Acoustics Today

Spring 2023 Volume 19, Issue 1

ASA ACOUSTICAL SOCIETY OF AMERICA

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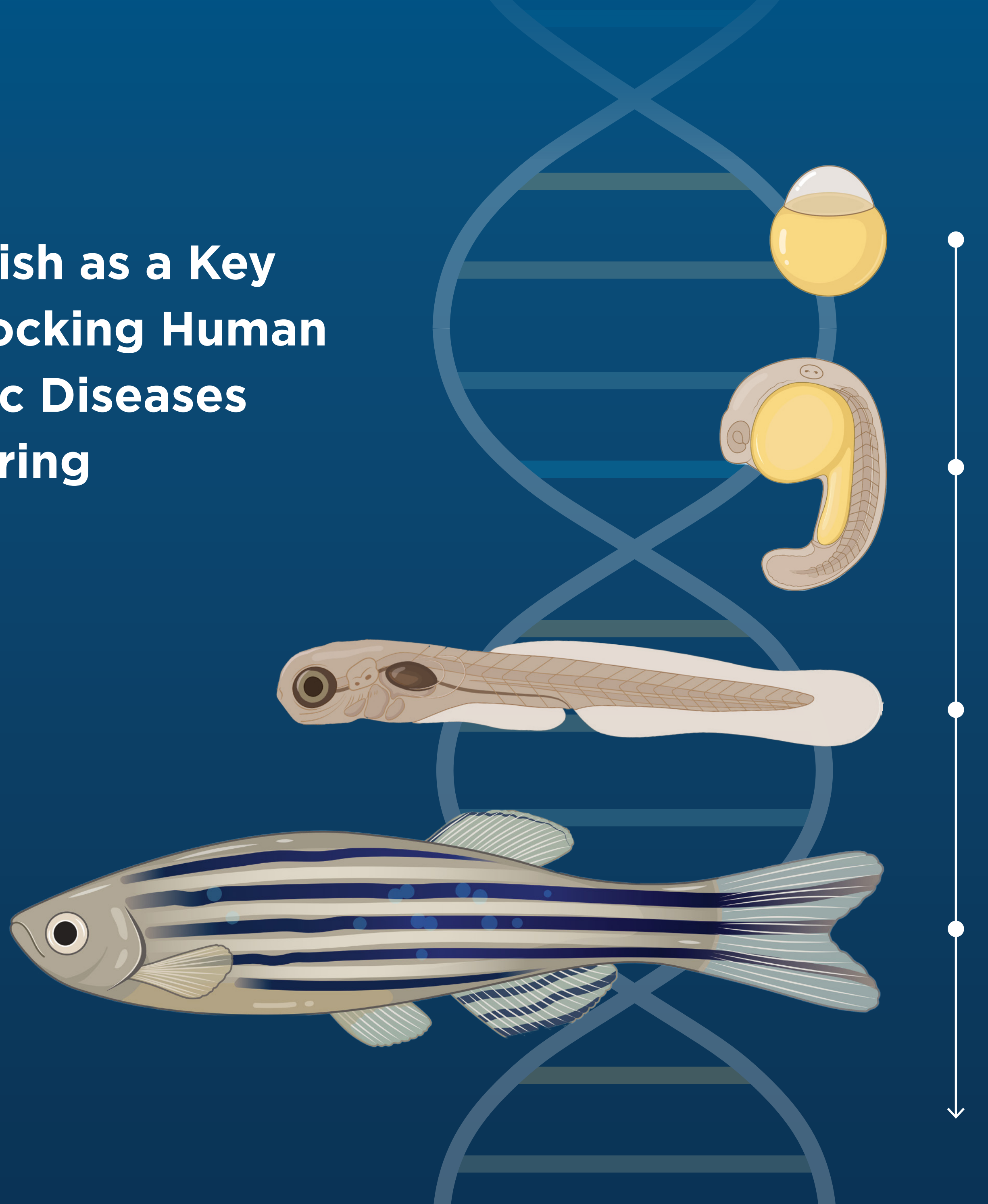
Zebrafish as a Key to Unlocking Human Genetic Diseases of Hearing

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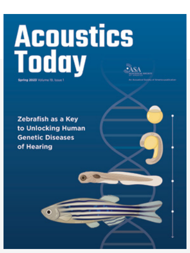

About the Cover

Schematic of zebrafish life stages, from "Zebrafish as a Key to Unlocking Human Genetic Diseases of Hearing" by Erin Jimenez and Ashwin A. Bhandiwad (page 20). Journal cover created with BioRender.com.


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From the Editor

Arthur N. Popper

You will note a small change in this issue of *Acoustics Today* (*AT*). In the past, we have included short biographies of each author at the end of each article. However, we discovered that in many issues of *Acoustics Today*, the cumulative space taken up by the biographies was several pages. Because we are limited in the number pages in each issue and wanted to be able to devote more space to the articles and essays, we decided to move the biographies to the web. Therefore, the author listing at the end of each article now includes a URL and a QR code that takes you to the biographies for that article. (We did consider eliminating the biographies, but a quick survey of some readers supported the view that readers like and value learning a little about the authors, especially when the authors are younger members.) If you have any thoughts about this change or whether there should even be the short biographies, please don't hesitate to send me an email (apopper@umd.edu).

This issue of *AT* has five articles. The first by David R. Dall'Osto, Peter H. Dahl, and N. Ross Chapman discusses the sounds from underwater explosions. As you read the article, you will see that I have been collaborating with David and Peter to examine the effects of explosions on fishes, and my curiosity about the signals to which we were exposing the animals led me to suggest their doing this article. Other *AT* articles on underwater acoustics can be found at bit.ly/AT-Underwater_Acoustics.

The second article by Erin Jimenez and Ashwin A. Bhandiwad is about one of the most important biological models being used today to help understand the genetics of human development and disease, the zebrafish. Erin and Ashwin focus on one very important aspect of work with this diminutive species: its role in understanding the genetics of human hearing.

This is followed by a discussion of informational masking by Gerald Kidd Jr. and Christopher Conroy. In their article, Gerald and Chris give what I think is the best explanation I have seen of the differences between informational and energetic masking. Indeed, most readers will easily relate to the fascinating issues associated with informational masking because we all encounter it in our daily lives and in special situations like the social events at meetings of the Acoustical Society of America (ASA). See bit.ly/AT-psychoacoustics for more articles on human hearing.

Hearing is also the subject of the fourth article by Nicole Nguyen, Larissa Curry, and Matthew J. Goupell. The authors discuss the use of cochlear implants (CIs) in improving human hearing. They not only compare the value of CIs with that of more typical hearing aids, but they also consider a range of other things about CIs, including adapting to their use and the impacts of getting the devices at different ages. "*AT* Collections" has more articles on devices used to improve human hearing (see bit.ly/AT-Health).

The fifth article adds to our series about the use of ultrasound in biomedicine (see bit.ly/AT-ultrasound). The authors, Matthew W. Urban, Tuhin Roy, Wilkins Aquino, Murthy N. Guddati, and James F. Greenleaf, focus on how ultrasound is used in investigating the biomechanics of the arteries that are part of the human circulatory system. As the authors show, developing noninvasive methods to understand the biomechanics of the circulatory system is of great value as humans age because things like blood vessel elasticity changes.

We have three "Sound Perspectives" essays. The first is part of our "Conversation with a Colleague" series (see bit.ly/ATC-CWC). This essay, edited by Micheal Dent, features Ruth Litovsky, a faculty member at the University of Wisconsin-Madison, who has made major contributions to the understanding of how the brain processes and uses sounds from two ears (binaural hearing).

Our second essay by Brian G. Ferguson, R. Lee Culver, and Kay L. Gemba introduces the latest international student challenge from the ASA Technical Committee (TC) on Signal Processing in Acoustics. All ASA student members are invited, individually or in groups, to participate in the challenge and compete for a cash award. I would also encourage others to look at the challenge because it is quite

Continued on Page 10...

ACOUSTICS 23
Sydney

4–8 DECEMBER 2023

Acoustical Society of America
Australian Acoustical Society
Western Pacific Acoustics Conference
Pacific Rim Underwater Acoustics Conference

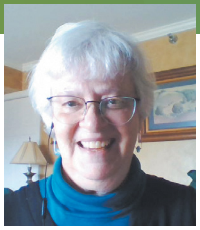
The Acoustical Society of America (ASA) and the Australian Acoustical Society (AAS) invite acousticians from around the world to participate in the joint meeting to be held 4–8 December 2023 in Sydney, Australia. A broad range of topics in acoustics will be covered in technical sessions and keynote lectures. Presentations on emerging topics are especially encouraged. The meeting is cosponsored by the Western Pacific Acoustics Conference and the Pacific Rim Underwater Acoustics Conference. Social events, student events, and an accompanying persons program will be organized. The best features of meetings of all organizations will be combined to offer a premier venue for presenting your work to an international audience.

Sydney is located on the east coast of Australia and is the state capitol of New South Wales. Situated on Darling Harbor, Sydney was established in 1788, and is best known for its harbor front Sydney Opera House, with a distinctive sail-like design.

Please Join Us!

From the President

Peggy Nelson



It was terrific seeing so many of you at the Acoustical Society of America (ASA) meeting in Nashville! Just as soon as the meeting was over, we continued planning for a fabulous meeting in Chicago. There's no substitute for seeing one another, exchanging technical information, and celebrating our awardees. I do hope that you'll be there in Chicago and that many of you are planning to make the trip Down Under for the joint meeting in Sydney in December 2023. Sydney promises to be an exciting venue. I hope you're considering that trip. I've been watching and planning for my first visit to Sydney, checking out information from a recent article in *The New York Times* (see bit.ly/3Gd0EWa). We have waited a long time for both of these meetings! Each was postponed during the early days of Covid, so it's a great relief to see them come to fruition.

That said, I am also proud to announce that we have decided to proceed with a trial fully virtual meeting for Fall 2024. Representatives of the Executive Council (EC), Technical Council, and Student Council have been discussing this idea for months, and the EC voted to approve it. This will be a one-time trial of a fully virtual meeting that is planned well in advance. The reasons to hold such a meeting are many, but the primary motivation is *access*. We have thousands of members who do not, or cannot, attend our meetings in person. For some, the barrier is cost; for others, it is health or travel restrictions; whereas for many members, it is time restrictions or family obligations. Whatever the reason, we recognize that we have many people who log on to our virtual events who do not attend the in-person meetings. The plan is to try this virtual meeting experiment and see if it is something that we want to do from time to time. Perhaps we will find that many people who are not otherwise able to present their work at an ASA meeting will present at this virtual conference. On the other hand, perhaps we will say "never again." The Society leadership is open to all options.

We hope you will plan ahead for the Fall 2024 virtual meeting and be a part of it. Above all, please spread the word to your colleagues and students who do not often attend in person. Perhaps it will be a good time for people from your laboratory or company to present their work. Multiple team members from your business or industry (who otherwise might not be able to attend) can be encouraged to present. A major goal in planning is to not only ensure a great experience in presenting and hearing papers but to also ensure that the virtual meeting is filled with opportunities for virtual networking.

There are many other things we are considering with regard to the virtual meeting. For example, we are tentatively planning on a shorter meeting rather than re-creating the typical five-day in-person meeting. We also intend to avoid conflicts with major holidays. And, of course, the total cost of attending the meeting will be lower.

As we enter 2023, I am still reminded that I am exceptionally proud to be serving as the president of the ASA and I am extremely excited for the future.

I look forward to seeing you again in person soon. As always, I hope to see you on a webinar, at a committee meeting, and again in person soon. Let me know what you think we can do together.

From the Editor, Continued from Page 8

interesting and challenging. And, as I've mentioned in the past, if other TCs have similar challenges, we would be more than pleased to include information about them in *AT*. Just contact me well in advance of the challenge.

We conclude with one of a continuing series of essays by L. Keeta Jones, ASA Education and Outreach Coordinator. In this essay, Keeta shares insights into how to prepare a lay language paper about one's scholarly activities to help communicate work with reporters, teachers, and others. As Keeta points out, effective communication to a lay audience, such as about work presented at an ASA meeting, is very useful and very important. Her essay provides tips on helping make the lay paper interesting to a wide audience and attract interest in one's work. For other articles in *AT* on science communications, see bit.ly/ATC-Communications.

The Sound from Underwater Explosions

David R. Dall'Osto, Peter H. Dahl, and N. Ross Chapman

Introduction

Explosives have played a prominent role in the history of underwater acoustics. In fact, much of our understanding of sound propagation in the ocean was developed from analysis of data from experiments at sea using explosive charges. Some of the early research was done under highly dangerous conditions during World War II (WWII) when experiments needed to be carried out in the very waters patrolled by enemy submarines. Many lasting innovations were developed out of these wartime studies, including cutting edge air-dropped radio buoys with hydrophones that were critical to mitigating submarine threats (Muir and Bradley, 2016).

Another lasting example of these early efforts was the development of a dense hydrophone infrastructure initially designed for rescue of pilots and aircrew lost at sea. This system, called the SOund Fixing And Ranging (SOFAR) system, was developed after the surprising discovery of the deep ocean sound channel, the SOFAR channel. This sound channel exists due to the natural structure of sound speed in the ocean. Sound speed is higher in the upper ocean due to solar warming and at great depths in the lower ocean due to the extreme hydrostatic pressure. A minimum sound speed is thus established at middle ocean depths. This natural structure of sound speed creates an acoustic lens in the ocean that enables sound originating in the channel to propagate to very long ranges.

As a consequence, a small explosion detonated at a depth near the sound speed minimum can be detected tens of thousands of kilometers away. During WW II, a system was developed where downed pilots would drop a small explosive charge, using a reference table to first set an appropriate depth in the SOFAR channel for the detonation. Through detection and timing of the sound received at multiple listening stations, operators would generate a fix on the aircrew's position to dispatch a search and rescue. Although satellite technology has replaced this method, these early efforts identified the feasibility and utility of long-range hydroacoustic networks. As an aside, it was not only oceanographers who used the SOFAR channel but is also used by baleen whales to communicate across the world's oceans (Schulze et al., 2022).

Beyond use of the SOFAR channel, there have been many other important contributions to understanding the oceans using explosives. In this article, we discuss how their use continues to add to our understanding of underwater acoustics. We focus on the sound emanated from a standard naval ordinance called Signal, Underwater Sound (SUS) charges that have been used for over 60 years and are still used in underwater acoustic research today.

Signal, Underwater Sound Charges

SUS charges were mass produced in the United States throughout the 1960s to the 1990s to support antisubmarine warfare (ASW). In a typical ASW mission, aircraft and ships would first set out a network of listening buoys. After the network was deployed, SUS charges would be dropped (typically from an airplane) into the water and operators would analyze the sound, specifically listening for reflections of the shockwave from the submarine's hull. If an echo was heard (a contact!), the process would repeat to track the submarine. Such operations ceased in the 1960s as explosive SUS charges were phased out in favor of less dangerous (and more effective) electronic variants as sound sources.

Small explosives, like SUS charges, are appealing for use in experiments at sea because their deployment is relatively straightforward from ships or aircraft, and they provide

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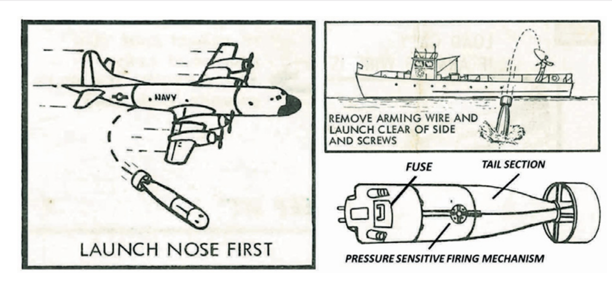


Figure 1. *Images from the instructions and warnings included with signal, underwater sound (SUS) charges manufactured in the 1960s.* ***Left:*** *SUS charge deployment from an aircraft.* ***Top right:*** *deployment from a surface ship.* ***Bottom right:*** *detail of a SUS charge, with its three sections: the "fuse," the "pressure-sensitive firing mechanism," and the aerodynamic "tail section" that is packed with a high-energy (HE) explosive. A typical operational SUS charge (Mk82) contains 0.82 kg of HE explosive, whereas a practice charge (Mk64) only contains 31 g of HE in its fuse and has an inert tail section. Image credit: NAVAIR DWG 695611.*

strong broadband, or wide-frequency-range, signals, with appreciable energy at frequencies well below 1,000 Hz. Somewhat conveniently, a supply of explosive SUS ordinance is still available and used in present day research.

