Hearing Aids

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> *"Blindness cuts you off from things; deafness cuts you off from people."*
>
> *Immanuel Kant (Philosopher, 1724–1804).*

Abstract

This chapter presents an overview of the current state of a hearing aid tracing back through the history. The hearing aid, which was just a sound collector in the sixteenth century, has continued to develop until the current digital hearing aid for realizing the downsizing and digital signal processing, and this is the age of implanted hearing devices. However, currently popular implanted hearing devices are a fairly large burden for people soon after they become aware of their hearing loss, although auditory stimulation to the nerve in the early stage can avoid accelerated cognitive decline and an increased risk of incident all-cause dementia. For this reason, we tend to stick to wearable hearing aids that are easy to be put on and take off. Although the digital hearing aid has already reached the technical ceiling, the noninvasive hearing aids have some severe problems that are yet to be resolved. In the second half of this chapter, we discuss the scientific and technical solutions to broaden the range of permissible users of hearing aids.

Keywords: dementia, EuroTrak, bone-conducted ultrasonic hearing aid, cartilage conduction hearing aid, autocorrelation analysis

1. Introduction

When the ability to hear declines, people become uncomfortable during conversations and gradually begin to speak less and less. This worsening situation can lead to depression and an increased risk of dementia. In 2015, the Ministry of Health, Labour and Welfare in Japan published an initiative for preventing dementia (New Orange Plan), which states that hearing loss is a risk for declining cognitive function [1]. The first report to show the relationship between hearing impairment and dementia was published in 1989 [2], and several longitudinal studies that included auditory and nonauditory cognitive testing have shown that people with hearing loss have a 30–40% rate of accelerated cognitive decline [3] and an increased risk of incident all-cause dementia [4, 5]. The implications are that auditory stimulation that reaches the brain can delay aging of the brain and allow communication with family and society to continue. Thus, the earlier that people can receive audiological treatment and hearing aid prescriptions, the better.

2. The history of hearing aids

When we cannot hear what someone nearby is saying, we cup our hand behind our ears. This is actually a type of hand reflector, which can aid hearing by emphasizing in the middle and high frequency range (>500 Hz) between 5 and 10 dB and by blocking unnecessary noise from extraneous directions. The first documented evidence of a hearing aid dates back to the sixteenth century [6] and describes wooden panels that imitated animal auricles and were meant to be worn behind the ear. **Figure 1** shows a 1673 sketch depicting a hearing device called the "*Ellipsis Otica.*" This is one of the oldest illustrations of a hearing aid and was published in *Phonurgia nova*, the first known book to deal with the nature of sound, acoustics, and music in 1673 [7]. Horn-shaped hearing aids called "*Ear Trumpets*" (**Figure 2**) became a common remedy for hearing loss for the next 300 years [8] until the development of electric hearing devices. Before the twentieth century, hearing aids were always thought of as sound collectors. The narrow end of the ear trumpet was inserted in the user's ear, and the broad end faced toward the speaker. Thus, like a cupped hand, the ear trumpet was used between two people standing at close range.

Early on, ear trumpets were made from animal horn, but over time people began making them from wood and metal. The preferred color was black because it blended in with the dark clothes that were often worn by European people of that time. This was perhaps an effort to avoid drawing attention to the horn for fear that one's hearing loss would be exposed. In the eighteenth and nineteenth centuries, hearing aids were designed to be hidden from public view, as can be seen in **Figure 3**. For females, the hearing aid body was placed into a hair band (**Figure 3a**, *Aurolese Phones*) or a handy fan (**Figure 3b**, air conduction fan), which they used in daily life. For men, the hearing aid body was covered by their own beard (**Figure 3c**). The

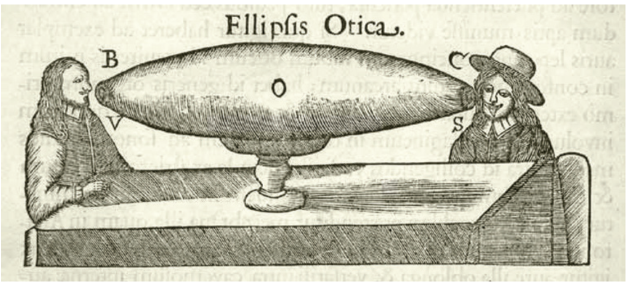


Figure 1. Speaking tubes (*Ellipsis Otica*) from *Phonurgia nova* (1673) [7].

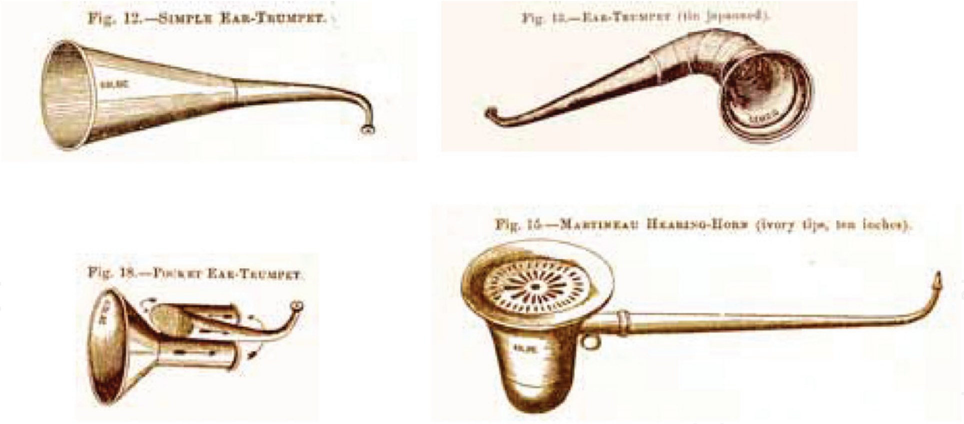


Figure 2. Illustrations of *Ear Trumpets* in *A clinical manual of the diseases of the ear* (1887) [8].

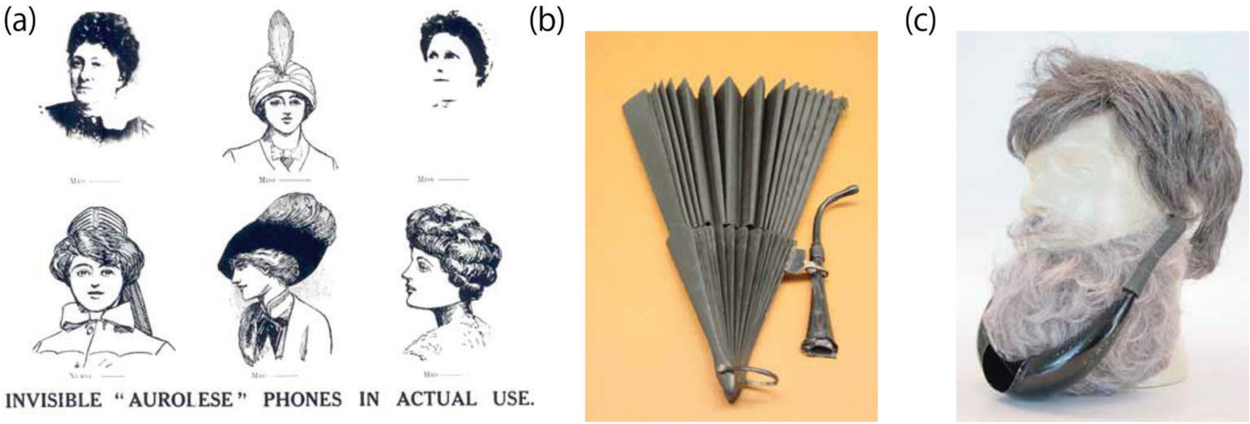


Figure 3. (a) *Aurolese Phones* simulated in hair bands (F. C. Rein co.) from the 1810s. (b) Acoustic fan with ear trumpet from the 1850s. (c) Beard receptacle (Hawksley co.) from the 1830s.

desire to hide hearing aids has not changed with new technology, as evidenced by the current popularity of small, skin-colored hearing aids.

