrillo, R.T. (1968). “A duplex mechanism of mechanoreception,” in D.R. Kenshalo (ed.), The skin senses, Thomas (Springfield, IL), pp. 139-156.

Verrillo, R.T., Fraioli, A.J., & Smith, R.L. (1969). “Sensation magnitude of vibrotactile stimuli,” Percept. Psychophys. 6, 366-372.

Von Gierke, H., & Brammer, A.J. (2002). “Effects of vibration and shock on people,” in M. Crocker (ed.), Encyclopedia of Acoustics, Academic Press, New York.

Von Gierke, H., & Brammer A.J. (2002). “Effects of vibration on people,” in Harris’ shock and vibration handbook (edited by C. Harris and A. Piersol), McGraw-Hill (New York).

Weber, E.H. (1826). De tactu (The sense of touch), translated by H.E. Ross, English publication 1978, Academic Press (New York).

Weinstein, S. (1968). “Intensive and extensive aspects of tactile sensitivity as a function of body part, sex, and laterality,” in D.R. Kenshalo (ed.), The skin senses, Thomas (Springfield, IL), pp. 195-218.

Weisenberger, J. M. (1986). “Sensitivity to amplitude-modulated vibrotactile signals,” J. Acoust. Soc. Am. 80, 1707-1715.

Weisenberger, J. M., Broadstone, S. M., & Saunders, F. A. (1989). “Evaluation of two multichannel tactile aids for the hearing-impaired,” J. Acoust. Soc. Am. 86, 1764-1775.

Wiener, N., Weisner J.B., David, E.E., & Levine, L. (1951). “FELIX (Sensory Replacement Project),” Quarterly Progress Reports 12-21, Research Laboratory of Electronics, MIT.

Wilska, A. (1954). “On the vibrational sensitivity in different regions of the body surface,” Acta Physiol. Scand. 31, 285-289.

Biomedical Timeline

1826 ••••	Weber publishes De Tactu, a treatise on tactile sensitivity.
1890's ••	VonFrey argues for receptor specificity in tactile response.
	First documentation of hand-arm vibration syndrome in quarry workers.
1920's ••	Gault develops several prototype vibrotactile speech perception aids.
1920-40	Studies of perceptual response to vibration frequency (Knudsen, Geldard).
1930's ••	Alcorn publishes description of the Tadoma method of tactile speech reception.
1930-60	VonBekesy publishes experiments on tactile sensitivity.
1940's ••	Nafe and Wagoner propose the notion of "stimulus failure" for pressure sensation.
1950's ••	Development of first vibrotactile speech vocoders.
1950-00	Development of criteria for whole-body vibration exposure by von Gierke and colleagues.
1960's ••	Verrillo proposes duplex mechanoreceptor hypothesis.
1970's ••	'Rediscovery' and formal evaluation of Tadoma (MIT, Children's Hospital and Harvard University).
1970-90	Development and evaluation of multichannel tactile speech aids and wearable devices.
1980's ••	Development of criteria for exposure to hand-arm vibration (hand-arm vibration syndrome (HAVS) (Brammer).
1984 ••••	Establishment of ASA Technical Committee on Bioresponse to Vibration.
1988 ••••	Bolanowski publishes 4-channel model of vibratory perception.
1992 ••••	Srinivasan organizes seminal session on Haptic Interfaces, Virtual Reality and Telemedicine at an ASA meeting.
1990-00	Studies of damage to mechanoreceptors in HAVS (Brammer, Piercy and co-workers).

Past and Present Chairs of the Technical Committee on Biomedical Ultrasound/ Bioresponse to Vibration

1984-87	John Erdreich
1987-90	Anthony J. Brammer
1990-93	Ronald T. Verrillo
1993-96	Janet M. Weisenberger
1996-99	Ronald A. Roy
1999-02	E. Carr Everbach
2002-	Robin O. Cleveland

Recipients of the Silver Medal in Bioresponse to Vibration

1989 - Floyd Dunn - For contributions to the understanding of the interactions of ultrasound with biological media.

Recipients of the Silver Medal in Biomedical Ultrasound/Bioresponse to Vibration

1999 - Ronald T. Verrillo - For contributions to the psychophysics and physiology of vibrotactile sensitivity.

Recipients of Interdisciplinary Silver Medals

Silver Medal in Physical Acoustics and Bioresponse to Vibration

1990 - Wesley L. Nyborg - For technical contributions in the application of physical acoustics to biology and medicine.

Helmholtz-Rayleigh Interdisciplinary Silver Medal in Physical Acoustics and Biomedical Ultrasound/Bioresponse to Vibration

2000 - Lawrence A. Crum - For advancing the understanding of the physical, chemical and biological effects of acoustic cavitation and of high-intensity ultrasound.