Figure 1 shows a 1960s era instruction/warning sheet included with the SUS charges that were recently used in experiments off the New Jersey coast. We use measurements of a "practice SUS charge" (model Mk64) and an "operational SUS charge" (model Mk82) to illustrate the sequence of events in the acoustic signal and to demonstrate the fundamental scaling laws universal to all underwater explosions.

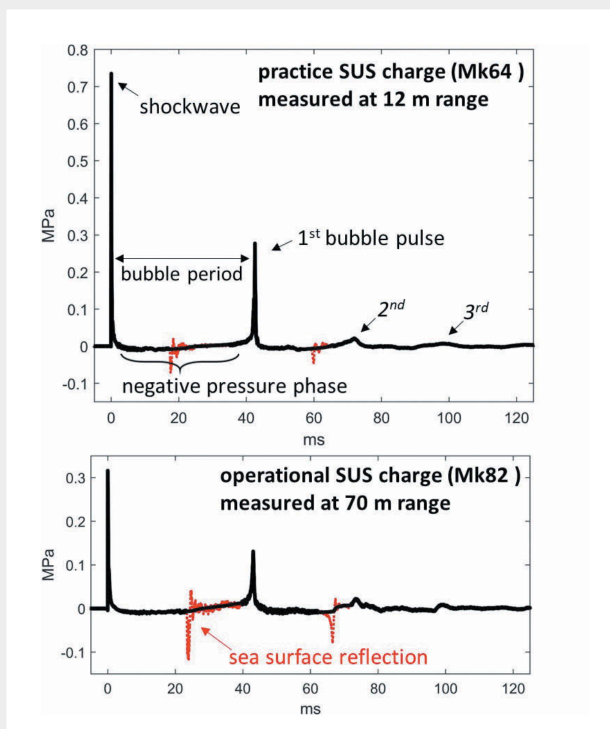
Pressure Signal Sequence of an Underwater Explosive Source Measured at Close Range

The initial sound from an underwater explosion radiates as a shockwave, producing a near instantaneous rise in pressure that can be hundreds of times greater than the ambient hydrostatic pressure. The shockwave appears as a sharp spike in hydrophone measurements made relatively close to the source. The peak pressure of the shockwave from a practice SUS (Mk64) charge at a 12 m range is about 0.73 MPa (see **Figure 2**, *top*), and for the operational SUS (Mk82) charge at a 70 m range is about 0.33 MPa (**Figure 2**, *bottom*). Although the operational SUS charge contains 26 times the amount of explosive, the smaller practice charge produces a higher peak pressure at the recording hydrophone because it was measured at a closer range.

After the initial sudden rise in pressure when the shock impulse arrives at the hydrophone, the pressure decays quickly and returns to the ambient level within a few milliseconds. The initial part of the decay is generally modeled as being exponential. However, high-resolution data of the shock impulse reveals that the decay is a complicated process, with the rate of decrease becoming slower as the pressure falls from the initial high values (Wilson et al., 2019). On cessation of the shock impulse, the pressure signal sequence more gradually shows a negative pressure.

This "negative pressure phase" corresponds to the decreasing pressure within an expanding bubble of gaseous by-products of the explosive material that occur in the wake of the shockwave. The bubble expansion causes the pressure to

Figure 2. *Pressure signal from a Mk64 (**top**) and Mk82 (**bottom**) SUS charge measured by a hydrophone suspended 20 m below the surface.* ***Red lines:*** *reflection from the sea surface.*



match and briefly go below the hydrostatic pressure, forcing a rapid collapse that produces a second sharp impulse. The collapse and rebound cycle of the gas bubble generates a series of "bubble pulses" that are a hallmark of underwater explosions. It is this bubble pulse series that generates the high signal energy at low frequencies.

This brief summary of the characteristics of an underwater explosion provides a rough introduction. Some additional details are now provided on the two hallmark features of an underwater explosion: the scaling law governing peak acoustic pressure relative to explosive weight and the properties of the bubble pulse.

Scaled Range Theory and Long-Range Propagation

The peak pressure levels one would experience when hearing an explosion depend primarily on two things: (1) how far away the receiver is from the explosion and (2) the total explosive weight. Moreover, the peak acoustic pressure levels from an explosion follows an important scaling law (Chapman, 1985), discovered over a century ago. This scaling law shows that peak pressure levels of the shockwave follow a function of range divided by the cube root of the explosive weight (i.e., scaled range). Scaling constants have been derived from a vast set of empirical measurements, made at a very close distance and at some distance from charges of varying weights, to establish the accurate predictions of peak pressure for many types of explosives. Thus, with scaled range, one can predict the peak pressure of the shock impulse emanating from an underwater explosion.

Although there is a limit of validity for scaled range, the relationship seems to be surprisingly robust. **Figure 3** shows the peak pressure of SUS charges as a function of scaled range. These include measurements of operational SUS charges (**Figure 3**, *gray triangles*) made in deep water (Chapman, 1985) at short enough ranges where the reflections from the sea surface or seafloor do not interfere with the direct (shortest) path, and measurements of practice SUS charges (**Figure 3**, *yellow stars*) made in shallower water (75 m deep) where multiple echoes from the sea surface and seafloor can interfere, causing a deviation from the scaled range theoretical curve. As expected, the peak pressures follow the scaled range law (**Figure 3**, *dashed line*) and deviate only at long ranges where the echo interference is inevitable (and at most only 2 times, or 6 dB, the predicted level). Perhaps to some surprise, the operational SUS (**Figure 2**, *bottom*) was also measured 8,000 km away, with a peak pressure of about 1 Pa, which coincidently matches the prediction from scaled range theory (**Figure 3**, *open circles*).

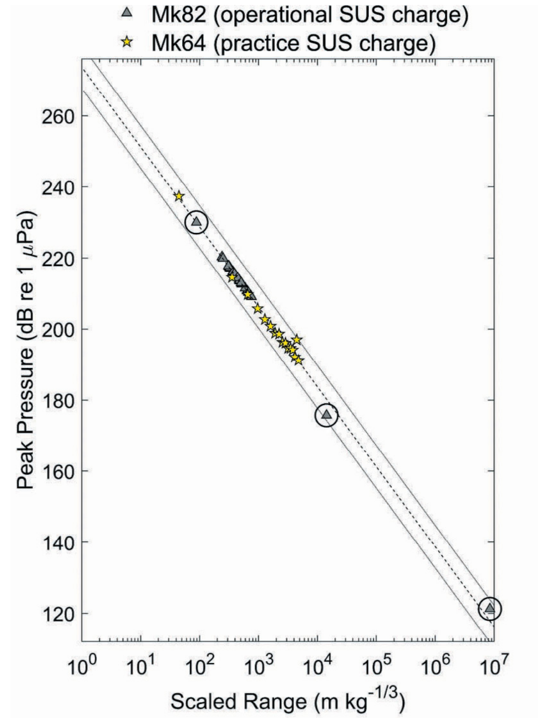


Figure 3. *Measurements of peak pressure from operational SUS charges (**gray triangles**) and practice SUS charges (**yellow stars**), shown as a function of scaled range. Near the source, the peak pressure levels follow scaled range predictions (**dashed line**) and fall within ±6 dB out to 10 km. **Open circles:** simultaneous measurement of the Mk82 charge shown in **Figure 2** at three locations, including a hydrophone station over 8,000 km away.*

The Bubble Pulse and Effect of Detonation Depth Below the Water Surface

The sequence of events following an underwater detonation reveals a spherical globe of gas growing outward from the point of detonation. This void in the water is filled with water vapor and the vaporized by-products of the explosive material, which, for conventional explosives, are chiefly carbon and nitrous oxides (Keevin and Hempin, 1997). The inertia of the expanding globe creates a low-pressure bubble that expands to a maximum radius, which if large enough may break the surface and vent the gases into the atmosphere. However, if the explosion is deeper, the bubble stops growing due to the opposing force of the surrounding ocean, and it is rapidly recompressed. The inward inertia overshoots equilibrium, compressing the gas bubble to a significant pressure that generates a second strong sound pulse. The time between the shock wave and this first bubble pulse is referred to as the bubble period.

After the first bubble pulse, the repeated collapse and rebound continues for several more cycles. Each time the cycle repeats, an additional sound pulse is generated, with diminishing peak pressures because the gas volume loses energy during the oscillations. The bubble rises vertically in the water throughout its series of oscillations, like a rising balloon, and subsequent bubble pulses originate from shallower depths than the detonation depth.

The twin impulses in the explosive charge signal (shockwave + first bubble pulse) establish a feature in the spectrum of the sound source that persists as it propagates, even when the signal is compounded with many echoes and becomes highly dispersed. The acoustic signal thus has encoded within it information about the properties of the explosion, specifically, the explosive weight and detonation depth. Thus, this bubble pulse feature is a unique identifier of an explosion, one that assists in its detection across ocean basins (Dall'Osto, 2019) and in discriminating explosions from the other impulses in ocean noise like tsunami-generating earthquakes (Simons et al., 2021).

A simple relationship exists for predicting the bubble period, following the same scaling by the cube root of the explosive weight as the scaled range. This is particularly useful when trying to identify an unknown explosion, from which one can infer its magnitude and depth. Revisiting the SUS data to demonstrate this application, even though the operational SUS charge has 26 times more explosive than the practice charge, it detonated 5 times deeper, resulting in bubble pulse signals from these 2 SUS charges that are remarkably similar (both signals have a sharp bubble pulse peak at 42 ms; see **Figure 2**).

We can also gather the size of the bubble created by the explosion from these same empirical curves. The practice SUS charge, which detonated at an 18-m depth, produced an 84 cm diameter bubble. The operational charge detonated 5 times deeper than the practice charge and produced a bubble twice that in diameter (1.6 m). Even though the larger operational SUS charge generated a bigger bubble, the greater hydrostatic pressure collapsed it in the same time as the smaller bubble of the practice charge at its shallower depth.

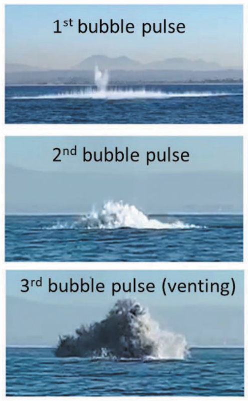
In comparison to the near instantaneous rise in pressure for the shock pulse, a closer inspection of the bubble pulses in **Figure 2** shows that the rise times to the peak pressures are gradual (a few milliseconds compared with less than a microsecond). Moreover, the rise and decay times of the bubble pulses are not symmetrical due to the energy loss during the cycle. **Figure 2** also demonstrates that the periods between sequential bubble pulses and their amplitudes both decrease. Interestingly, the explosions of these SUS charges were totally contained in the ocean with no visible disturbance on the sea surface. However, if either explosion were much shallower (say within a few bubble radii), its bubble could break the surface and burst, abruptly ending the bubble pulse sequence. This doesn't generally happen with SUS charges, which are small enough and detonate deep enough that their bubble remains totally contained underwater.

The scaled relationships for the bubble size are also useful in determining what "type of surface eruption" will be observed (**Figure 4**, *right*), which compounds and grows with each bubble pulse. **Figure 4** shows a photo of the surface phenomena from a 4.7-kg underwater explosion detonated at a 10-m depth; the accompanying table details the types of surface phenomenon expected for a detonation depth in terms of the maximum radius of its gas bubble. This explosion produced a roughly 4-m-diameter bubble, so at a 10-m depth, the surface above the explosion appears as a mound of frothy water (its whiteness caused by the cavitation of the water under the extreme pressures). The reflection of the bubble pulses from the sea surface can be observed in the surface eruption, each bubble pulse sending plumes of water jetting through the cavitation layer.

Considerations and Applications

Effect of Reflections

Underwater shockwaves from an explosion will eventually encounter and reflect from boundaries, although the effect of the sea surface and seabed are starkly different. The sea surface, which is a pressure release boundary,



detonation depth (in bubble radii)	type of surface eruption
> 40	total containment
25 – 40	upwelling
7 – 25	mounds
4 – 7	mounds developing into plumes
1 – 4	ring of plumes
0.2 – 1	column with central jet
< 0.2	column with smoke crown

Figure 4. ***Left:*** *photo sequence of the surface eruption from a 4.7-kg explosion at a 10-m depth, taken off San Diego, California. The white froth on the surface is a cavitation layer generated by the intense pressures, and water erupting out of the layer is due to the bubble pulse series.* ***Right:*** *accompanying table (Mellor, 1986) predicting the surface expression for any sized explosion based on the detonation depth relative to the radius of its gas bubble. Photo from 2018 LMR Field Team.*

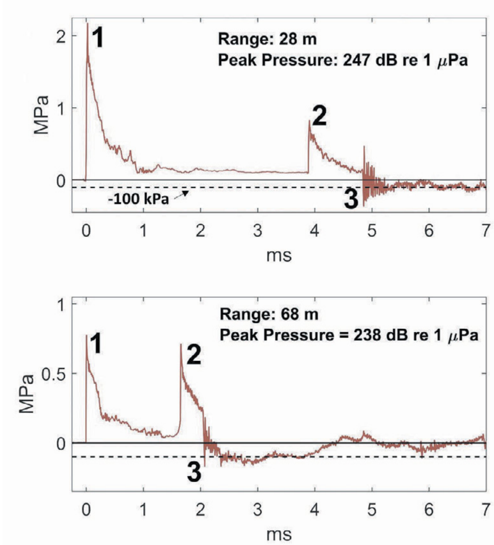
cancels the incident energy of the shockwave, producing a reflected echo that is a negative copy of the shockwave. As discussed with respect to **Figure 4**, there is a limit as to how large the negative peak pressures can be because cavitation sets in when pressure drops below the atmospheric pressure.

Reflections from the seafloor depend on the sediment composition and, importantly, the angle at which the shockwave reflects from the seafloor. At steep angles of incidence (i.e., near vertical), only a fraction of the energy is reflected, thereby reducing the amplitude from scaled range predications. At shallow reflection angles, particularly angles less than the critical angle, where this angle is defined as $\cos^{-1}(c_w/c_b)$, where c_w and c_b are seawater and seabed sound speeds, respectively, the reflected amplitude is much higher.

These effects are illustrated in **Figure 5** using pressure waveform data measured at 28 m and 68 m from an explosive source in waters of approximately 20 m in depth. The data originate from a study (Dahl et al., 2020) examining the effects of underwater explosions on fish (see ***Conserving Marine Life***). A 7-ms period for each graph contains the arrival of the primary shockwave (**Figure 5**, *number 1*) and a reflection from the sea surface (**Figure 5**, *number 2*) and seafloor (**Figure 5**, *number 3*). Well beyond this period (not shown), the waveforms contain the arrival of the first, second, and, in some cases, a third bubble pulse. These are observed at successive delays of about 250 ms, as predicted for an explosive charge at this depth (about 10 m) and equivalent weight of 4.7 kg of TNT (see **Figure 4**).