In contrast to the wearable hearing aids described earlier, larger types of hearing aids were placed or mounted on furniture. **Figures 4a** and **b** show a flower-vase-type hearing aid that was placed in the center of a table to collect sound from a number of people conversing during a meal, while the user put the end of tube on his ear. **Figure 4c** shows a chair that was designed to function as a hearing aid. The mouths of the lions carved at the front of the wooden armrests gathered sound, and hollow cavities running through the armrests transmitted the amplified sound to the end of the tube that the user inserted into his ear. Because wearable hearing aids required the speakers to be at very close proximity, those in high positions or peerage used these types of acoustic thrones to keep a suitable distance from unknown speakers that might make them uncomfortable.

In the latter part of the nineteenth century, the invention of the telephone and microphone had a tremendous impact on hearing aid design. Once sound signals (longitudinal wave in air) could be converted into electric signals, hearing aids changed from classical sound collectors

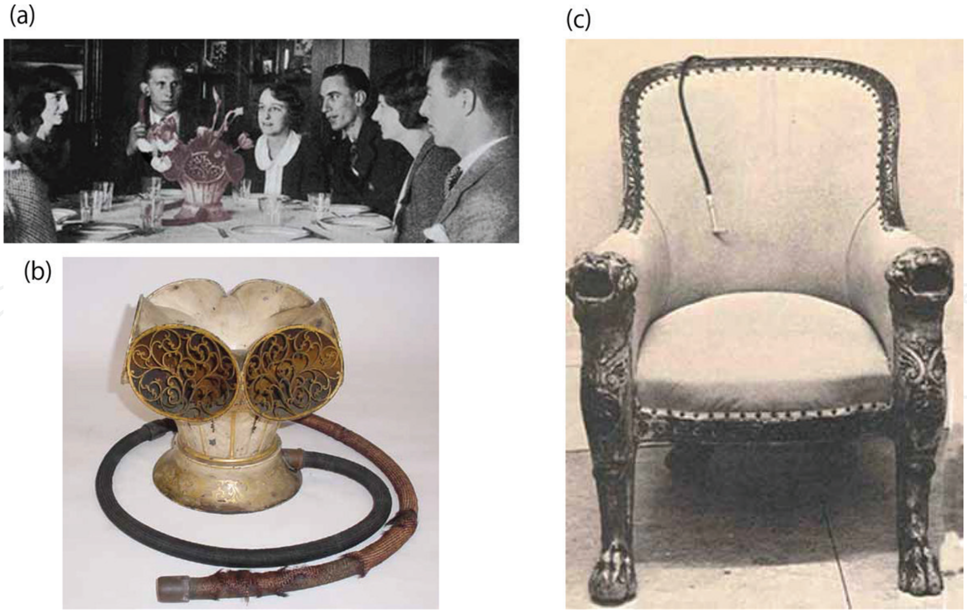


Figure 4. (a) and (b) Flower-vase-type hearing aid for gathering multiple speakers' voices (F. C. Rein Co.) in 1810. (c) Acoustic throne for European royalty in 1819.

to devices that could amplify sound through an electric circuit. The history of the electronic hearing aid is thus very similar to that of the technological evolution of the microphone, amplifier, and battery cell. Between 1989 and 1900, the Akouphone Company produced the first electronic hearing aids called "*Akoulallion*" and "*Akouphone,*" introducing a carbon microphone technique. The carbon transmitter was able to use an electric current to amplify weak signals by 20–30 dB [9]. The *Akoulallion* was large and was used on a table, while the *Akouphone* was portable. Miler Reese Hutchison—one of the company's founding presidents—established the Hutchison Acoustic Company in 1903 and produced "*Acousticon,*" an improved electric hearing aid that was further miniaturized (**Figure 5a**). Users wore the microphone and main body, put the battery in a bag, and held the earphone in their hands. The Danish company *Oticon* and the German company *Siemens* are two current makers of hearing aids that begun operations during this period.

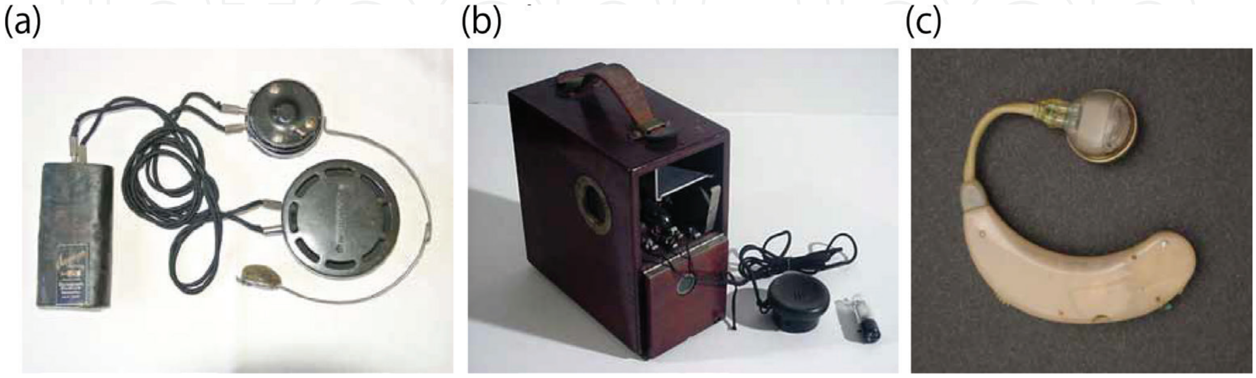


Figure 5. (a) Early electronic hearing aid with carbon components: *Acousticon* model A (Hutchison Acoustic Company, 1905). (b) Early vacuum tube hearing aid: *Vactuphone* (Globe Ear-phone Company, 1921). (c) Behind-the-ear hearing aid-embedded transistor amplifier (Zenith Diplomat Company, 1956).

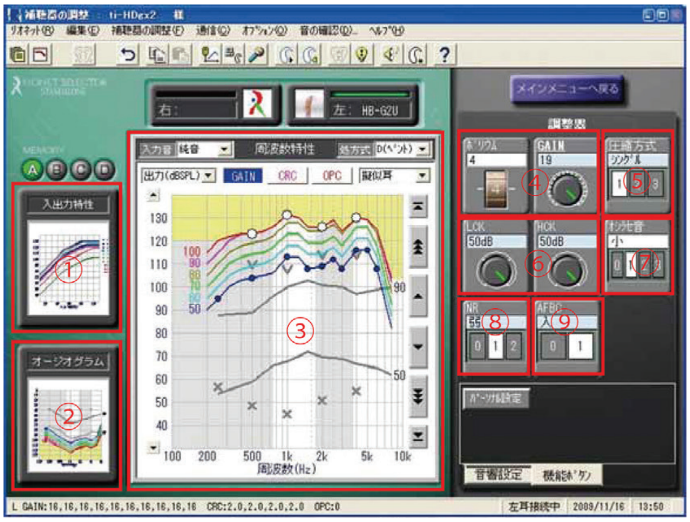
In 1920, a new type of hearing aid was developed using vacuum tubes to amplify sound by 70–130 dB. The vacuum tube aid contains a filament (heated electron-emitting cathode) and a plate (the anode), and the amount of applied voltage can control the current traveling from cathode to anode. Although the vacuum tube hearing aid was able to have a high gain and accurate frequency response, it was quite large because two batteries were needed for heating the filament and controlling the electric circuit, and batteries at that time were not small. **Figure 5b** shows the earliest vacuum tube hearing aid, called the "*Vactuphone*" (1921). Because the body was about the same size as the box camera of its day, the "*Vactuphone*" included an unnecessary lens that helped disguise it as a box camera.

Over time, advances in vacuum tube and battery technology allowed hearing aids to be made much smaller, until eventually the vacuum tube hearing aid was small enough to be worn. However, the invention of the transistor 1952 put an end to the vacuum tube era. The transistor is a semiconductor device used to amplify or switch electronic signals and electrical power. The transistor was much smaller than the vacuum tube, consumed much less power, and thus allowed for much smaller battery sizes. A predecessor of a current behind-the-ear (BTE) hearing aid appeared in this period (**Figure 5c**). By wearing it on the head, noise from moving clothes was avoided, the direction of sound could be partially perceived, and the cord could be as short as possible. As technology advanced further with the integrated circuit (IC) and button-sized zinc-air battery (1960s–1970s), miniaturization and technical performance were further improved. The end of the twentieth century saw a steady progression of innovation from in-the-ear (ITE) hearing aids that fit into the concha (1980s) to in-the-canal (ITC) and completely-in-the-canal (CIC) hearing aids (1990s). ITC and CIC hearing aids allowed maximized sound collection from the auricle and sound insulation from environmental noises, as well as cut out wind noise. With these inventions, sound could be amplified by more than 100 dB and people with hearing loss could completely hide their problem with an invisible hearing aid.

3. Digital hearing aid

After achieving this level of hearing aid output gain and miniaturization, scientists and engineers began looking for further ways to improve hearing-aid convenience. For example, analog hearing aids amplify sound from all frequency ranges, which means that both speech and unnecessary background noises are amplified equally. Another problem was that the small size of the devices caused the speaker and microphone to be too close, and acoustic feedback generated uncomfortable levels of amplified sound. In 1996, these problems began to be addressed when hearing aids entered the age of digital sound. The digital hearing aid converts sound into a binary digital signal, which can then be modified by computer software. This type of signal modification is called digital signal processing (DSP) and is the biggest advantage of the digital hearing aid.

Figure 6 shows a computer interface through which the DSP installed in a hearing aid can be controlled after connecting the hearing aid to the computer. The most beneficial aspect



① Balance of output and input level
② Audiogram of user
③ Gain controller in each frequency band
④ Total volume controller
⑤ Selector of compression systems
⑥ Selector of compression ratio
⑦ Alarm sound volume
⑧ Slector of noise reduction system
⑨ Slector of acoustic feedback canceler

Figure 6. Example of software used to adjust a hearing aid's digital signal processing.

of the DSP is the ability to adjust the output gain in each one or one-third octave frequency band. The computer program designs the shape of a digital filter and modifies the signal passing through the filter (multichannel analysis). Because sound energy in human voice is distributed in a frequency range of 200 Hz to 4 kHz, unwanted noise can be weakened by amplifying only the desired frequency range. Audiograms of people with hearing loss differ according to individual sensitivity to each frequency band (e.g., high tone deafness, horizontal deafness, convex deafness, or concave deafness). The multichannel output can thus limit compensation to the frequency bands for which a person has difficulty in hearing.

The multichannel output is also useful for suppressing acoustic feedback. Acoustic feedback occurs when the following happens simultaneously: (1) attenuation of the speaker's voice by the time it reaches the microphone is less than the amount of sound gain and (2) the phases of the original and feedback signals are mostly overlapped. ITC and CIC hearing aids have a vent to reduce the uncomfortable feeling that can occur in the occluded ear, and the output sound transmitted through the vent can cause acoustic feedback. The solution is a feedback canceller in the hearing aid that identifies the offending frequency-repeating amplification and reduces the sound gain in the corresponding band.

The other important role of DSP is to create a compression system for the output sound. If a hearing aid amplifies sound linearly, it makes already loud sounds excessively loud. Patients with sensorineural hearing loss hear sounds above a certain sound level louder than normal listeners (recruitment hearing). Thus, the sound of a closing door or a cry from a child can annoy hearing aid users. The compression system suppresses the amplification of sounds above a certain sound level and instead fits them within the restricted dynamic range of the user. This system can therefore avoid unpleasant sounds, normalizes the perceived loudness, and improves speech intelligibility.

Another advantage of digital hearing aids is their ability to work wirelessly. In their times, the BTE hearing aid only had a short cord, and the ITC and CIC hearing aids did not require any cords or cables. However, in modern society, wireless function is increasingly useful for connecting hearing aids to other electronic devices. For example, because holding a smartphone near one's ear is difficult when wearing a hearing aid, the wireless hearing aid can receive speech signals directly from the smartphone using Bluetooth technology. In the near future, users will be able to control the DSP from a smartphone app. Wireless hearing aids can also help when watching television. By wirelessly connecting to the TV, users can hear clear sound from a TV program without the sound needing to travel through the air. Thus, environmental noise can be minimized and reverberations in a room can be ignored.

Digital hearing aids will likely continue to evolve and add new features and functions. For example, a hearing aid with Global Positioning System will make it easier to be found if it gets lost or misplaced. Like other wearable electronics, if hearing aids incorporate functions for measuring heart rate, step counts, and burned calories, they will become a type of wearable device that supports lifelong health.

4. User subjective assessment of hearing aids

Against a background of various technological advances, the hearing aid has continued to respond to user expectations. Are users today satisfied with the current hearing aid? Countries in Europe and Japan have conducted large-scale market research surveys called *EuroTrak* and *JapanTrak* since 2009 [10]. According to JapanTrak 2015, 1306 people with hearing loss filled out their marketing surveys. Along with a corresponding survey in the US (*MarkeTrak IX* in 2014), we can discuss how satisfied hearing-aid users are in countries whose citizens have access to the latest technology.