At a range of 28 m (**Figure 5**, *top*), the maximum observed peak pressure of the shockwave is 247 dB re 1 µPa (**Figure 5**, *number 1*), which is well predicted by the scaled range theory given the weight of explosive charge. The bottom reflection (**Figure 5**, *number 2*) arrives about 4 ms later, and its amplitude is reduced by about 40%. The reflection angle is about 35°, which is greater than the critical angle for this seabed, explaining the significant reduction in amplitude. Following this arrival (approximately 1 ms later), the surface-reflected path (**Figure 5**, *number 3*) arrives that causes an abrupt reduction in pressure. The

Figure 5. ***Top:*** *acoustic pressure (in MPa) versus time measured at range of 28 m from the source. Key features of the times (**1, 2, 3**) correspond to the arrival of the direct path, bottom-reflected path, and sea surface-reflected path, respectively. The onset of cavitation from the sea surface is indicated by the highly oscillatory behavior of the sea surface-reflected path that averages approximately −100 kPa.* ***Solid and dotted lines:*** *0 kPa and −100 kPa reference lines, respectively.* ***Bottom:*** *same as above but measured at a range of 68 m. Adapted from Dahl et al., (2020), with permission of Acoustical Society of America. © 2020, Acoustical Society of America.*



sequence of sharp spikes at **Figure 5**, *number 3*, the first of which is negative, identifies the leading edge of the surface-reflected pulse before the onset of cavitation (Wentzell et al., 1969) during which the waveform reaches an approximate average value of about −100 kPa, indicative of cavitation.

At a range of 68.5 m (**Figure 5**, *bottom*), the maximum observed peak pressure is 238 dB re 1 μPa. The sequence of arrivals (**Figure 5**, *numbers 1-3*) is compressed owing to the longer range; **Figure 5**, *numbers 1-2*, is now closer in amplitude that might be anticipated given the grazing angle of ~18°, which is less than the critical angle. The surface echo (**Figure 5**, *number 3*) arrives about 0.5 ms after the bottom reflection (**Figure 5**, *number 2*) and represents an excellent example of the cavitation surface cutoff effect, and, in this case, the expected cavitation amplitude of about −100 kPa is more easily seen.

Measuring Sediment Properties

The shockwave of a SUS charge provides an effective signal to study the structure of the seabed and its stratigraphy, the layers of distinct sediment formed over millennia. The stratigraphy of a continental shelf contains valuable information relating to the geological processes and climatic history. SUS charges are powerful enough to propagate sound through kilometers of sediment, echo off bedrock below and back into the water column. Stratigraphy can be interpreted from the echoes, and geoacoustic parameters (density, sound speed, and attenuation) are inverted to identify layers of different media.

One recent example of the use of a SUS charge is in the US Office of Naval Research's Seabed Characterization Experiment (SBCEX), an ongoing series of field experiments focused on a large patch of seabed with a thick layer of mud, roughly 100 km south of Martha's Vineyard, Massachusetts. Marine mud has a unique geoacoustic property that renders it almost acoustically transparent except at low angles (Ballard and Lee, 2017). Importantly, the broadband shockwave from an SUS charge provides the necessary bandwidth to identify the layering structure within the mud, layers that have been deposited over thousands of years spanning multiple ice ages.

Figure 6 shows a zoomed-in view of the shockwave from an Mk64 (**Figure 6**, *gray line*) and its low-angle bottom reflection from the muddy seabed reflection (**Figure 6**, *black line*). Note how the bottom reflection appears modulated at a particular frequency (its period [T] is annotated in **Figure 6**). This modulation is attributed to the trapping of specific frequencies in a low-speed sound channel formed in the upper layers of the muddy seabed (Dall'Osto and Tang, 2022). Inversions of SUS charge data like this, taken along with the stratigraphy as determined by prior seismic surveys of the mud patch, have identified the spatial dependence of the mud geoacoustic properties (Knobles et al., 2020), which provide insight into the physical processes that have led to this large deposit that supports a thriving lobster fishery.

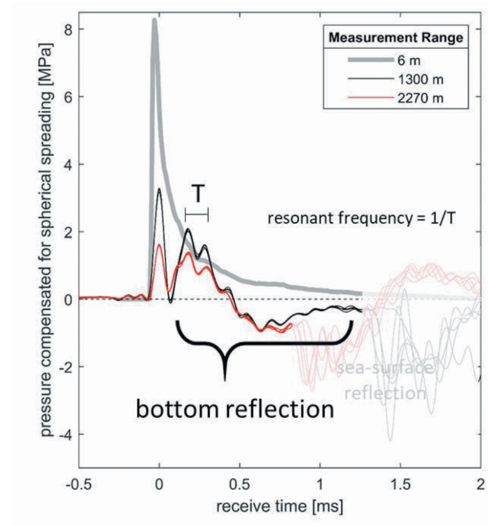


Figure 6. *A zoomed-in view of the shockwave from a Mk64 SUS shockwave (**gray line**), and the waveform recorded 1.1 m above the seafloor at a range 1.30 km from the explosion (**black line**) and at 2.27 km (**red line**). The signal levels have been corrected by the spherical spreading (i.e., multiplied by the respective range). In the bottom-reflected signal, the sediment layering imparts a modulation, annotated by its characteristic timescale (T). Adapted from Dall'Osto and Tang (2022).*

Conserving Marine Life

Underwater explosions are occasionally necessary for activities such as demolishing derelict oil rigs or wind farm pilings, marine construction, and military training. The great body of work developed to understand sound propagation from SUS charges has created the predictive measures that apply to nearly all explosions. These relationships even apply to the charges used to protect fish stocks from marine mammals, called "seal bombs"

(Wiggins et al., 2021) that are small waterproof firecrackers used, for example, to scare away sea lions looking for an easy meal of salmon waiting to jump through the fish ladder on a dammed river.

The use of underwater explosions, however, requires a careful consideration about their potential effects on marine life. Much like the protocols for using large explosives in demolition and mining, a safety perimeter around the detonation site is monitored to minimize impact on marine life.

For example, the US Navy at-sea training activities involving underwater explosive charges, the use of which must comply with a suite of US federal environmental laws and regulations to protect marine life. However, almost nothing is known about the potential effects of explosions on fishes (nor on marine invertebrates). Thus, two of the authors (Dall'Osto and Dahl along with *Acoustics Today* editor Arthur Popper) have been involved in a project to conduct field-based experiments on the effects of underwater explosions on fishes. The goal is to examine explosive effects on fish species with differing anatomical characteristics (e.g., swim bladder morphology) and size at varied water depths and distances from the source. Such data are needed to develop guidelines and threshold criteria for the effects on fish resulting from exposure to underwater explosives. The results will help predict potential effects that may occur during Navy training activities.

Among the several acoustic measures, peak sound pressure expressed in decibels has emerged as an important a key predictor of severe internal tissue injury as result of exposure to an underwater explosion (Dahl et al., 2020; Jenkins et al., 2022; Smith et al., 2022). Scaled range clearly helps to predict the distance animals need to be away from a particular explosive, although figuring out how many are too close is not always easy to determine for submerged animals.

Underwater Explosions and the Future of Marine Research

Early underwater acoustic research relied on underwater explosions as sources of sound. The unique high-source level and broadband nature (covering both low and high frequencies) of underwater explosions are invaluable for current research efforts. The existing stockpile of SUS charges still enables research, from probing the earth's structure deep under the oceans to rapidly characterizing the ocean's temperature distribution to identify the anomalies that fuel tropical storms. Balancing what we know about the danger from underwater explosions, including the ranges required to minimize their impact, small SUS charges can be used responsibly to provide answers to some very difficult questions.

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Zebrafish as a Key to Unlocking Human Genetic Diseases of Hearing

Erin Jimenez and Ashwin A. Bhandiwad

Introduction

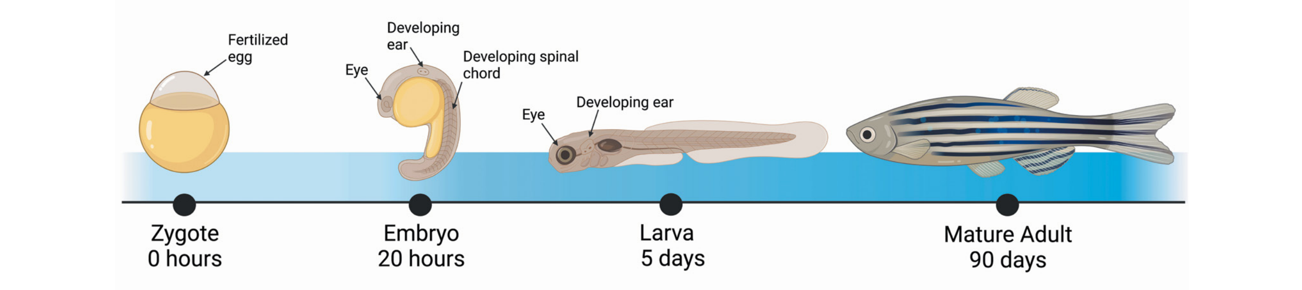
Hearing loss is a major cause of a disability affecting approximately 5% of the world's population and significantly decreases the quality of life (Leek and Molis, 2012). Although most hearing loss cases are caused by aging or noise exposure, congenital deafness affects 1 in 1,000 children (Toffler et al., 2015). Thus, a major motivation in hearing research is to understand how genes and the environment interact to affect auditory system development and function in hearing individuals and how the system fails in congenital and age-related diseases of hearing. If the system fails, are there any tools to reverse the process and restore hearing?

One of the most important tools for understanding the genetic causes of disease and potential avenues for treatment is genome sequencing. When the human genome was first sequenced in 2001, it cost an estimated $300 million and required coordination between 20 institutions across 6 countries. Today, the same task can be accomplished by a single research group for approximately $1,000 (Wetterstrand, 2013). Importantly, advances in computational power and analytical tools have generated large datasets of patient populations that have identified more than 110 deafness-related genes (Toffler et al., 2015). However, to bridge the gap between gene discovery and understanding how those genes influence hearing, we need a biological system with a similar genome to that of humans but that allows rapid experimentation with as little invasive surgery as possible.

Introducing Zebrafish as a Genetic Model

The study of zebrafish (*Danio rerio*), a freshwater minnow from south and southeast Asia, fills that gap and provides a biological system that allows us to model the genetics of human deafness and understand the mechanisms governing hearing. Zebrafish have become ideal organisms for studying genetics, development, and regeneration. This is because zebrafish share more than 70% of their DNA with humans. Thus, genetic discoveries in zebrafish are readily translatable to help study and understand human disorders such as hearing loss.

Figure 1. *Schematic of zebrafish life stages. Zebrafish exhibit rapid development with optical clarity and a functional auditory system within 5 days postfertilization. Stages (**left to right**): zygote (fertilized egg) contains a single cell; embryo (20 hours postfertilization) is transparent and has developing eyes, ears, and spinal cord; larva (5 days postfertilization) is free swimming with fully functional sensory systems; and adult (90 days postfertilization) is sexually mature but has pigment in characteristic stripes and is no longer transparent. **Arrows** point to relevant developing organs. Distance between points is not to scale. Image created with BioRender.com.*



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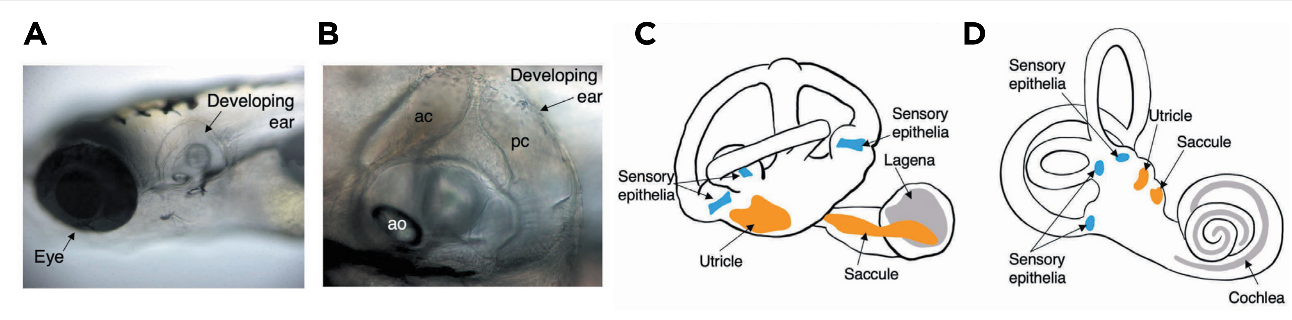


Figure 2. *The zebrafish hearing organ.* ***A:*** *lateral view of the head of a 10-day-old zebrafish with the inner ear. Arrows point to the eye and inner ear.* ***B:*** *close-up of zebrafish ear. Major structures of the developing inner ear are the anterior canal (ac), posterior canal (pc), and the anterior otolith (ao).* ***C:*** *schematic representation of the adult zebrafish inner ear showing three looped canals and associated sensory epithelia (**blue**) and the utricle (**orange**), saccule (**orange**), and lagena (**gray**) that have overlapping hearing and balance functions. Sensory epithelia are associated with the anterior and posterior canals and are involved in balance.* ***D:*** *schematic representation of the human inner ear showing the canals and associated epithelia and the major organs of hearing and balance: utricle (**orange**), saccule (**orange**), and cochlea (**gray**). The cochlea is the main structure for hearing and is closely related to the zebrafish lagena.*

Zebrafish, besides sharing much of the human genome, have other unique characteristics that make them ideal model systems. For example, they produce hundreds of transparent eggs at a time, and these develop into an adult within 90 days, allowing studies of heritability across multiple generations within very short time periods (**Figure 1**). Moreover, zebrafish larvae are nearly transparent in the first week of development, providing visual access to the entire organism without the need for invasive surgery (**Figure 2**). Together, these properties allow the study of how genes influence physiology and how genetic dysfunction causes disease in an intact animal.

Zebrafish are also important models for understanding many early symptoms of hearing loss, including perceptual issues such as the loss of sound identification and localization in noisy environments. In particular, because auditory neural pathways of zebrafish are like those in humans, zebrafish studies can help understand the genetic basis of hearing diseases and identify the neural pathways that are perturbed during hearing loss.

In this article, we discuss how studies of zebrafish, coupled with the recent advances in molecular biology and genetics, have given insights and developed tools for understanding the mechanisms of hearing. We discuss how genetic manipulations in zebrafish can allow us to turn genes on and off to understand their mechanisms of action in the auditory system. We show how zebrafish mutants with nonfunctioning genes have been used to model human hearing diseases. Finally, we discuss how the remarkable regenerative ability of zebrafish is revealing new molecular pathways to restore hearing function after damage to the hearing organ.

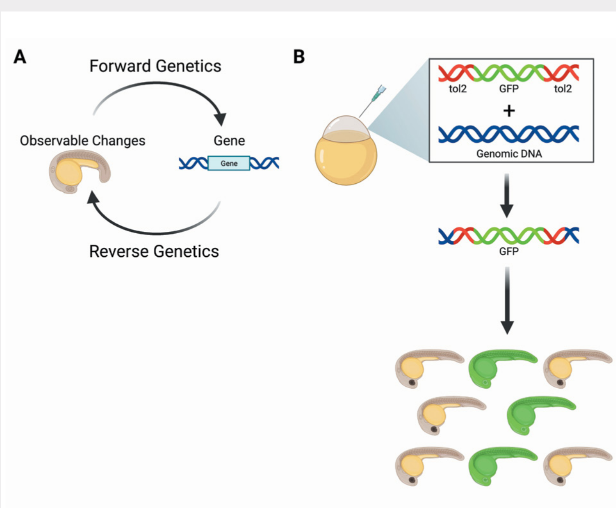
The Genetic Toolkit in Zebrafish

Early genetic experiments in zebrafish were conducted in the form of genetic screens, which generated large numbers of mutants (i.e., animals with characteristic biological changes caused by DNA alteration) by making random changes to the genome. The largest group of mutants was identified by a multi-institute consortium using a strategy called forward genetic screening (Nicolson et al., 1998). Forward genetics is a search strategy that starts with observed differences in behavior or physiology in mutant animals, followed by genome sequencing to find the mutation that gave rise to the observed effect (**Figure 3A**). Early genetic screens identified mutants with defects in hearing and balance and disrupted behaviors like the acoustic startle response, where the animal engages in a distinctive rapid swim away from the direction of a loud sound. Subsequent work isolated the genes that were disrupted in these mutants to understand the molecular machinery of hearing.