Figure 7 shows basic demographic information. The percentage of people with hearing loss is higher for countries with aging populations (i.e., Germany, Italy, and Japan). However, the percentage of people with hearing loss who own hearing aids is lower in these countries than

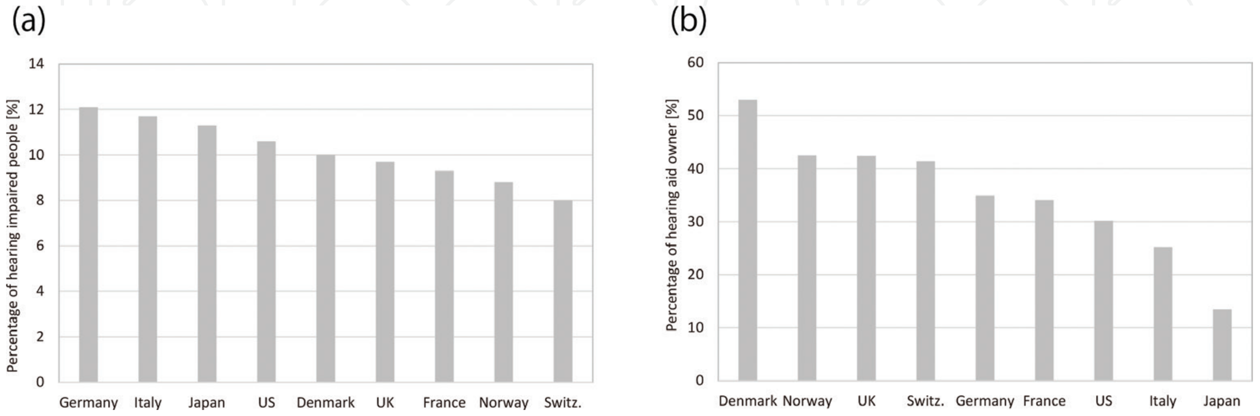


Figure 7. (a) Percentage of people with hearing loss in several high-tech countries. (b) Percentage of people using hearing aids to the number of people with hearing loss in each country.

Country	Amount granted
Denmark, Norway, UK	All expenses paid
Germany	840 Euro
Switzerland	840 CHF (about 740 Euro)
Italy	600 Euro
France	120 Euro
US	Almost none
Japan	Almost none

Table 1. Amount of money granted by governments for hearing aids.

in other countries. This trend is easy to understand after considering how much support people receive to mitigate the cost of hearings aids. **Table 1** shows public financial support for the purchase of hearing aids for each country listed in **Figure 7**. Not surprisingly, the countries showing the highest percentages of people with hearing aids are Denmark, Norway, and the UK, all of which prescribe hearing aids at no cost when a patient is diagnosed with hearing loss. We can thus say that government aid is needed to increase hearing aid distribution or the cost for these hearings aids is too high.

Figure 8 shows the percentage of people in each country who are satisfied with their hearing aids. It is interesting that people in different countries have different views about the performance of their hearing aids, even though the specification criteria are almost the same in all these countries. The countries with established social security systems are ranked in the bottom half, while more than 80% of the people with hearing loss in France, the US, and

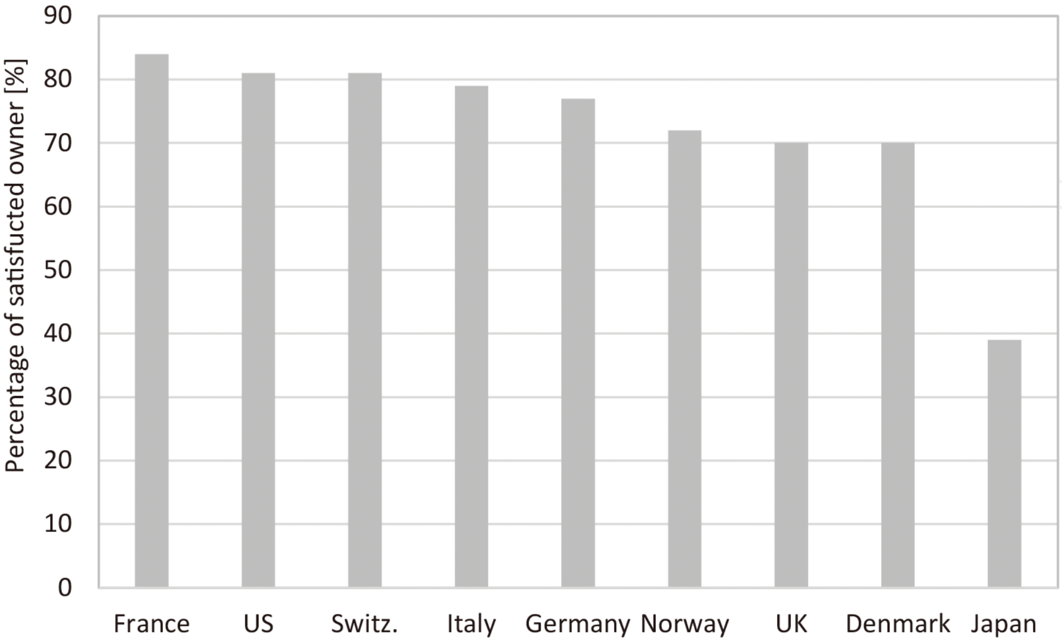


Figure 8. Percentage of people in each country who are satisfied with their hearing aids.

Switzerland (whose out-of-pocket expenses are higher) were satisfied with their hearing aids. This result seems to support the idea that the user's own expense adds value to the hearing aid. However, users in Japan who receive no public assistance feel the most dissatisfied among the surveyed countries and have one of the lowest percentages of people with hearing aids (**Figure 7b**). Aside from Japan, other countries believe that rehabilitation for hearing loss is a medical practice, and only a state-certified technician can permit a hearing aid to be sold or adjusted. In Japan, however, a private association (The Association for Technical Aids) certifies hearing aid technicians, who can then recommend people to buy hearing aids or to have their hearing aids adjusted. These data imply that a government guarantee earns the trust of hearing aid owners and is related to satisfaction. In terms of hearing aids, the role of government is not to disburse tax money but to make people with hearing loss feel secure. Thus, the current digital hearing aid has already reached the technical ceiling, and satisfaction will depend only on the user's feelings.

5. Implanted hearing devices

Although wearable hearing aids come close to the goal desired by people with hearing loss, implanted hearing devices allow room for further improvements. Several types of implanted hearing devices exist, with one being the bone-anchored hearing aid (BAHA), shown in **Figure 9a**. People have known for centuries that we can perceive sound when our skull bones vibrate, and bone conduction hearing was first described in the sixteenth century [11]. Currently, some commercially available hearing aids utilize bone conduction, and the user fixes a vibrator over the mastoid bone using a hair band. However, vibrating the skull through skin and fat tissue effectively is difficult. Therefore, the BAHA implants a titanium anchor on the temporal bone (behind the ear) to work as a bridge for vibration transmission [12, 13]. The other end of the anchor appears on the skin, and the user attaches the vibrator and receiver to the edge. Compared with previous bone

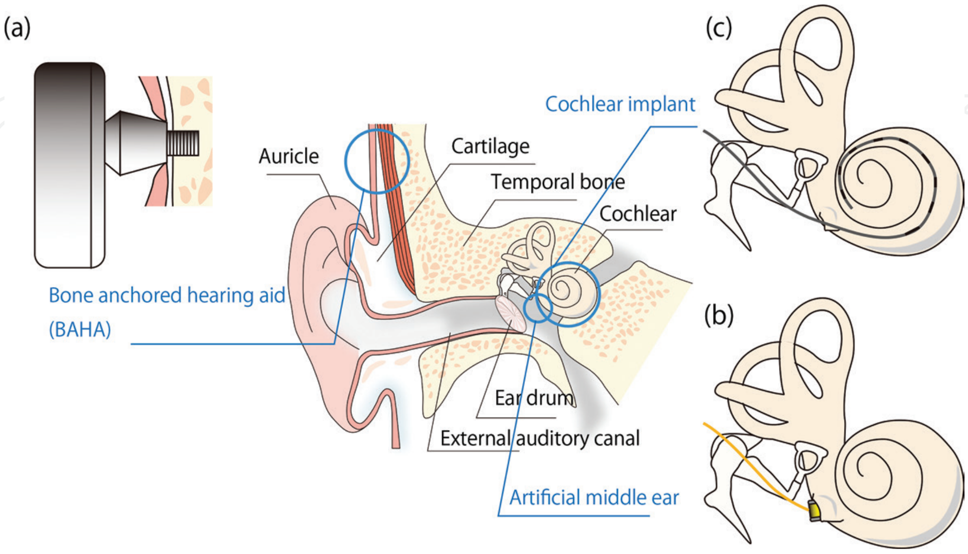


Figure 9. Implanted hearing devices: (a) bone-anchored hearing aid, (b) artificial middle ear and (c) cochlear implant.

conduction hearing aids, this technique has better amplification of higher frequency ranges, which improves speech intelligibility [14, 15].

Another implanted device is the artificial middle ear, which is used when vibration from the ear drum does not smoothly travel through the ear ossicles even after tympanoplasty operations (**Figure 9b**). A sound receiver with a built-in transmitting coil is magnetically attached behind the ear to an implanted receiving coil on the temporal bone, and the signal is transmitted through the skin by the reciprocation of the two coils. The receiving coil activates a transducer that touches the round window of the cochlea, which directly stimulates the basilar membrane. The artificial middle ear was originally developed by a Japanese hearing aid maker (RION Co., LTD.) in 1983, and other makers are currently developing a new stimulation approach using artificial ear ossicles [16].

A third device is the cochlear implant, which converts sound into an electrical current and directly stimulates hair cells in the cochlea using an implanted electrode (**Figure 9c**). The first prototype cochlear implant was conducted by William House and John Doyle in 1961 [17], making the history of this method older than either the BAHA or the artificial middle ear. Subsequently, Clark developed a multichannel electrode cochlear implant in 1977 and produced the first commercialized multielectrode device in 1978 [18]. The cochlear implant is adaptive for profound deafness (hearing level > 90 dB) in Japan. The cochlear implant is reported to be especially useful for children who have not acquired language skills for the linguistic development in the future.

Unlike implanted hearing devices, another future option could utilize stem cells, as inner ear stem cells were found in 1999 [19], and studies in regenerative medicine have developed even further since that time. This means that surgical approaches might become mainstream hearing-loss treatments. One irony is that in Japan, medical expenses for implanted hearing devices are more economic for the individual than the cost of hearing aids because they are considered within the scope of the health-care system.

6. Future of hearing aids

Although implanted hearing devices are a rapidly evolving research field and market, noninvasive hearing aids remain the first approach for treating hearing loss. Although these hearing aids have approximately achieved their aim, three severe problems are yet to be resolved.

The first is the adaptation for profound hearing loss (hearing level > 90 dB). Hearing aids are recommended when hearing level is higher than 40 dB but do not have much effect for profound hearing loss. The exception is the cochlear implant, which can work in some instances.

The second problem concerns how the hearing aids are worn. In the long history of hearing aids, some part is always inserted in the ear. The earplug occludes the external auditory canal, and the annoyance this causes is always a high-ranking reason for discontinuing use. Although the vent in CIC hearing aids as well as open-fitting hearing aids seems to reduce this feeling and the accentuation of the user's voice, they lead to acoustic feedback. Additionally, earplugs are not possible for patients with atresia of the external auditory canal or microtia, who do not have enough space to insert it.

The third problem deals with the adaptation for sensorineural hearing loss. Unlike conductive hearing loss that affects sound waves conduction anywhere along the route through the outer ear, tympanic membrane, and middle ear, the root cause of sensorineural hearing loss lies in the inner ear or between the auditory nerves and audio cortex in the brain. Some types of hearing loss, like presbycusis, have mixed causes. Patients with conductive hearing loss are able to achieve nearly 100% accuracy on speech intelligibility tests when the speech is presented at a sufficiently loud volume. However, patients with sensorineural hearing loss including presbycusis can only achieve the maximum peak accuracy between 40 and 80%, even when the speech is presented at an optimal volume. In this condition, patients can hear but cannot identify the syllables. Because the main function of a hearing aid is to amplify sound, it may offer limited benefits for sensorineural and mixed hearing loss when used during conversation.

The following subsections describe the solutions or potential clues for solving these three problems and introduce the next-generation hearing aids.

6.1. Bone-conducted ultrasonic hearing aid

Ultrasonic sound waves are those with frequencies greater than 20 kHz, which is the audible limit of human hearing. Although airborne ultrasound cannot be perceived, we can hear ultrasound delivered to the mastoid bone of the skull via a transducer [20]. Importantly, bone-conducted ultrasound can even be perceived by people with profound hearing impairment. One study has reported that these individuals are able to identify ultrasound amplitude-modulated speech signals as speech [21]. Additionally, Hosoi used magnetoencephalography and positron-emission tomography to show that bone-conducted ultrasound can activate auditory cortex of people with profound hearing loss [22]. Although the mechanisms underlying this phenomenon are still only hypotheses, the best guess at the moment is that bone-conducted ultrasound stimulates residual inner hair cells in the base of basilar membrane [23, 24].

An accumulation of research has led to the development of several different bone-conducted ultrasonic hearing aids (**Figure 10**). The HD-GU was a test model developed by Nara Medical University in Japan. Connected to a computer, parameters from various digital signal processors (e.g., noise reduction and nonlinear gain) were controlled on a monitor via software. AIST-BCUHA-003 and AIST-BCUHA-005 were developed by the National Institute of Advanced Industrial Science and Technology (AIST) in Japan [25]. AIST-BCUHA-003 was able to control amplitude and carrier frequency (i.e., ultrasound), while the AIST-BCUHA-005 contained digital signal processors and could control the degree of modulation. Another device was HiSonic, a commercial product that controlled sound amplitude for hearing aids and as therapy for suppressing tinnitus [26, 27]. Using these models, Shimokura was able to see vast improvement in speech intelligibility in a woman with profound hearing loss who he advised to try bone-conducted ultrasonic hearing aids. [28]. The results demonstrated significant improvement from the outset of therapy, and her perceived-speech intelligibility reached 60%, as measured by correctly answered questions in a closed-set test of word intelligibility