In contrast to forward genetics, reverse genetic approaches disrupt the function of specific genes that are suspected to have a role in hearing, followed by observing behavioral and physiological changes linked with that disruption. The most powerful reverse genetic approach to date is CRISPR, a genome editing tool that enables precise genome editing by removing, adding, or changing sections of the DNA sequence. Completion of the zebrafish genome (Howe et al., 2013) in combination with CRISPR technology has democratized reverse genetics and has made it possible to edit the genome easily and efficiently. Researchers can now test any "candidate" gene implicated in hearing and look for disruptions in auditory system development and function in zebrafish. These recent advances present an opportunity to explore the molecular mechanisms involved in hearing and position the zebrafish as an advantageous model system for studying hearing disorders.

In addition to forward and reverse genetic approaches, researchers have also developed methods to insert whole genes into zebrafish, a process called transgenesis (**Figure 3B**). A major technological breakthrough occurred in 1999 when researchers in Japan discovered a gene called *tol2*, which allows viruslike parasites to insert their own genes into the fish genome. Researchers co-opted this gene to insert custom engineered genes into the zebrafish genome (**Figure 3B**) (Kawakami and Shima, 1999). This was a transformational finding that allowed researchers to manipulate and observe a gene's effects on biological function. For example, *tol2* has been used in mutant fish that lack a gene called *clarin1* that is implicated in human hereditary hearing loss and renders the fish deaf. Using *tol2*, it is possible to insert a functional copy of the human *clarin1* gene into the zebrafish genome and restore hearing (Gopal et al., 2019). Together with forward and reverse genetics, *tol2*-based transgenesis has become a powerful tool to interrogate the development and function of the auditory system in zebrafish.

Figure 3. *Schematic of genetic tools used in zebrafish.* ***A:*** *forward genetics starts with an observed change in the zebrafish and identifies the gene mutation that causes it. Reverse genetics approaches generate mutations in the DNA sequence of a gene of unknown function and observe the effect on development and function of the zebrafish.* ***B:*** *schematic of transgenesis* tol2. *Green fluorescent protein (GFP) DNA, flanked by* tol2, *is injected into a single cell zebrafish zygote. GFP is randomly integrated into the zebrafish genome. If integration is successful, the embryo fluoresces green. Image created with BioRender.com.*



How Do Fishes Detect Sounds?

Zebrafish larvae provide a unique window into understanding how the inner ear structures detect and process sounds. When they are five days old, zebrafish larvae are almost completely transparent and have a fully functional auditory system (**Figure 2**).

At the cellular level, zebrafish and human auditory systems are almost identical; both use specialized sensory cells called hair cells to convert sound into electrochemical signals. Hair cells are identified by flexible hairlike structures on their surface called stereocilia, which are linked with one another at their tips (**Figure 4A**). Sound exerts a mechanical force on stereocilia and causes them to bend, resulting in a strain on the tip links. Strain on the tip links opens molecular pores called mechanoelectrical transduction (MET) channels and causes an influx of electrical current into the hair cell.

The current influx into the top of the hair cell stereocilia tip links propagates to the bottom of the cell to a specialized structure called the "ribbon synapse," named for its ribbonlike shape in cross section. Each cell contains three to five synaptic ribbons (Obholzer et al., 2008), which form the interface between hair cells and neurons that send information to the brain. Ribbon synapses act as a storage unit for large amounts of chemical signaling molecules and as a "conveyor belt" that releases stores of signaling molecules to activate neurons following cur-

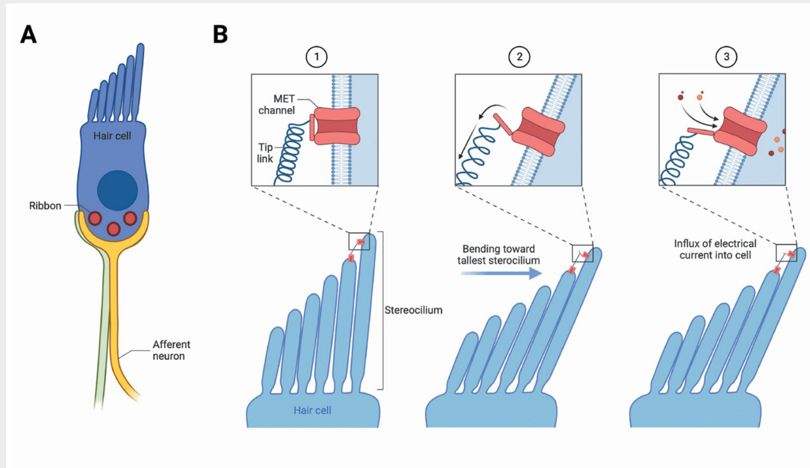


Figure 4. *Schematic of the hair cell.* ***A:*** *schematic of hair cell (**purple**) and auditory neuron (**yellow**) connected via ribbon synapses (**red**).* ***B:*** *schematic of mechanotransduction through hair cell tip links. Stereocilia are connected via tip links: (**1**) mechanotransduction channel (MET; **orange**) attached to a tip link (**blue**); (**2**) sound waves cause the cell bundle to "bend." When the bundle bends toward the tallest stereocilia, it creates a strain on the tip links and opens the MET channel; and (**3**) an open MET channel causes an influx of positively charged ions, resulting in an inward current. Image created with BioRender.com.*

rent influx. The mutation of genes associated with the ribbon synapse or chronic exposure to loud noise causes disruption and, in the extreme, detachment of ribbons from the hair cell-neuron interface. This process leads to auditory synaptopathy, a form of sensorineural hearing loss (Kindt and Sheets, 2018).

How Do Genes Regulate Mechanotransduction in Hair Cells?

Hair cells must transduce sounds with speed and precision, and they accomplish this through the interplay between the ribbon synapse and the MET channel **(Figure 4B)**. Because many of the genes that are implicated in hearing loss are associated with the tip links and the MET channel, this region within the hair cells has been a focus of study. Substantial evidence implicates two proteins, transmembrane-like channels (TMCs) 1 and 2 (TMC1 and TMC2, respectively), as crucial components of the MET channel (Pan et al., 2018). These proteins can be conceptualized as gates, with parts on the inside and outside of the cell. When multiple gates come together, they form a ring that allows positively charged ions to pass through. In zebrafish and humans, TMC mutations cause deafness and recent estimates suggest that TMC mutations are responsible for 3-8% of human hereditary hearing loss cases (Nist-Lund et al., 2019).

TMC1 and TMC2 are made in the cell body, far away from the stereocilia tips. How are they transported to the stereocilia tips correctly to form the MET channel? The answer starts from a serendipitous observation in a group of zebrafish larvae that failed to perform reflexive auditory escape behaviors. Genetic analysis of these fish showed a mutation in the gene *tmie,* which is also implicated in heritable congenital deafness in humans (Gleason et al., 2009). When hair cell stereocilia are bent manually with a small glass probe in zebrafish *tmie* mutants, there is no resulting current. However, if a fully functional *tmie* gene is inserted in hair cells using the *tol2* system, auditory function is restored (Pacentine and Nicolson, 2019).

Functional *tmie* can also be fused to a green fluorescent protein (GFP) that allows visualization of *tmie* proteins within the hair cell and its movement. Similarly, TMC1 and TMC2 can be fused with GFP to show their movement from the cell body to the stereocilia. A combination of transgenic expression techniques and live imaging experiments show that TMC1 and TMC2 fail to move into the hair bundles in *tmie* mutants. Conversely, if there is too much *tmie*, there is an overabundance of TMC1 and TMC2 in the stereocilia tips. Therefore, *tmie* seems to be a critical player in targeting the pore-forming units of the MET channel to hair cell bundles.

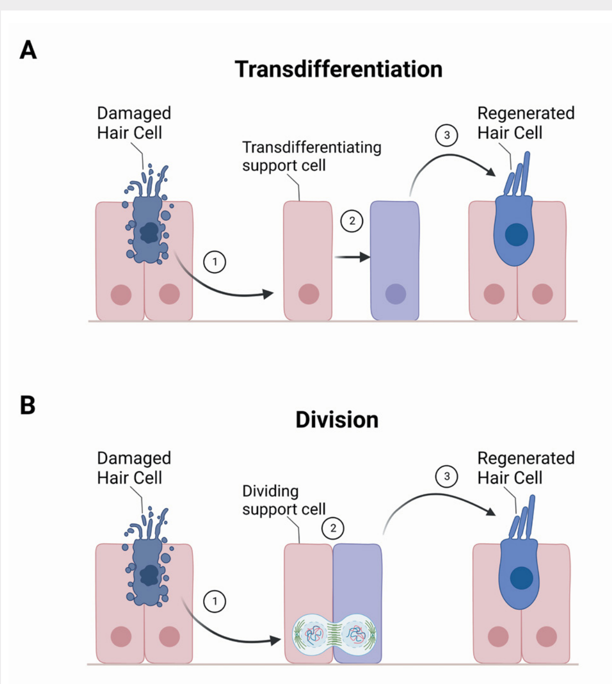
The transparency of the zebrafish inner ear has enabled the study of the ways mutations disrupt ribbons. The genes responsible for coding ribbon-specific proteins in zebrafish are *ribeye* and *ribeye b*, which make up two-thirds of the ribbon volume in hair cells (Chen et al., 2018). Nonfunctional *ribeye* genes coding ribbon proteins result in the reduction in size or loss of ribbons (Sheets et al., 2011) and failure of neurons to connect to and receive information from hair cells that subsequently cause hearing loss.

Hearing Regeneration and Zebrafish

Sensorineural hearing loss is the most common type of environmental exposure-related hearing loss and is caused by hair cell damage and death (Müller and Barr-Gillespie, 2015). In humans and other mammals, sensorineural hearing loss is permanent. However, zebrafish, like all fish species, continually produce hair cells throughout their lifetime or regenerate them in response to damage (Popper and Hoxter, 1984). New hair cells are born from neighboring cells called supporting cells. After damage and hair cell death, nearby supporting cells undergo molecular changes to either give birth to a new hair cell or directly transform from a supporting cell to a hair cell (**Figure 5**).

In contrast, supporting cells in mammals are thought to have lost this ability. One intriguing hypothesis for this loss of regeneration in mammals is that because hearing loss generally occurs after the reproductive age, there is a lack of evolutionary pressure on regenerative processes (Groves, 2010). However, mammalian support cells can be converted into hair cells in limited cases in the balance organ or in early development, suggesting that the molecular pathways are still present (White et al., 2006). Understanding how and why hair cells regenerate in zebrafish could therefore provide genetic and therapeutic targets to potentially initiate regeneration and reverse permanent hearing loss in humans.

Figure 5. *Hair cell regeneration in zebrafish.* ***A:*** *hair cell regeneration through direct transdifferentiation: (**1**) hair cell damage initiates transdifferentiation in supporting cells; (**2**) support cell is converted into a precursor hair cell (**purple**); and (**3**) precursor cells generate structures to become a new hair cell (**blue**).* ***B:*** *hair cell regeneration through division: (**1**) hair cell damage causes the support cell to divide into two; (**2**) newly formed support cell becomes a hair cell precursor (**purple**); and (**3**) it matures into a regenerated hair cell (**blue**). Image created with BioRender.com.*



Lateral Line Hair Cell Regeneration Is Experimentally Induced by Toxic Drugs

To find genes that stimulate hair cell regeneration, researchers have extensively studied the zebrafish lateral line, a distributed mechanosensory organ on the skin surface that detects water flow around the animal. The lateral line consists of morphological units called neuromasts, which are flower-shaped arrangements of the same sensory hair cells as in the ear, surrounded by supporting cells (Chagnaud and Coombs, 2013). Because lateral line hair cells are located on the skin surface, they are easy to visualize using fluorescent chemical dyes that enter hair cells only through a functional MET channel (Owens et al., 2008). This feature allows easy access with drugs and rapid testing of candidate genetic and therapeutic targets to assess regeneration.

Although hair cells are damaged by loud noise, it is more common and easier to induce damage using drugs such as neomycin and copper sulfate (Mackenzie and Raible, 2012). Like vital dyes, drugs can enter hair cells through MET channels. New genetic tools in zebrafish permit damaging adult zebrafish hair cells at will or through conditional targeted ablation. Conditional ablation allows precise control to damage hair cells without injuring the surrounding tissue throughout the adult inner ear and in the lateral line (Jimenez et al., 2021). Hair cell regeneration in both the lateral line and adult inner ear of zebrafish is rapid; hair cells grow back within 48 hours after initial damage. Rapid regeneration therefore enables capture of molecular responses that occur during regeneration; functional recovery is observed either behaviorally or through vital dye labeling.

Using Zebrafish to “Screen” for Hearing Regeneration Genes

Zebrafish studies make it possible to identify and catalog which genes control hair cell regeneration. Researchers identified three sequential waves of genetic responses on the regenerating zebrafish lateral line. First, an inflammatory response is initiated after hair cell damage; second, a regeneration-specific program is activated; and finally, the developmental program is reactivated. Collectively, the dynamic molecular responses that occur in the zebrafish lateral line enable supporting cells to reenter the cell cycle and replace lost hair cells (Varshney et al., 2016).

Zebrafish lateral line regeneration studies have resulted in the identification of many hearing regeneration candidates with overlapping functions in regeneration and normal hair cell development. Because mutations in these genes are unhelpful to study regeneration because they also disrupt the overall development of other organ systems in zebrafish, researchers are focused on identifying hearing regeneration-specific genes that may be used as targets for therapeutics in humans. To date, only a few zebrafish regeneration genes have been identified that impact hair cell regeneration without disrupting normal development of other organs, including the ear. Combining the zebrafish model with the genome editing tool CRISPR, researchers can now test every candidate gene that is likely important for hearing regeneration, inactivate them in zebrafish, and look for disruptions or improvements in zebrafish hearing regeneration.

A mechanistic understanding of how many genes interact with each other to control hair cell regeneration has been accomplished in the adult zebrafish inner ear. By surveying active genes in the animal and using machine learning to analyze interactions of those genes with each other and the environment, we have found that zebrafish hair cell regeneration relies on a network of genes called transcription factors that work together to turn genes on and off (Jimenez et al., 2022). During early hair cell regeneration, one class of transcription factors initiates the regeneration response in the nearby supporting cells by turning on genes that convert support cells into stem cell-like immature hair cells. Another set of transcription factors then activates genes that give rise to the proteins and cellular structures that fully transform support cells into functional hair cells (**Figure 5**). Using genomics on regenerating zebrafish inner ears, the field is beginning to understand the molecular switches that activate hair cell regeneration from the surrounding cells in the inner ear. This technique suggests that the same transcription factors can be switched on in the mammalian inner ear to stimulate a regenerative response in humans.

Functional Hearing Regeneration in Zebrafish

In addition, sensorineural hearing loss can occur due to damage to the neurons that carry signals to the brain. It turns out that zebrafish can also regenerate neurons after damage and show functional recovery, again distinguishing them from mammals. Recent experiments have revealed that neurons also promote hair cell regeneration because when lateral line neurons are damaged, hair cell regeneration is disrupted (Hardy et al., 2021). Moreover, experiments in transgenic zebrafish with fluorescent dye-labeled hair cells and neurons have shown that regenerating neurons find and bind hair cells to reform the same connection pattern (Faucherre et al., 2010). The study of cellular and molecular mechanisms of hair cell and neuron regeneration in zebrafish is still nascent but already shows promise in co-opting these mechanisms to repair and reverse sensorineural hearing loss in humans.