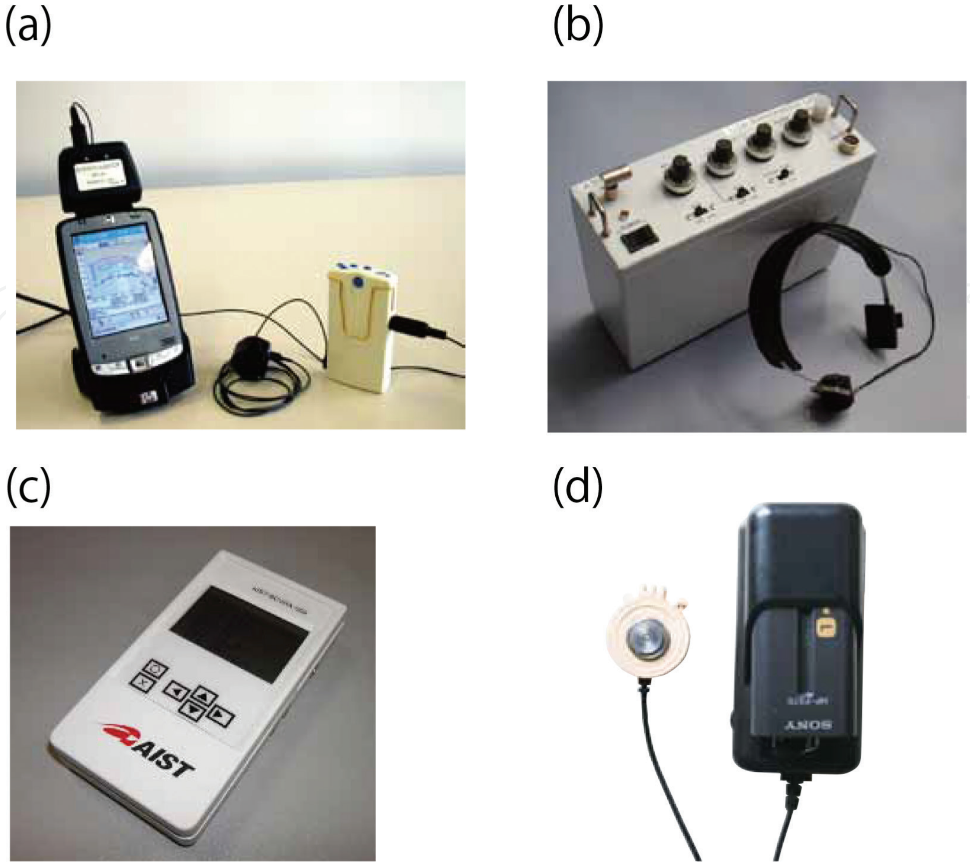


Figure 10. Bone-conducted hearing aids: (a) HD-GU, (b) AIST-BCUHA-003, (c) AIST-BCHA-005, and (d) HiSonic.

with three options. For patients with profound hearing loss, the bone-conducted ultrasonic hearing aid might be a good option before risking cochlear implant surgery.

6.2. Cartilage conduction hearing aid

The uncomfortable feeling that results from an occluded ear is a major hurdle for hearing aid users, and this feeling is always a top reason for discontinuing hearing-aid use. One study tried using active noise control to reduce this feeling [29]. Unlike this digital approach, a cartilage conduction hearing aid reduces the "full ear" feeling with an analog procedure. In 2004, Hosoi found that a specific type of transducer could be used to create clear audible sound when gently placed on aural cartilage [30, 31]. Aural cartilage comprises the outer ear and is distributed around the exterior half of the external auditory canal. Transducer-induced cartilage vibration generates sound directly in the external auditory canal as shown in **Figure 11b** [32–35]. In this case, the cartilage and transducer play the roles of a diaphragm and a loudspeaker voice coil, respectively. When the transducer is ring shaped, it can amplify the sound without occluding the ears (**Figure 11a**). Sound pressure levels in the canal show that the ring-shaped transducer produces an average gain of 35 dB for frequencies below 1 kHz [32]. Although the cartilage conduction hearing aid does not work for those with profound hearing loss, it can help those with moderate loss of hearing. One advantage of cartilage-conducted sound is its unique property of remaining in the canal regardless of the amount of ventilation, and the less sound leakage reduces the risk of acoustical feedback [36].

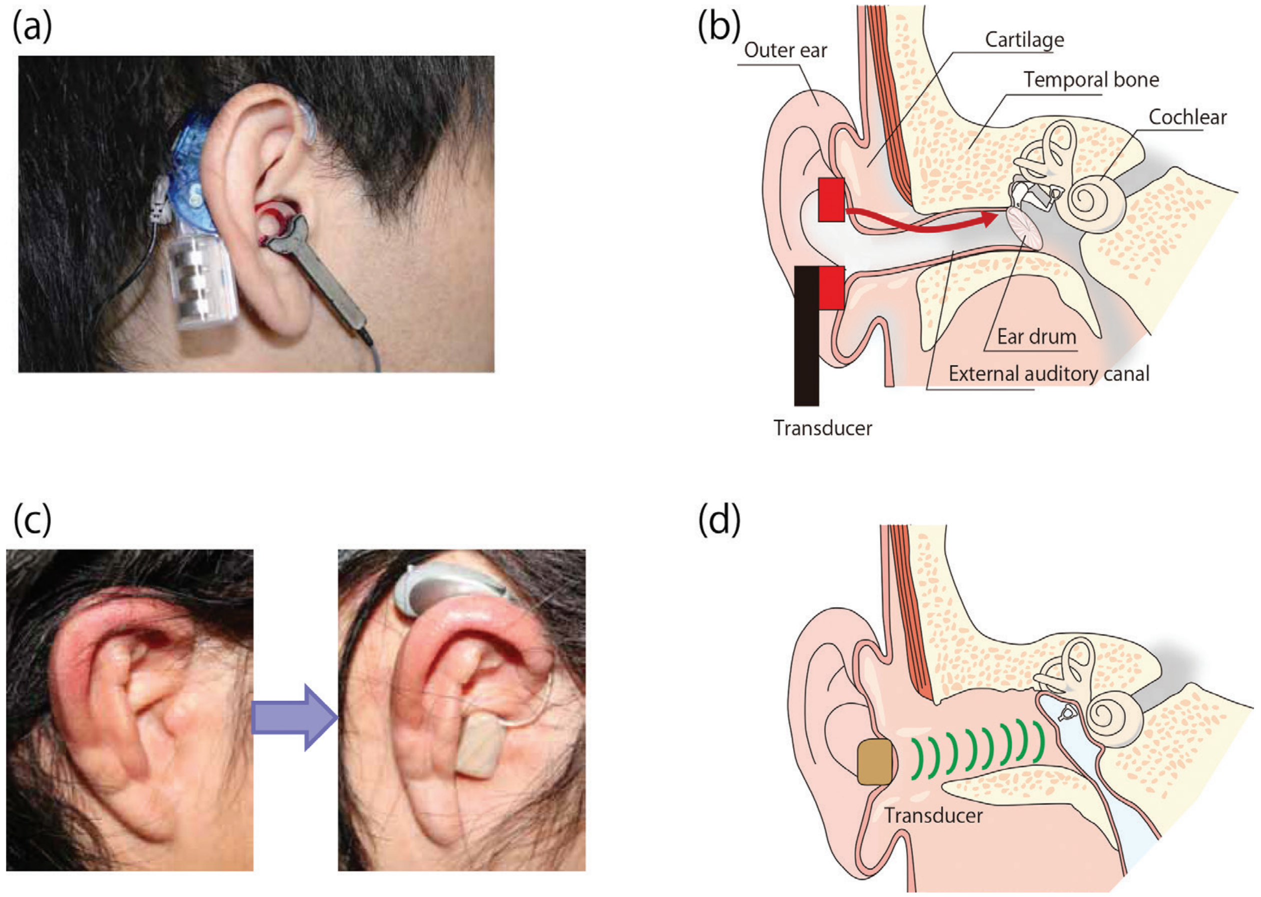


Figure 11. (a) Cartilage conduction hearing aid with a ring-shaped transducer. (b) Sound-transmission pathway in the ear. (c) Cartilage conduction hearing aid with a small transducer. (d) Sound-transmission pathway for people with atresia of the external auditory canal.

The cartilage conduction hearing aid can be used by patients with atresia of the external auditory canal [37, 38]. Because patients whose canal is occluded by fibrotic tissue cannot use a conventional hearing aid because they lack a sound pathway (**Figure 11c** and **d**), they are usually advised to use a bone conduction hearing aid or a BAHA. However, the bone conduction transducer must be pushed tightly against the head insufferably when using it for a long period of time, and the BAHA needs surgery. In contrast, the cartilage conduction transducer only needs to be softly put on the end of the canal because the excitation force required for light cartilage is much smaller than that for heavy skull bone. Despite this, hearing levels for bone and cartilage conduction are almost equivalent at frequencies below 2 kHz [38].

6.3. Autocorrelation analysis of speech signals

The third problem is the speech intelligibility for people with sensorineural hearing loss. As mentioned earlier, patients with sensorineural hearing loss can perceive sound but cannot recognize speech. For example, all Japanese medical institutions use the same list of monosyllable signals for an intelligibility test, which are delivered by a professional female speaker, and studies investigating speech intelligibility in patients with sensorineural hearing loss have identified the less discernible consonants within Japanese monosyllables [39–41]. According to [41], 90% of patients identified monosyllable /i/ correctly, while only 10% could identify /de/.

To explain the difference, studies have investigated several physical parameters. For example, voice onset time (VOT) is the length of time in milliseconds that passes between the release of a stop consonant and the onset of voicing [42]. Another example is the speech intelligibility index (SII), which is a measure of the proportion of a speech sound that is discernible under different listening conditions, such as filtering related to hearing decline or reverberation [43]. Loudness level [phon] can be calculated based on the averaged spectra of a signal, but the masking effects of neighboring auditory filters may be included [44].

All these parameters are related to mechanisms of peripheral perception in the auditory pathway. However, the causes of sensorineural hearing loss are in the inner ear or the auditory nerve. Therefore, subsequent processing after peripheral functions is complete and has to be considered when trying to explain speech intelligibility. A major candidate for imitating subsequent processing is autocorrelation function (ACF). ACF is an established method for temporally analyzing auditory nerve processes [45]. Neural representations that resemble the ACF of an acoustic stimulus have been detected in distributions of all-order interspike intervals in the auditory nerve [46, 47]. Mathematically, the normalized ACF and ACF can be represented by

$$\varnothing(\tau) = \frac{\Phi(\tau)}{\Phi(0)} \tag{1}$$

where $\Phi(\tau) = \frac{1}{2T}\int_{-T}^{T} p'(t)\, p'(t+\tau)dt$ and where $2\ T$ is the integral interval, τ is the time delay, and $p'(t)$ is the signal after it is passed through an A-weighting filter. **Figure 12** shows an example of the calculated monosyllable /sa/. In this case, the ACF was calculated for the integral interval ($2\ T = 80$ ms) that moves with the duration of the monosyllable (running ACF). In the fricative consonant part of the sound (before 0.3 s), the normalized ACF decays suddenly to 0, while in the extended vowel portion of the sound (after 0.3 s), it gradually decays as a function of the delay time. To evaluate the slope of the decay, an effective duration (τ_e) has been proposed [48] that is defined by the delay such that the envelope of the normalized ACF becomes smaller than 0.1. When the consonant component-containing noise element (e.g., /s/ and /d/) occupies the monosyllable, τ_e becomes shorter because it expresses the amount of noise (i.e., $\tau_e = 0$ for white noise and $\tau_e = \infty$ for a pure tone). Indeed, τ_e represents the SN ratio (S: speech and N: noise or reverberation) of a monosyllable itself.

Figure 13 shows the relationships between the physical parameters and the percent of monosyllables articulation presented to patients with sensorineural hearing loss at an optimal volume [49]. Each symbol is the average for a consonant, and $(\tau_e)_{med}$ indicates the median of the time-varied τ_e of the running ACF. Among the four physical measures examined, only τ_e was correlated with speech intelligibility. Effective duration is a measure of temporal pattern persistence, that is, the duration over which a waveform maintains a stable pattern. These data have led to the hypothesis that poor speech recognition is related to the degraded perception of temporal fluctuation patterns. DSPs that prolong the effective duration (e.g., shorten the consonant length or smoothen the voicing frequency) may therefore improve speech intelligibility for those with sensorineural hearing loss.

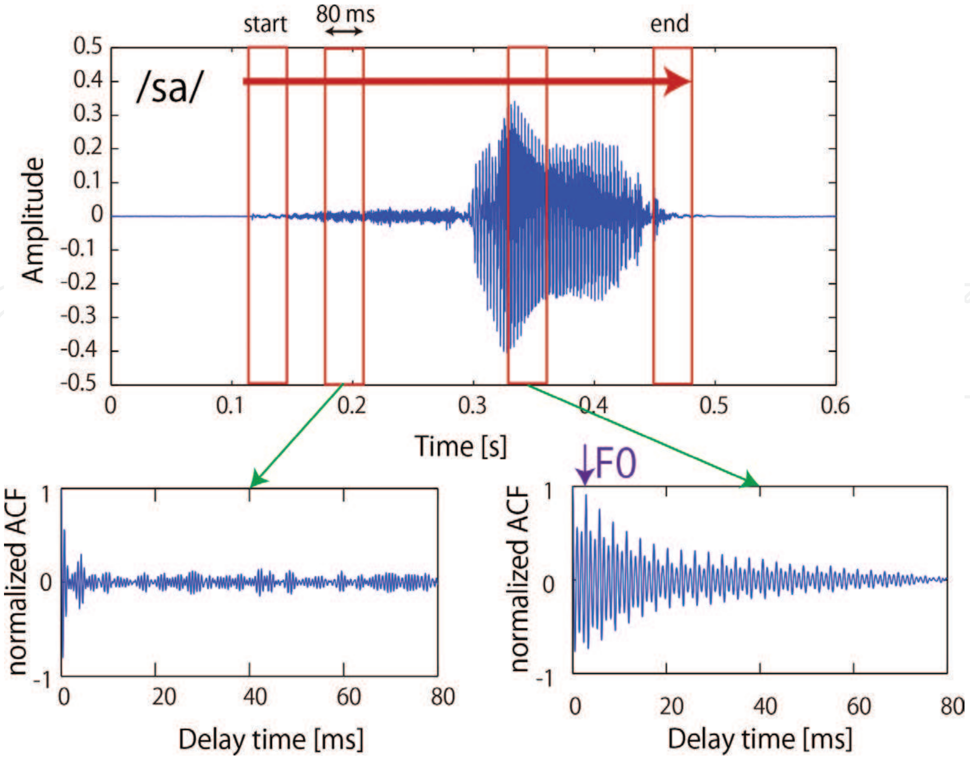


Figure 12. Example of an autocorrelation function calculated for the Japanese monosyllable /sa/ (F0: Fundamental frequency of voice).