How Do Sound Signals Travel from the Ear to the Brain?

Simply detecting sound by hair cells is not enough; inner ear neurons are critical for conveying sound information to the brain, which integrates information to generate the perception of hearing. Auditory neuron function and development studies in zebrafish have revealed remarkable specificity and selectivity of which signals get transmitted to the brain. Because of the abundance of high-resolution images, transgenic manipulations, and computational image analyses in zebrafish, it is possible to label individual neurons in a zebrafish and aggregate across multiple zebrafish to generate a map of all neurons. Aggregation reveals biological principles of how neurons connect with the inner ear and with each other to convert sound into hearing.

One common biological principle is preferential neuron wiring between hair cells and primary auditory-processing brain regions. For example, preferential neuron wiring is used for transmitting information selectively to brain regions that control behavioral responses. In early development, zebrafish use their auditory system primarily for threat detection. A loud and unexpected noise signals a predator's attack, and zebrafish respond with an escape response away from the direction of the sound with a reaction time of 5 milliseconds, about 30 times faster than in humans (Burgess and Granato, 2007). Given the importance of this behavior for survival, sensory neurons that connect the auditory system to initiate this startle response develop earlier than sensory neurons used for other sensory modality pathways (Liu et al., 2022).

However, not all sounds are threats; performing escape behaviors to every sound is inefficient and energetically costly. Therefore, sensory signals need to be robust to the environmental context and filtered before reaching the escape-activating neurons. Sensory filtering is an important role of the brain; failure to filter irrelevant signals is a symptom of disparate neurological conditions from tinnitus to schizophrenia (Swerdlow et al., 2001). Because zebrafish and humans use the same signaling molecules for sensory signal filtering, zebrafish have also become an important animal model for understanding the genetics of schizophrenia and for developing new antipsychotic drugs (Langova et al., 2020).

How does the inner ear filter auditory information to prevent unnecessary escape responses? Simple and selective neuronal wiring also plays an important role in filtering out irrelevant sounds. In the escape system, auditory neurons that initiate the escape response also send information to regulatory neurons within the escape system. When the animal hears a moderately loud noise, regulatory neurons are preferentially activated and prevent the initiation of subsequent escape responses. The effect of these neurons can be seen in zebrafish by expressing a protein called iGluSnFr (pronounced "I glue sniffer"), which increases brightness in the presence of activating signaling molecules. When iGluSnFr is used to label escape neurons, sudden loud sounds cause an increase in iGluSnFr brightness and indicate a strong activation of the escape-response neurons. However, if the animal hears a moderate sound preceding the loud sound, iGluSnFr brightness does not increase. This phenomenon, also known as prepulse inhibition in studies of other animals, is specific to signaling between the auditory and escape neurons, suggesting that regulatory neurons block auditory neuron signals to suppress escape neurons (Tabor et al., 2018). Neurons can not only relay directional and contextual information (e.g., predator alert) but can also signal to self-regulation systems. Zebrafish, therefore, allow us to precisely understand how neurons communicate with each other to accomplish complex processes and ultimately to understand diseases where those processes fail, such as tinnitus and schizophrenia.

Conclusions

The zebrafish is a powerful model organism for the study of human disease. This is particularly the case for the study of human hearing because zebrafish and humans share common features such as the auditory and vestibular organs that play roles in hearing and balance. Zebrafish as a model system has many advantages over mice, including the ability to generate many offspring, trace living cell types, observe mutants that mimic genetic mutations found in human hereditary hearing loss, and learn the regenerative instructions involved in hearing regeneration.

Advances in molecular biology and genome-sequencing technology combined with the power of the zebrafish have provided an opportunity to understand auditory function and explore human deafness. With zebrafish, it is now possible to validate and interrogate nearly every human hearing loss gene to understand their mechanisms in a vertebrate. Moreover, the available genetic tools and transparency of the zebrafish embryo make it possible to visualize the hair cells, auditory neurons, and brain regions that convert sound signals into the sense of hearing.

Death of hair cells in the human inner ear results in permanent impairments to hearing and deafness. However, the zebrafish can regenerate their hair cells, offering unprecedented opportunities to identify new strategies to stimulate hair cell regeneration in mammals. By using the highly regenerative zebrafish combined with revolutionary approaches in biology, we are beginning to understand the molecular mechanisms involved in hearing regeneration.

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Auditory Informational Masking

Gerald Kidd Jr. and Christopher Conroy

Informational Masking (or Why Car Horns Shouldn't Talk)

Early in the career of one of the authors (Kidd), he worked as a research assistant on a project devoted to improving the emergency warning signals in airplanes (Tobias and Kidd, 1979). Tobias and Kidd investigated the use of auditory displays that spoke messages like "this way out" or "move toward exit," thereby providing verbal spatial indicators of the exit location in addition to the usual visual displays directing passengers. In such a context, even under the hectic and noisy scenario being emulated (using Gaussian noise), spoken messages could plausibly have beneficial effects on performance by helping passengers exit an airplane in an emergency.

Extrapolating from that situation, one could imagine that replacing the typical sound of a car horn with audible speech conveying meaningful messages might provide a similarly informative signal that could improve driving performance. Typical car horns currently produce sounds that serve as immediately identifiable warnings (although multiple similar-sounding horns honking simultaneously can be quite confusing) and that may provide indicators of the physical location of surrounding vehicles but otherwise convey little additional meaning. Why not increase the information a car horn conveys by having it produce messages comprising intelligible speech? Imagine if horns could say "passing on left" or "braking" or "get out of my way, you turkey!"

However appealing this might seem on the surface, equipping all cars with talking horns and creating a "cocktail party problem" (i.e., the difficult problem of conversing in situations like noisy, crowded rooms; see reviews in Middlebrooks et al., 2017) on the highway, strikes the current authors as a very bad idea for reasons that go to the heart of the phenomenon referred to as "informational masking" (Pollack, 1975). Informational masking means interference in understanding a signal that cannot be accounted for simply by the spectrotemporal overlap of competing sounds. This is in contrast to "energetic masking" that *can* be accounted for by the spectrotemporal overlap of competing sounds (cf. Kidd and Colburn, 2017).

Indeed, energetic masking is what usually comes to mind when one thinks of auditory masking. It occurs when one sound physically overpowers another and renders it inaudible. In contrast, informational masking is a broad characterization applied to many diverse listening situations. It typically refers to situations where the information necessary to solve the task is available, but for various reasons (e.g., perceptual, cognitive, linguistic), the listener cannot solve the task. In the talking car horn example, too many simultaneous sources of information that must be parsed and evaluated, especially when uncertainty and/or the acoustic similarity of the sources is high, can have a detrimental effect on communication leading to errors that could be catastrophic in certain real-world situations. We have learned through studies of masking that identifying and interpreting the messages from concurrent, independent sources of sound can be a challenging task even when there is no special

Figure 1. *Illustration of "talking car horns" (**message bubbles**) in traffic while our driver listens to a podcast (**rectangle**).*

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information or urgency that is being conveyed. Processing more complicated messages can be taxing and may take resources away from other tasks, such as operating a moving vehicle. Some of the complexities of this imagined multitalker horn scenario are illustrated in cartoon fashion in **Figure 1**.

In **Figure 1**, our driver (listener) faces an extremely challenging task. They are trying to pay attention to a nontraffic acoustic source (the imaginary podcast *The Life of Bob*). Uncertainty is high because spoken messages could occur unexpectedly from different directions and each source must be parsed and interpreted as it occurs. Also, some proportion of the acoustic signals from different sources fall into the same frequency region(s) at the same time(s), obscuring whatever information the less intense sound conveys. This is also one way of describing energetic masking (e.g., a loud trash truck idles next to our driver's car and momentarily drowns out the podcast).

In a colloquial sense, the "information" conveyed by several talking car horns is much greater and more complex than if the sounds were simply car "honks," even though the number and level of the sound sources could be the same. All the sounds may be clearly audible and distinct (easily segregated) in either case, but the listener would have much greater difficulty navigating the sound field with the added burden of attending/ignoring/processing meaningful speech (i.e., understanding the messages of the talking horns and deciding on any actions that should be taken as a consequence). Such a complex task requires considerable mental processing that takes time and effort (e.g., Rennies et al., 2019).

There is also the fundamental problem that a sound source designated at one moment as an unwanted masker may suddenly become the desired target source requiring the refocusing of attention and, for speech, engaging the linguistic structures required to interpret the message. A basic function of audition is to constantly monitor the sound field even while focusing primarily on the current target source so that such source priority/designation shifts may occur. This means that we are always expending some of our available processing resources to evaluate (i.e., segregate, attend, remember, and, importantly, anticipate) the information from the various sources. The point is that multiple sources in a sound field producing complex messages concurrently pose a very significant challenge to a listener and tap into many levels of processing well beyond the acoustic overlap of the sounds or the associated competition for neural representation of the sounds in the auditory periphery. This is an example of auditory informational masking.

The Problem with Noise

Either unwanted car honks or the distracting verbal messages in the imaginary case illustrated in **Figure 1** could be considered "noise" if the goal of the listener was to only focus on the podcast and ignore everything else. More typically, some or all the sounds from the other cars would require some degree of processing, a portion of which might be obligatory for the task of safe driving.

The term noise has both scientific and everyday meanings. For that reason, unfortunately, there often is a great deal of imprecision in the way the term is used or how it is interpreted. Gaussian noise is a well-defined stochastic signal, whereas any type of unwanted or undesirable sound also qualifies as noise (e.g., American National Standard Institute, 2013). That definition depends, then, on the internal and changeable state of the listener. Thus, both Gaussian noise and the unwanted speech from another talker could be considered as noise, although either could also be the intended focus of attention under the appropriate circumstances. A classic illustration of this is the exchange between Sybil and Basil Fawlty in the episode "A Touch of Class" in the TV series *Fawlty Towers:* "Racket? That's Brahms! Brahms's *third* racket…" (BBC Productions, 1975), where "racket" is in the ear of the beholder.

In studies of auditory masking, the imprecise definition of noise often causes problems with the interpretation of experimental findings if all types of noise are considered the same because they qualify as "unwanted sounds." This means that the standard metric of signal-to-noise ratio may not be a reliable predictor of signal detection or recognition when considered across different types of noise.

Historically, perhaps because of the early development of the Gaussian noise generator and the predictable, repeatable masking such noise produces, the emphasis has been on energetic masking that has more or less served as the default masker for much of the perceptual and physiological work found in the literature. In fact, the difficulties and limitations caused by different types of unwanted sounds on the reception and understanding of a target sound vary dramatically and are based on many physical, perceptual, cognitive, and, for speech maskers, linguistic factors. For example, the speech from a masker talker may create less masking if it is spoken in a language that the listener does not understand than if it is spoken in the listener's primary language (e.g., Calandruccio et al., 2013) even if both signals are equally "unwanted." Or simply time reversing a speech masker (i.e., playing the waveform for each word in reverse so it is unintelligible but produces roughly the same energetic masking) can greatly reduce its effectiveness in masking an intelligible speech signal (Kidd et al., 2016). Indeed, it is the recognition of these important differences among various types of unwanted sounds that has, as much as anything, led to the subdivision of different classes of maskers into "energetic" and "informational" categories.

Additional Masking

A persistent problem in understanding the interference one speech source has on another for any task ranging from "simple" detection to comprehension is that the acoustic overlap between the two signals typically varies in different regions of the spectrum from moment to moment. This dynamic acoustic overlap and its counterpart in the internal neural representation in the listener makes the task of determining energetic masking for speech masking speech difficult. How, then, can we isolate and identify the different sources of masking in a speech mixture and, in particular, determine the influence of informational masking?

There have been many attempts over the years to find ways of separating energetic from informational masking in speech-on-speech situations (see Kidd and Colburn, 2017, for a review). **Figure 2** depicts a particularly successful approach, first reported by Brungart et al. (2006), that is called "ideal time-frequency segregation" (ITFS).

Figure 2 shows the spectrogram produced by a mixture of two different, concurrent words. One word was spoken by talker A while the other word was spoken by talker B. The relative intensities of the two words were plotted. Because these signals are known exactly, it is possible to calculate the relative intensities of each signal in each time-frequency (T-F) unit.

In **Figure 2**, the T-F units in which talker A are more intense than B are *red* (outlined with *boxes*) while the T-F units dominated by talker B are *blue*. If talker A is the target, the units that are blue are considered to be *energetically masked* by talker B because there is more energy from talker B than talker A in those units. If we remove all the blue units by signal processing, what remains are the "glimpses" of the target speech that the user must rely on for intelligibility. For a highly informational masker like an intelligible talker, removing the masker-dominated T-F units can have an enormous effect because it eliminates the informational masking that is present.

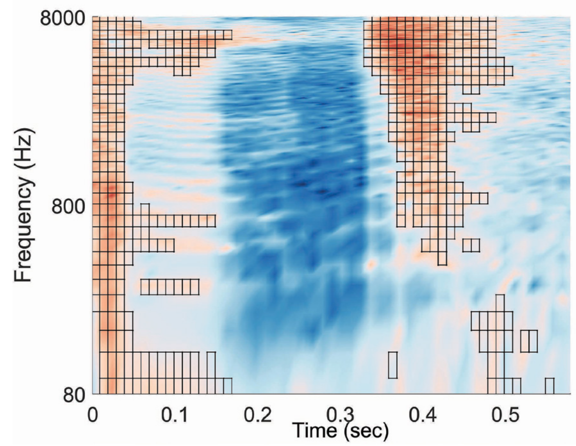


Figure 2. *A sound spectrogram of two words spoken concurrently by two different talkers. One word is in* ***red*** *and the other word is in* ***blue****. In time-frequency (T-F) regions where the two spectra overlap, the higher intensity signal is plotted. For the target (****red****) talker, the T-F units that are target dominated (****black rectangles****) are retained after ideal time-frequency segregation (ITFS) processing.*

What matters for intelligibility is the number of and/or the energy contained in the remaining glimpses (cf., Conroy et al., 2020), which depends on the level of the target relative to that of the masker (target-to-masker ratio [TMR]). It is possible to find a point of equal intelligibility (e.g., the proportion of energy that yields 50% correct performance), for target speech in noise or in speech maskers after ITFS processing. If one then takes the glimpsed stimuli derived from speech in noise and speech in speech that are equally intelligible and fills back in the full masker (i.e., restoring the unprocessed speech/noise mixture), the difference in intelligibility can be substantial (about 4 dB at threshold for noise compared with about 30 dB for speech; cf. Kidd et al., 2019), with much greater loss of intelligibility caused by

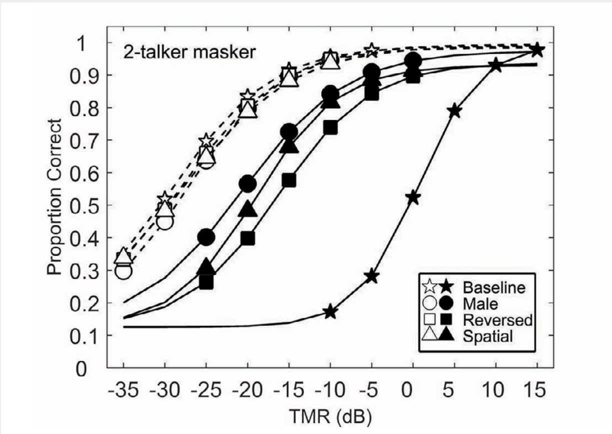


Figure 3. *Performance-level functions adapted from Kidd et al., (2016). The target is a female talker located at 0° azimuth.* ***Solid lines and symbols****, intelligibility for nonglimpsed speech;* ***dashed lines and open symbols****, for glimpsed speech (see text). The baseline condition (****stars****) comprised two same sex, colocated, natural speech maskers. The masker segregation conditions were male, time reversed, and spatially separated talkers. TMR, target-to-masker ratio. Reprinted from Kidd et al., (2016), with permission of Acoustical Society of America. © 2016, Acoustical Society of America.*

the speech masker than by the noise masker, even though the target information (i.e., the available glimpses of target speech) is about the same. This "additional masking" for the speech masker is informational masking. Examples of these sounds are provided in **Multimedia File 1** (see acousticstoday.org/kiddmedia). Some of the experimental findings supporting this point are shown in **Figure 3**.