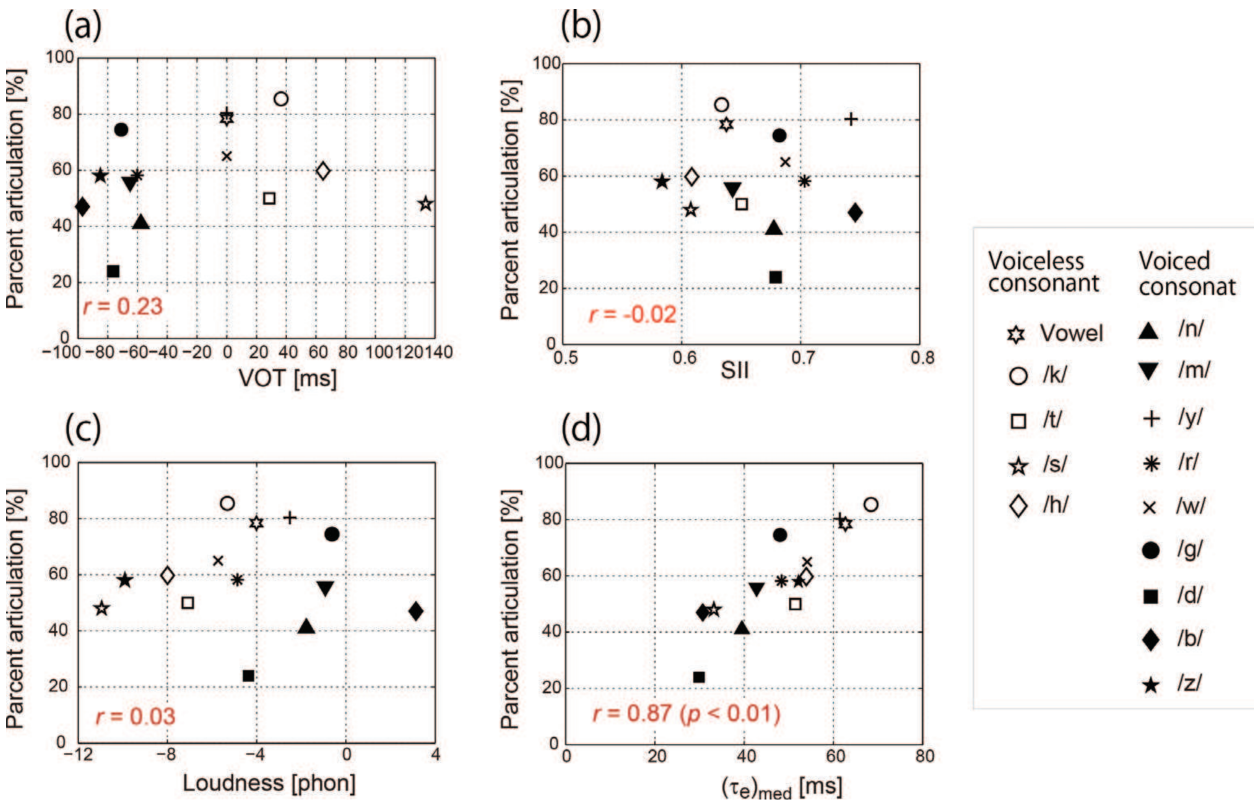


Figure 13. Relationship between the percent of articulation and four physical parameters: (a) VOT, (b) SII, (c) loudness, and (d) $(\tau_e)_{med}$ (R: Correlation coefficient). The different symbols indicate different consonants. Reproduced from (**Figure 5**) in [49].

7. Concluding comments

To avoid advanced hearing loss and instances of hearing loss-related dementia, it is important to recognize hearing loss at an early stage and provide treatment that prevents the loss of hair-cell or auditory-nerve stimulation. In particular, for those who wear hearing aids in only one ear, speech intelligibility is known to degrade more in the other ear [50, 51]. However, currently popular implanted hearing devices are a fairly large burden for people soon after they become aware of their hearing loss. For this reason, we tend to stick to wearable hearing aids that are easy to be put on and take off. Researches are therefore using the scientific method to remove technical barriers for hearing aids. Further, governments should try to remove other barriers by providing services such as financial support or public qualification for handling hearing aids, and companies that make hearing aids should charge less money. This will help slow down hearing loss and lead to a healthier society.

Index of technical terms

Active noise control, p11	Active noise control is a technique for minimizing undesired sound by acoustic interference with a secondary sound source.
Audiogram, p5	Audiogram represents hearing thresholds for standardized frequencies in a dB-scale.
Aural cartilage, p11	Aural cartilage is flexible fibrous tissue shaping an auricle and a part of external auditory canal.
Autocorrelation function (ACF), p12	Autocorrelation function is correlation of a signal with decayed copy of itself as a function of decay.
A-weighting filter, p12	A-weighting filter is designed by a loudness curve (IEC 61672:2003) around 40 phone, and the filtered sound pressure level can quantify the loudness partly.
Bone conducted ultrasonic hearing aid, p10	Bone conducted ultrasonic hearing aid has an ultrasonic transducer which is attached to a mastoid to transmit vibration in ultrasonic range modulated by speech waveform.
Bone-anchored hearing aid (BAHA), p8, p11	Bone-anchored hearing aid is a hearing device which transmit vibration to skull bone through the intermediary of an implanted titanium projection.

Cartilage conduction hearing aid, p11	Cartilage conduction hearing aid transmits sound information by vibrating aural cartilage.
Cochlear implant, p8	Cochlear implant bypasses the normal hearing process and stimulates hair cells in the cochlea using an implanted electrode directly.
Conductive hearing loss, p9	Conductive hearing loss occurs when there is a problem conducting sound waves anywhere along the route through the outer ear, tympanic membrane (eardrum), or middle ear (ossicles).
Effective duration (τ_e), p12	Effective duration is defined by the delay time at which the envelope along the early decay of the normalized autocorrelation becomes below 0.1, and signifies the degree of periodicity contained in a signal.
Fricative consonant, p12	Fricative consonant is produced by forcing air through a narrow channel made by placing two articulators close together.
Full ear, p11	Full ear is uncomfortable feeling when ears are occluded by something, and it emphasize excessively own voice and sound of mastication during a meal.
Loudness level, p12	Loudness level [phon] quantifies the subjective perception of sound pressure and is calculated by spectral energy applied to the equal loudness chart for each 1/3-octave band (ISO 532).
Magnetoencephalography, p10	Magnetoencephalography (MEG) is a non-invasive technique for measuring neuromagnetic signals generated by the brain.
Open-fitting hearing aid, p9	Open-fitting hearing aid has an earplug with a significant leak venting for the purpose of reducing the full ear.
Positron-emission tomography, p10	Positron-emission tomography is non-invasive technique for measuring a positron (positive electron) emitted by a nucleus after blood flow, metabolism, neurotransmitters, and radiolabelled drugs.
Profound hearing loss, p9	Profound hearing loss is an inability to hear sound even in 90 dB in silent condition.

Recruitment hearing, p6	Recruitment hearing is an auditory disorder to exaggerate loudness for sound over a certain amount of sound pressure.
Sensorineural hearing loss, p6, p9, p12	Sensorineural hearing loss is a type of hearing loss, in which the root cause lies in the inner ear or sensory organ (cochlea and associated structures) or the vestibulocochlear nerve (cranial nerve VIII) or neural part.
SN ratio, p13	Signal-to-noise (SN) ratio compares the level of a desired signal to the level of background noise.
Speech intelligibility index (SII), p12	Speech intelligibility index (SII) is a measure of the proportion of a speech sound that is discernible under different listening conditions, and is calculated according to the signal (i.e., speech) to noise (i.e., environmental noise) ratio and the hearing threshold (i.e., audiogram) of each 1/3-octave band.
Voice onset time (VOT), p12	Voice onset time (VOT) is the length of time in milliseconds that passes between the release of a stop consonant and the onset of voicing.

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