Figure 3 shows the results of a speech-on-speech masking experiment in which several types of maskers were tested and ITFS processing was applied to each. The key point to focus on is the set of four psychometric functions on the left side of the graph (*dashed lines*). These psychometric functions show the intelligibility of the glimpsed target speech for each masker after removing the masker-dominated T-F units (i.e., after removing the informational masking) and are all about the same. However, the corresponding nonglimpsed maskers (**Figure 3**, *solid symbols*) produce markedly different amounts of informational masking depending on the particular target segregation cue available to the listener. This may be seen by comparing the TMR distance for glimpsed and nonglimpsed functions for the same masker types.

The take-away message here is that performance in speech-on-speech mixtures; specifically, those in which uncertainty and/or source similarity is high, is often dominated by informational rather than energetic masking. In realistic listening situations, many source segregation cues are available to help cause a release from informational masking. The ability to apply these various cues, which varies markedly across listeners, depends heavily on *context* and a priori *knowledge*.

Informational Masking and Detection Threshold

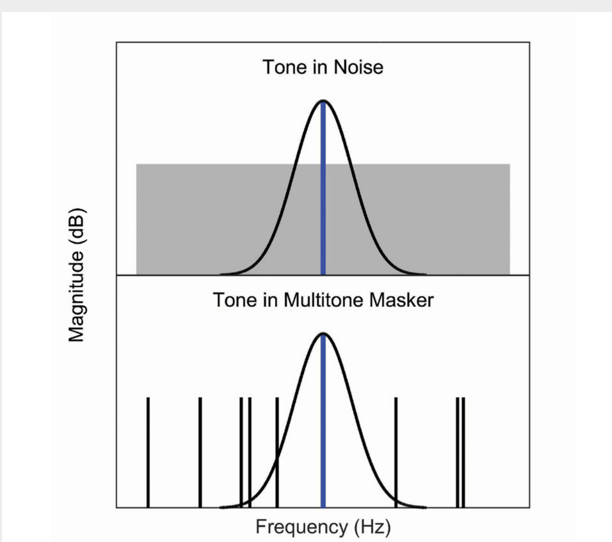
In the speech-on-speech masking experiment discussed in **Additional Masking** where all the signals are equal in level (i.e., 0 dB TMR equals a −3 dB signal-to-noise ratio for two masker talkers), there is enough information remaining after accounting for energetic masking (by ITFS) that the speech of the target talker would be nearly perfectly intelligible (see percent correct for glimpsed functions at 0 dB TMR in **Figure 3**). The interference the masker talker causes on the intelligibility of the target talker, then, is informational masking and is not due to a lack of audibility of the target speech. Thus, we say that the speech of both talkers is at *suprathreshold* levels. This raises the question, though, of what exactly is meant by detection threshold under informational masking?

A common theme in the interpretation of a masked detection threshold is that there is at least a rough correspondence between the physiological representation of the target signal and the behavioral performance on a psychophysical task. Framing this as a signal detection problem, the idea is that whatever distribution of physiological activity is relevant for solving the task, adding the signal shifts the distribution along the decision axis, resulting in better detection/discrimination performance (i.e., performance specified as the index of detectability [d′] improves as the distributions are separated; cf. Green and Swets, 1966). However, informational masking means that signals that presumably *should be* detectable based on the relevant underlying physiological distributions *are not*, as inferred from the behavioral performance of the observer. It should be noted, however, that demonstrations of the robust nature of the distributions of relevant physiological quantities for a target signal under informational masking conditions are difficult to obtain and the direct evidence for the relevant comparisons is limited.

Figure 4 illustrates how the energy from a masker falling in a hypothetical auditory filter measured psychophysically at a detection threshold for a pure-tone target is much less under informational masking than under energetic masking. Although the plots are illustrative and not drawn to scale, the evidence from the multitone masking literature (e.g., Durlach et al., 2005) suggests that, in some cases, detection thresholds may be more than 20 dB higher for equivalent masker energy in the signal's "critical band" under informational masking than under energetic masking (see Kidd et al., 2008, for a review).

For both cases, the spectra shown are for a single random sample of the masker; in an actual experiment, the noise varies from sample to sample as does the draw of tones in the multitone masker. An ideal observer (i.e., a model of performance in which decisions are based on selecting the most likely options; cf. Green and Swets, 1966) operating on the distribution of peripheral neural activity presumably would outperform the human observer considerably more for informational than for energetic masking conditions (e.g., Durlach et al., 2003). Thus, a paradox in defining informational masking for a detection threshold (and, by extension, some other tasks) is that the robustness of the neural representation of the target in the auditory periphery, yielding an equivalent psychophysical performance, presumably is much different under energetic and informational masking.

Figure 4. *A schematic illustration of a tone in noise detection task for two types of "noise."* ***Top:*** *the target tone (**blue line**) is masked by a broadband Gaussian noise (energetic masker; **gray rectangle**).* ***Bottom:*** *the target tone is masked by a random frequency (**black lines**) multitone masker (informational masker). A "critical band" filter is shown centered on the target frequency (**bell-shaped black curve** centered on **vertical blue line**).*



Suprathreshold Masking and the Cocktail Party Problem

Although informational masking has been shown to affect performance on many tasks ranging from detection through various types of suprathreshold discrimination and nonspeech pattern identification, it is the influence of informational masking on speech understanding that is most familiar and of the broadest general interest. Among the various factors that contribute to speech communication in multitalker listening situations, binaural analysis has perhaps received the greatest attention due in large part to the common takeaway message of the importance of spatial hearing from Cherry's (1953) seminal article defining the "cocktail party problem." As discussed in Kidd et al., (2008), Cherry (1953) also identified several other important factors in solving the cocktail party problem, notably source or message transition probabilities and presumably the understanding/exploitation of those probabilities in speech communication.

The preponderance of work on the benefits of binaural hearing for speech reception in noise has, in fact, examined masking conditions that were high in energetic masking or that did not attempt to separate energetic from informational factors. Historically, the "masking level difference" (MLD; Hirsh, 1948) and the "speech intelligibility level difference" (SILD; Licklider, 1948) for detecting a tone in Gaussian noise and for recognizing speech in Gaussian noise, respectively, have been advanced as compelling evidence for the important role of binaural analysis in improving speech recognition in noisy listening environments (cf. Green and Yost, 1975).

There is, however, an important distinction to be made between detecting or identifying speech in Gaussian noise and the same tasks for a speech signal under competition from concurrent talkers. In the former, high-energetic masking case, the phenomenon is an at- or near-threshold process limited in effect by a narrow dynamic range from chance-to-perfect performance, whereas in the latter, high-informational masking case,

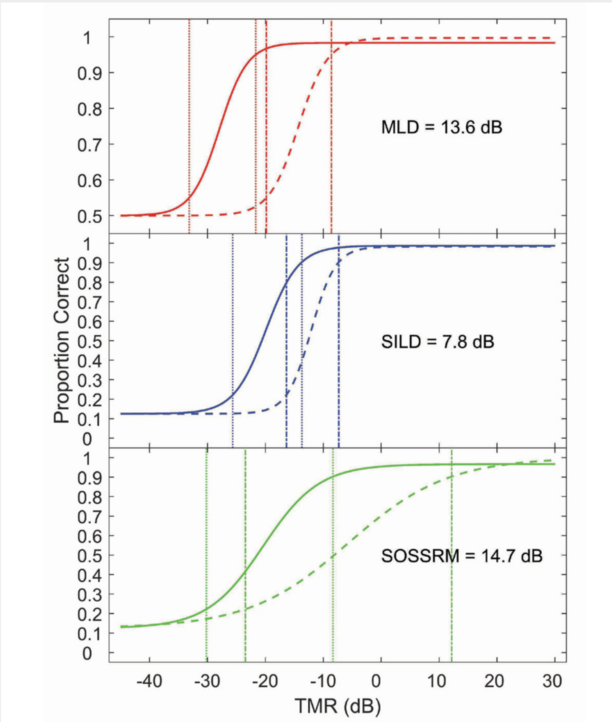


Figure 5. *Psychometric functions for three tasks.* ***Top:*** *homophasic (target and masker same in both ears;* ***dashed line****) and antiphasic (target π radians out of phase masker in phase) performance for detecting a tone in Gaussian noise (masking level difference [MLD];* ***solid line****).* ***Center:*** *same conditions for the task of speech intelligibility (speech intelligibility level difference [SILD]).* ***Bottom:*** *colocated (****dashed line****) and spatially separated (****solid line****) performance on a speech-on-speech masking task (SOSSRM).* ***Vertical lines:*** *points indicating 10% to 90% of the range of each function. The improvement in performance, release from masking, computed roughly at the middle of each function is indicated.*

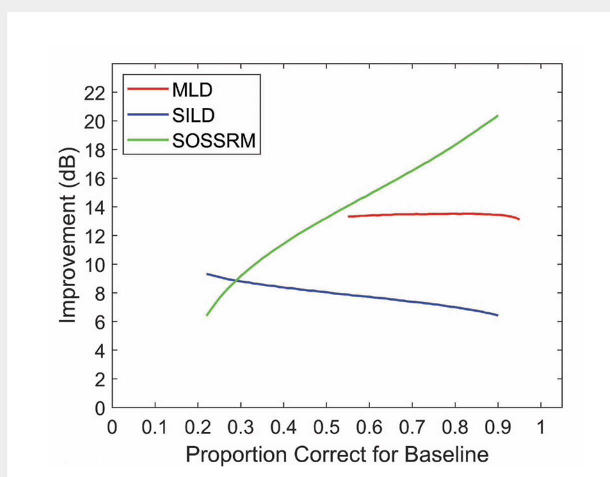
the phenomenon may be considered suprathreshold in nature and extends over a much wider range of levels above threshold. **Figure 5** illustrates this point.

Figure 5 shows the psychometric functions that illustrate the binaural advantages for three headphone-based tasks. **Figure 5**, *top and center*, demonstrates how binaural analysis provides a release from energetic masking (Gaussian noise masker) for detecting a pure tone (the MLD; **Figure 5**, *top*) and for speech intelligibility (the SILD; *center*). **Figure 5**, *bottom*, shows the release from informational masking through the spatial separation of sources (i.e., creating binaural differences at the ears via head-related transfer functions) for speech masking other speech (SOSSRM). **Figure 5**, *vertical lines*, indicate the *range* computed from 10% to 90% of each psychometric function.

In all cases, there is a significant separation between conditions where the waveforms are the same at the two ears ("diotic"; **Figure 5**, *dashed lines*) versus different at the ears ("dichotic"; **Figure 5**, *solid lines*). The improvement in performance, release from masking, computed roughly at the middle of each function is indicated. The slopes of the functions provide some indication of the mechanisms underlying performance. For the MLD, the slopes are parallel for the diotic and dichotic presentations, with function ranges of about 10 dB in each case. This is consistent with many past studies of the MLD (cf., Kidd et al., 1995). The SILDs are slightly less than the MLDs, and the slope of the dichotic function is shallower.

The conclusion is that, for these energetic maskers, the range between detecting a speech signal and fully understanding it is about 10-15 dB. Thus, the SILD operates near masked detection threshold. The functions for the speech maskers (SOSSRM) are much shallower than those for the SILD and extend over a broader range. The very shallow slope for the colocated condition reflects

Figure 6. *Release from masking for tone-in-noise detection (MLD;* ***red****), speech-intelligibility-in-noise (SILD;* ***blue****) and speech-on-speech masking (SOSSRM;* ***green****) calculated from the data plotted in* ***Figure 5****. The functions show release from masking as a function of the percent correct point on the reference (homophasic or colocated) psychometric function.*



the performance of some subjects who could segregate the sources by level and attend to the lower level talker (i.e., the target talker is intelligible at negative TMRs; cf. Byrne et al., 2022). These trends are shown in **Figure 6**.

When engaged in natural conversation, talkers typically raise the intensity of their voices to achieve high levels of intelligibility, usually requiring positive TMR values (cf. Weisser et al., 2021). It may be seen from **Figure 6** that the benefit of binaural/spatial cues increases as the intelligibility of the message is raised to comfortable conversational values. Because the long-term average speech spectrum peaks below 1 kHz and falls off above that value, the SILD is a mixture of the contributions of unmasking at different frequency regions at different TMRs. This means that the near-threshold binaural advantage for the SILD can be distributed over a wider range than occurs in any single frequency band (see discussion in Kidd et al., 1995). As energetic masking decreases (i.e., as the TMR increases), the relative influence of informational masking increases, as illustrated in **Figure 6** by the magnitude of the release from masking produced by the spatial separation of maskers. In other words, informational masking is primarily a suprathreshold phenomenon that dominates speech-on-speech masking across the range of TMRs typical of everyday speech communication.

Conclusions

Energetic masking is most likely a minor factor in cocktail party communication situations, with the greatest effect occurring within a few decibels of the detection threshold in any given frequency region. This conclusion is based on a consideration of the relative levels at which typical conversation takes place and an analysis of the glimpsed information available at those levels. However, it is probable that energetic masking interacts with informational masking in such situations to increase the communication difficulty (e.g., Best et al., 2020). Considering informational masking as what remains after accounting for energetic masking is a very broad definition and does not provide for the various, independent (to some degree) underlying physiological mechanisms and the subtleties of linguistic processing, especially under speech masking conditions.

Because of the high rate of word confusions found in some speech-masking tasks (e.g., Kidd et al., 2016) it is tempting to attribute informational masking in multitalker mixtures exclusively to misdirected attention. However, this too seems to be an oversimplification and difficult to support, in part because of the imprecision of the term "attention" (cf. Watson, 2005) as well as the existence of various other phenomena such as "linguistic informational masking" (e.g., Mepham et al., 2022), which argue against such a narrow interpretation. In the cocktail party problem, a listener must process the speech signal that has just arrived, drawing on memory and previously stored linguistic information while concurrently taking in new/ongoing information (see review in Kidd and Colburn, 2017). Uncertainty about the target speech along any of several dimensions undoubtedly imposes delays or even errors in accessing such information that could interfere with the processing of newly arriving sounds causing informational masking. There is also the very complex problem of actively disregarding unwanted sound sources while paradoxically monitoring them to a sufficient degree that the focus of attention may be redirected to them if circumstances warrant. Perhaps as important, though, is the ability of listeners to use recently arrived sounds to anticipate impending events; this may include leveraging expectation based on syntactic (e.g., Kidd et al., 2014) and semantic (e.g., Brouwer et al., 2012) probabilities. Although we have not discussed these issues in any detail in this article, both prediction and environmental monitoring are likely important in the context of informational masking.

Acknowledgments

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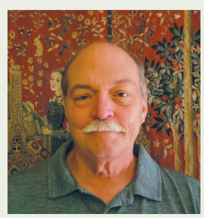

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Bionic Hearing: When Is It Time to Get a Cochlear Implant?

Nicole Nguyen, Larissa Curry, and Matthew J. Goupell

The Most Successful Restoration of Sensation

Cochlear implants (CIs) are the most successful sensory prosthetics available. These devices can provide or restore audibility to individuals with significant hearing loss. The trajectory with which CIs rose to fame is quite steep. In 1983, the Australian Broadcasting Corporation science program *Towards 2000* reported on a remarkable electronic device that could "provide a sense of sound to someone profoundly deaf or severely hard of hearing" (see bit.ly/3AdC8kf). Highlighted in the broadcast was the sixth person in the world ever to have such an implant, and much of the discussion focused on the seemingly "science fiction" nature of the technology.

Forty years later, CIs have been adopted widely and are changing the lives of adults and children worldwide. As technology has advanced, the indications for cochlear implantation have expanded over the years, resulting in better speech-understanding outcomes. Despite this, uptake rates globally are low among adults. The recently expanded coverage of CIs from the Centers for Medicare & Medicaid Services (see bit.ly/3OlBCqA) has made the procedure available to millions of additional hearing-impaired individuals. Still, it leaves many asking, "When is it time to get a cochlear implant"?

Hearing loss occurs for many reasons and comes in many forms. Some people acquire hearing loss at a young age for genetic reasons or because of life-saving medications that damage the inner ear. For others, exposure to loud sounds for an extended time damages hearing. The normal aging process includes hearing loss at high frequencies (Anderson et al., 2018). No matter the reason, hearing aids are usually an important first step in managing hearing loss. Increasing the amplitude or loudness of a signal through amplification helps regain access to sound. For some, however, hearing aids are not powerful enough to maintain both audibility and clarity because large amounts of amplification can distort the signal. When hearing aids are not helpful, a person can opt for a bionic auditory prosthesis to partially restore their hearing (Wilson, 2019). Approximately one million CIs are used worldwide across all ages (Zeng, 2022). Compared with other prostheses (e.g., for vision), CIs are the most successful sensory neural prosthesis and provide an average of 70-80% speech understanding in quiet situations.

When Is It Time to Get a Cochlear Implant?

Humans are social beings, and communication is critical to most people's daily lives. There are relatively easy communication environments, such as speaking one-to-one with another individual in a quiet place. There are also relatively difficult communication environments because we live in a noisy world with numerous sound sources and social interactions come at a rapid pace. For individuals with typical hearing, the brain can easily and almost effortlessly manage the cacophony of incoming sounds from different locations. In the field of hearing science, we call this situation "the cocktail party problem" (Middlebrooks et al., 2017). However, hearing loss makes communication much more challenging to nearly impossible in noisy environments.

Consider, for example, a large boisterous family meal. Perhaps you have noticed a parent, grandparent, or even yourself struggling to follow conversations in such a situation. In this case, our struggling patient has worn hearing aids for many years and is not as engaged as the rest of the group. The patient sits at the table smiling and laughing on cue but misses most of what is said. This type of environment is challenging for the patient; there are multiple talkers, fast-paced conversations, and various topics discussed at once. Over the years, the patient

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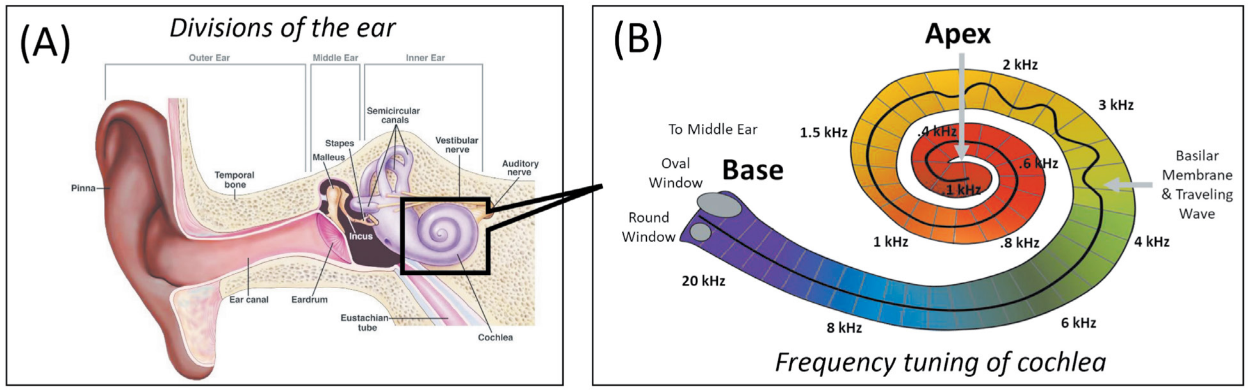


Figure 1. ***A:*** *the outer ear includes the pinna, temporal bone, and ear canal. The middle ear includes the eardrum and the three middle ear bones: the malleus, incus, and stapes. The inner ear includes the semicircular canals, Eustachian tube, cochlea, and vestibular and auditory nerves. See bit.ly/3iV0dXe.* ***B:*** *the frequency tuning of the cochlea along its length.* ***Black line:*** *basilar membrane that vibrates in a frequency-specific manner. See text for details.*

has learned to ensure that they can see the speaker's face, allowing the use of visual cues to help identify speech sounds. Unless someone is directly facing the patient while speaking, the patient must concentrate to stay engaged in conversations. It is difficult to align what the patient thinks was heard with what makes sense based on context. The conversation is exhausting, brought about by the large cognitive load and "listening effort" [defined as "the deliberate allocation of mental resources to overcome obstacles in goal pursuit" for listening tasks (Pichora-Fuller et al., 2016, p. S10)]. Furthermore, the patient has difficulty remembering the conversations. As the dinner unfolds, the patient tends to withdraw from conversations and social interactions, resulting in isolation, and, ultimately, our patient is at risk for depression, anxiety, and cognitive decline.

Our patient has already taken the first step in managing most types of hearing loss by utilizing hearing aids. However, despite the use of well-fit devices, the patient continues to have difficulties understanding speech. As the patient's hearing loss progresses, this technology no longer provides sufficient benefit. Understanding the patient's hearing loss helps explain why.

How We Hear

Auditory Structures and Functions

The outer ear captures sound waves, and that acoustic energy typically propagates through the middle and inner ears through a series of transformations (**Figure 1A**). As the mechanical vibrations of the middle ear reach the inner ear/cochlea, the energy causes a vibration of the fluid and the basilar membrane. This membrane is springy and light at the base near the middle ear, and heavy and floppy at the other end at the apex of the cochlea. This causes the membrane to vibrate in a frequency-specific manner (**Figure 1B**), with high frequencies at the base and low frequencies near the apex. Because this membrane vibrates in a frequency-specific manner, the hair cells, which are responsible for converting this mechanical vibration to a neural code, follow the same frequency organization. This frequency organization is represented throughout the auditory system, up to the auditory cortex. Therefore, we have a system that takes a sound, converts that sound through various systems (mechanical → hydraulic → mechanical → electrical), and provides information to the brain in a frequency-specific manner.

Masking

Understanding that single-frequency components are propagated by different neurons helps understand some of the difficulties with speech understanding in noise and the cocktail party problem. Sound energy from different talkers overlaps in frequency. Some voices may cover others, which also happens in a frequency-organized manner. Thus, sound energy at specific frequencies can cause the "masking" of other frequencies, meaning the loudest speech sounds at a particular frequency will obscure the encoding of the softer sounds at those same frequencies.

Segregation of Multiple Sounds

Luckily, all is not lost. Even when masking occurs between sounds, the brain can extract patterns in the information to reassemble the different sound sources such that they are perceived as separate sounds. These patterns include the frequency information. If the components are close together in frequency or are harmonically related, they tend to be grouped together. It also includes temporal information. If the components start or stop at the same time or are modulated in amplitude and frequency similarly over time, they tend to be grouped together. Finally, it also includes spatial information. If components originate from the same location in space, they tend to be grouped together (Shinn-Cunningham et al., 2017). Amazingly, humans and animals can use all these frequency, temporal, and spatial patterns to extract the individual sound sources from complex auditory scenes to solve that cocktail party problem! For someone with typical hearing, it is fairly easy to have a conversation during a family dinner with many people talking simultaneously.

Changes That Occur with Hearing Loss

Although the human auditory system functions amazingly when in pristine condition, things can go awry. Hearing loss occurs because of damage to the outer, middle, or inner ear or even to the auditory nerve and central auditory-processing structures. The most common type of hearing loss results from damage to the hair cells (Le Prell, 2022), which are activated by the physical vibration of the membrane in the inner ear (**Figure 1B**). Each hair cell encodes or amplifies the incoming sound, so hair cell loss diminishes access to sound or audibility. Addressing audibility may seem straightforward because devices like hearing aids can amplify frequencies where there is hearing loss. However, amplification comes at a cost because the frequencies become smeared, which causes problems like an *increase in masking* from other sounds. The loss of information and the distortions lead to additional problems like poorer speech-understanding abilities, particularly in the presence of other sounds. Thus, when someone goes to the audiologist to address their hearing loss, hearing assistive devices may restore access to speech sounds, but there will be ongoing problems with masking and impaired sound source segregation, making it difficult to communicate at those large family dinners, restaurants, and noisy cocktail parties.

Functional Implications of Hearing Loss: The Speech Banana

The degree and configuration of hearing loss can result in different functional outcomes. One way to visualize the functional impacts of a particular hearing loss is with the Audiogram of Familiar Sounds (**Figure 2A**) (Northern and Downs, 2002). This graphic has everyday sounds (birds chirping, leaves rustling, a motorcycle) plotted according to frequency and hearing level. Along with these everyday sounds, the sounds of spoken English are represented via a shaded region (**Figure 2A**, *yellow area*), referred to as the "speech banana." The speech banana indicates where sounds of a spoken language occur, in terms of frequency and level, when someone is talking at a normal conversational level (i.e., 50-55 dB hearing level, or the level above the quietest you can hear a particular sound). For example, many English vowels have most of their energy located at low frequencies, around 250-500 Hz. A /sh/ sound has most of its energy located at high frequencies (>2,000 Hz). The location of the speech sounds varies based on which spoken language is represented. Some languages have many more sounds than English (e.g., Thai), whereas others shift more toward the higher frequencies (e.g., Mandarin). When an individual's audiogram (their hearing sensitivity at each frequency) overlays the Audiogram of Familiar Sounds, sound above the marked thresholds is estimated to be inaudible to that individual. If someone has hearing loss at a particular frequency, they will lose access to that speech sound without amplification. Hearing loss that is concentrated in the high frequencies, for example, would not convey those frequencies to the auditory nerve, thus effectively filtering out higher frequency consonant sounds, like "t" or "p" that are important for discriminating between words (e.g., "cat" or "cap"?). This results in a more effortful conversation for that individual because they must rely more on contextual cues and speech reading to reconcile the confusion (see more in **Rehabilitation: Maximizing Performance Takes Work**).

Possible Coinciding Cognitive Changes

Not only can hearing loss impact one's ability to understand speech, but it is also correlated with cognitive impairment, although the reasons why the correlation occurs are still unclear. People with hearing impairment

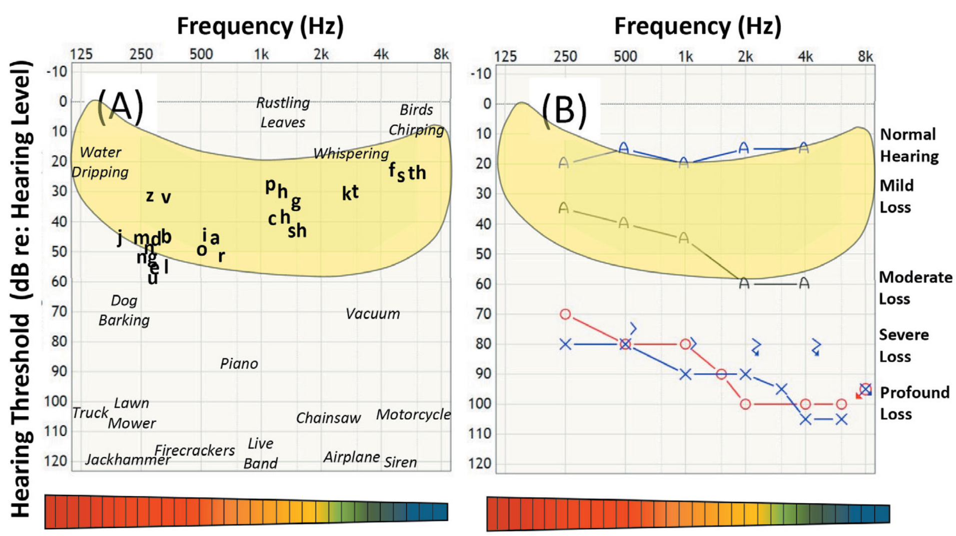


Figure 2. ***A:*** *example chart of the hearing level and frequency of everyday sounds. Because sound energy is distributed across a wide frequency range, the frequency is shown as a single value representing where most of the energy lies for that sound.* ***Yellow area:*** *location of speech sounds (speech banana) in English. See text for details.* ***B:*** *an audiogram, the chart on which audiologists denote how well a person hears (i.e., hearing sensitivity) as a function of frequency, with the speech banana from* ***A*** *superimposed. An individual's thresholds for sound detection are plotted as a function of the pure-tone frequencies tested. Thresholds near the top, at 0-15 dB hearing level (HL), are within normal limits. Compare this with a person with hearing loss where the* ***red Os*** *denote hearing thresholds in the right ear and* ***blue Xs*** *denote those in the left ear. The* ***black As*** *indicate access to sound through the hearing aids. These thresholds are better than the individual's natural hearing, reflecting improvements in audibility with the use of hearing aids; however, sound detection is still not within normal limits. The* ***blue As*** *denote detection thresholds with a CI, essentially within the normal limits of hearing.* ***Color bar:*** *how the audiogram follows the same frequency organization of the cochlea/basilar membrane in* ***Figure 1B****. See text for details.*

appear to develop Alzheimer's disease at higher rates compared with people with typical hearing (Zheng et al., 2017).

Although the evidence linking hearing loss and cognitive decline is distressing, hearing loss appears to be the most modifiable midlife risk factor for dementia (Livingston et al., 2017). Intervention with hearing aids and CIs appears to slow these accelerated cognitive declines (Dawes, 2019). Hence, the early identification of hearing loss in patients and successful hearing rehabilitation can mitigate the negative effects of hearing loss on cognition.

How Hearing Aids and Cochlear Implants Function

When the cochlear hair cells are damaged, such as with sensorineural hearing loss, patients experience a loss of audibility and sometimes clarity. A patient whose hair cells are so damaged that the maximum stimulation with a hearing aid does not significantly improve speech understanding is likely a candidate for a CI.

An audiological evaluation assesses a patient's hearing regarding *audibility* and *clarity*. The audiogram includes a graph that depicts the type, degree, and configuration of the hearing loss (audibility) and information regarding speech-understanding abilities (clarity). Inspection of the audiogram in **Figure 2B** shows that the patient has symmetrical severe-to-profound sensorineural hearing loss, defined as having an audiometric pure-tone threshold greater than 70 dB hearing level when averaging the hearing levels in both ears across frequency. However, the audiogram only tells part of the story.

Arguably the clarity of the sound is just as important as the audibility. If our patient's speech understanding is poor, regardless of the level and audibility of the incoming signal, their perception is distorted. Although hearing aids are excellent for increasing volume, there is a limit to what the technology can do to address declines in clarity. Hearing aids can only provide small improvements in speech understanding with precise adjustments to the output frequency response. When we have these limitations in addressing hearing loss with amplification, a CI may be the more appropriate option.

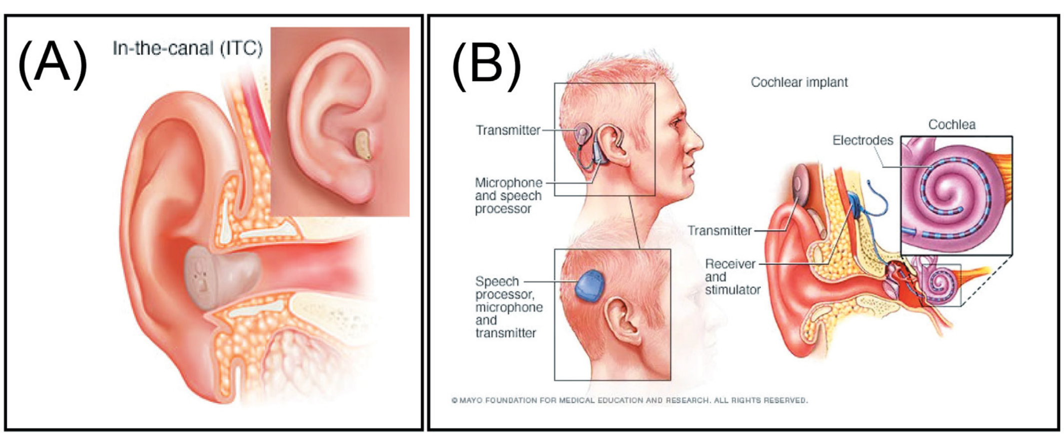
The Differences Between Hearing Aids and Cochlear Implants

There are many types of hearing aids, with one example shown in **Figure 3A**. Sound is collected by a microphone and sent to a microprocessor where the signal is amplified in a frequency-specific manner, prescribed according to a person's hearing loss. For example, if the person has a high-frequency hearing loss at 4,000-8,000 Hz, these frequencies are selectively amplified. The sound is then directed through the ear canal to vibrate the structures of the middle and inner ears (**Figure 1A**) where they encode the sound as best they can. The additional energy partially compensates for the person having fewer high-frequency cochlear hair cells to encode the sound and restores access to some sounds in the speech banana (**Figure 2A**). However, there is a limit as to how much volume the hearing aid can produce without distorting the signal. Therefore, at some point, one must abandon the hearing aid for a CI.

In contrast to a hearing aid, a CI has two parts (**Figure 3B**). There is *an external component* consisting of the processor, battery, transmitter coil, and magnet. The microphones on the processor pick up the sound, which is analyzed and converted into a digital signal by the processor. Then there is *an internal component* consisting of a receiver coil and electrode array. The receiver is surgically implanted under the skin, in the skull behind the pinna, and the electrode array is inserted into the cochlea. The external transmitter coil connects with the internal receiver using a magnet, and the two coils convey information via radio-frequency transmission. The signal is transmitted to the electrode array in the cochlea, stimulating the auditory nerve with electrical pulses. The frequency information provided by the electrode array follows the same frequency organization from high to low, as occurs with acoustic hearing (Goupell, 2015).

In contrast to hearing aids, the CI converts the acoustic signal into an electrical signal and conveys it directly to the auditory nerve, bypassing the middle-ear bones, the basilar membrane in the inner ear, and the damaged hair cells also in the inner ear. This is how a CI can ultimately restore access to sound clarity when hearing aids cannot. CI sound coding conveys primarily temporal information, which is enough information to understand speech in quiet. That information, however, is highly degraded spectrally and greatly reduced compared with acoustic

Figure 3. ***A:*** *hearing aids come in many shapes and sizes; some are located behind the ear and some fit completely in the ear. Regardless of the style, these devices provide comparable benefits. See bit.ly/3VMJ3Ke.* ***B:*** *CIs consist of two components, the external device worn on the ear/head and the internal component placed under the skin and in the ear. See bit.ly/3Pe2FEm. Used with permission of Mayo Foundation for Medical Education and Research, all rights reserved.*



hearing. Fortunately, acoustic speech signals have a large amount of redundant information such that losing some of it does not destroy the ability to understand it (see Goupell, 2015, for an overview).

To determine who would benefit from a CI, audiologists conduct testing while the patient is wearing hearing aids that are programmed appropriately and functioning well. The audiologist and otologist, who is a physician/surgeon with specialized training in disorders and illness of the ear, determine whether the patient will derive enough benefit from a CI to justify the cost and risks of this procedure. Implantation risks are low, the most common side effects being temporary dizziness and some loss of residual acoustic hearing in the implanted ear.

What Cochlear Implants Do for Speech Understanding

When to Get a Cochlear Implant and Outcomes in Adults

A CI's most immediate benefit is improvement in access to soft sounds, such as environmental and speech sounds (**Figure 2A**). Subsequently, speech-understanding improvements occur because of the restored access to many speech sounds.

Then, within about a year of CI use, speech understanding in quiet is usually quite good, averaging about 70-80% (Blamey et al., 2013). The improvement after initial activation is discussed in **Rehabilitation: Maximizing Performance Takes Work**. In contrast to speech understanding in quiet, however, speech understanding in noise and music perception is relatively poor with a CI because of the greatly reduced spectral information and diminished auditory grouping cues.

Those who receive a CI when they become a candidate, or soon after, appreciate more benefits than those who are implanted years after candidacy has been reached. As a result, the criteria for getting a CI have significantly relaxed, allowing patients to become candidates earlier. However, there is large variability in outcomes between different patients. Many factors contribute to this, including the cause of deafness and whether the patient wore hearing aids before getting the CI. One of the strongest factors is that longer durations of deafness are associated with poorer outcomes (Blamey et al., 2013) because of greater neural loss (Pfingst et al., 2015). This is shown conceptually in **Figure 4**. Thus, even though a CI can bypass damaged hair cells, if the underlying ganglia and neurons are nonfunctional or are no longer present, they cannot convey the signals to the brain. Having stimulation with a CI maintains the neurons (Leake et al., 1999). This means that once a patient no longer receives adequate benefit from hearing aids and becomes a CI candidate, they should consider the potential benefits of cochlear implantation. Every year that passes leads to less benefit from the device, and waiting too long can make the intervention not worthwhile.

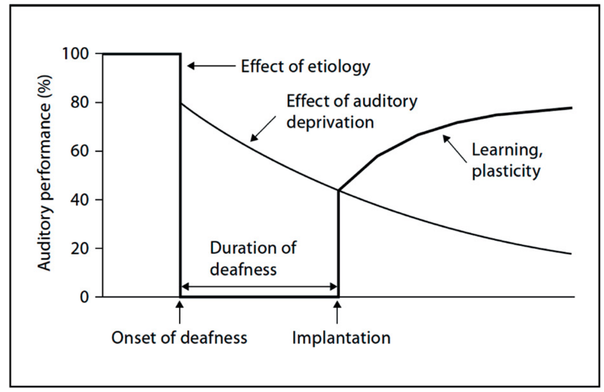


Figure 4. *Conceptual model of the factors contributing to the decrease and increase in hearing abilities before and after implantation. Auditory performance (e.g., speech understanding, with 100 being perfect understanding) is plotted against time. For example, the effect of auditory deprivation decreases auditory performance. However, with CI implantation and some period of learning, understanding improves. Reproduced from Blamey et al. (2013), with permission of S. Karger AG. © 2013, Karger Publishers, Basel, Switzerland.*

An audiologist programs and adjusts CIs across regular appointments to maximize outcomes. Programming and adjustments include determining the amount of electrical current each electrode emits to elicit a range of soft-to-loud sounds and assigning frequency ranges to each electrode. The frequency organization of the inner ear is maintained by programming the range of frequencies important for speech sounds (200-8,000 Hz) to the available electrodes. These electrodes often stimulate neurons at slightly higher frequencies than what is provided (Landsberger et al., 2015).

However, this mismatch can be overcome because the brain relearns its association between speech frequencies and the neurons that encode them. This is shown in **Figure 4** on the "learning, plasticity" portion of the curve. CI recipients improve in speech understanding for about one year after activation. Training and aural rehabilitation can facilitate this improvement (see **Rehabilitation: Maximizing Performance Takes Work**).

When to Get a Cochlear Implant and Outcomes in Children

Children who get a CI can function as well as adults who get a CI, although they have the same problems with listening to speech in noise and music perception. This occurs even for those who have never had acoustic hearing. For families who have listening and spoken language goals for their child, time to implantation is of the utmost importance. Therefore, earlier implantation also leads to better outcomes in children but for different reasons compared with those in adults. In the United States, children who are born with severe-to-profound hearing loss are often implanted with CIs by 9 to 12 months of age. Children born with significant hearing loss may have a "short" duration of deafness when considering the number of months or years, but in terms of the proportion of their life, the duration of loss is more impactful. When hearing loss is identified late in children or when hearing loss is progressive in nature, the sooner they are implanted once candidacy is confirmed, the better the outcomes. Although peripheral components of the auditory system (**Figure 1**) may still develop in a child with hearing loss, significant changes happen in the auditory cortex in a short amount of time. If the auditory regions of the cortex are not provided access to sound in early childhood, they could be reorganized for different purposes (Kral et al., 2019). Thus, the brain's ability to adapt to electrically encoded stimuli is much higher at the beginning of life when the cortex is more of a "blank slate" and has not yet reorganized (Kral and Sharma, 2012).

In addition to the critical period for auditory development, there is a critical period for speech and language development. For age-appropriate speech and spoken language milestones to be met, a child with hearing loss at birth (or loss that develops soon after) should receive a CI by 3 years of age (Geers and Nicholas, 2013).

Different Approaches Depending on Residual Hearing

When CIs were first developed, they were for profoundly hearing-impaired individuals, generally with an audiometric pure-tone threshold average greater than a 70 dB hearing level (**Figure 2B**). As technology advanced and outcomes improved, the guidelines for those who can get a CI have expanded. Decision making regarding who gets a CI has shifted from audiometric thresholds and solely improving audibility to focus on improving speech understanding and minimizing the duration of deafness. Consequently, individuals with more residual hearing are pursuing implantation.

There are now many different approaches to managing the various configurations of hearing loss. Following implantation in one ear, patients can continue to use a hearing aid on the other or even in the same ear. This causes a mixture of acoustic and electric stimulation where, ideally, the user has access to the full range of speech frequencies up to 8,000 Hz and low-frequency acoustic information, including pitch. Patients often find the sound quality more appealing with access to both electric and a small amount of acoustic hearing, particularly when listening to music (Polonenko et al., 2017). It has even recently become possible in the United States that people with single-sided deafness, or severe hearing loss in one ear and near-typical hearing in the other, are candidates for a CI (Buss et al., 2018). However, the interaction of acoustic and electric hearing is complex and is an area where researchers are trying to understand how to best integrate such information for an individual to maximize outcomes for speech perception, music appreciation, and spatial hearing.

Finally, many patients opt to receive a CI in each ear, which improves sound localization and speech understanding in noise (Kan and Litovsky, 2015). This is often the recommendation for young children with profound hearing loss and for adults who no longer benefit from the combined use of a hearing aid and CI.

Rehabilitation: Maximizing Performance Takes Work

No matter their listening configuration, once a person gets a CI, there is more work to do. Just as a person needs to strengthen the muscles after breaking a bone, one needs to learn to interpret the new way they hear with their CI.

Practice is needed to ensure that the brain makes the best use of the incoming CI signal. Hearing is a passive function that provides access to the auditory world. Listening and comprehension, however, go beyond just hearing by employing aspects of cognition. They involve listening with intention and making connections between sound and meaning. Consequently, people with hearing loss may expend more mental effort to listen because the auditory input has poorer quality (Hornsby, 2013). Most importantly, hearing, cognition, and comprehension are used for communication and relationship building when a spoken language is used. Hearing loss impacts not only one's ability to hear and listen but also impacts communication and connections to others. As a result, hearing loss can limit the activities we participate in, our employment opportunities, our leisure pursuits, and our overall quality of life.

Auditory rehabilitation aims to reduce the deficits caused by hearing loss and restore quality of life by using the brain's neuroplasticity, or ability to reorganize. People who have undergone a recent change in hearing status, such as a recipient of a CI, are prime candidates for an auditory rehabilitation program. The brain needs time to adapt to the new way speech information is conveyed (**Figure 4**).

One of the ways to shorten this adaptation period is to participate in a process called auditory training. This training involves practicing differentiating small changes in speech sounds as well as methods to use context to fill in missing sounds and words. Aural rehabilitation combines auditory training with education on how to use the new equipment and communication strategies most effectively, such as eliminating background noise during conversation, facing the person who is speaking, and reducing the distance between the listener and the talker (Bernstein et al., 2021).

In summary, cochlear implantation enables access to auditory information, but adjusting to the new way of listening takes practice. This training through focused aural rehabilitation maximizes the functioning of the listening brain of the CI user and improves overall quality of life (Brodie et al., 2018).

Summary

Hearing loss causes difficulties in maintaining access to and understanding of spoken language (remember the speech banana; **Figure 2A**); it is often thought of as a simple loss of audibility of sound, which is only partially true. Hearing aids amplify sounds in a frequency-specific manner, restoring audibility but only to a point. The more challenging aspect of hearing loss is sound distortion, including frequency smearing. When hearing aids cannot provide sufficient benefit, individuals should consider cochlear implantation. CIs bypass the damaged structures of the inner ear and provide access to speech information via direct electrical stimulation of the neural elements of the auditory system, providing loudness and clarity when hearing aids cannot. Due to neural plasticity, which is promoted through training and rehabilitation, the brain can often use the novel electrical signal to result in good outcomes. Originally, CIs were designed as tools to improve speech understanding in quiet environments. Most individuals who undergo cochlear implantation end up hearing better than they did with their hearing aids. Now, after advancements in technology and methods, CI users are demonstrating improvements in hearing during most listening situations; some are even enjoying music again. There is a range of variability in outcomes, mostly due to the duration of deafness, time to implantation, and postoperative rehabilitation. Looking back over 40 years, the developments in CI technology, programming, and rehabilitation have been substantial. The next 40 years will hopefully bring further advances. This may include better coordination across ears to improve spatial-hearing outcomes and auditory-grouping abilities; sound-processing strategies that help to better convey pitch and music by providing usable temporal fine structure and harmonic structures; perhaps using infrared light to stimulate the cochlea; and novel forms of electrical stimulation like auditory nerve implants.

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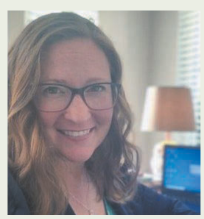

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Understanding Arterial Biomechanics with Ultrasound and Waveguide Models

Matthew W. Urban, Tuhin Roy, Wilkins Aquino, Murthy N. Guddati, and James F. Greenleaf

After finishing a three-mile run, you start your cooldown stretching and put two fingers to your neck to feel your pulse. Your heart rate is still elevated, and pulses are repeating fast and strong. After a few minutes, you check again, and you can feel that the rate has decreased, and the pulse strength has also diminished. The heart is doing its job to supply the body with oxygenated blood to supply the muscles that have been used during exercise.

In normal resting states, the heart supplies blood to the organs in the abdomen after a meal or to your brain for drafting that next paper for an academic journal. However, you may not think much about this process that occurs thousands of times a day and likely do not consider the blood vessels that carry blood all over the body to facilitate normal or more elevated function during an exercise.

The cardiovascular system consists of the heart and a series of vessels that carry blood away from the heart (arteries) and branch into smaller and smaller vessels to the level of capillaries that allow for diffusion of nutrients, oxygen, carbon dioxide, and other important molecules to maintain life. After the capillaries, the vessels merge into larger and larger vessels (veins) to carry blood back to the heart and lungs for oxygenation.

The vascular tree consisting of the arteries, veins, and capillaries has a high degree of variation in the makeup of the vessels used to take blood to each organ and back to the heart. The walls of these vessels include different proteins and tissues that maintain compliance or strength (collagen), the ability to stretch (elastin), and the ability to constrict or relax (smooth muscle) (Nichols and O'Rourke, 2005). The geometry changes from being more than a centimeter in diameter (aorta, the major vessel carrying blood from the heart) to capillaries that may be only slightly wider than a red blood cell to pass through. The associated makeup of the vessels gives rise to their respective function under different dynamic pressure loads, particularly their mechanical properties.

In the case of the cardiovascular system, it is well established that even in normal aging, structural changes occur in the vasculature that cause the arteries to stiffen. Over time or with disease, modifications of the elastin, collagen, and muscular components can cause the arteries to stiffen. For example, over time, elastin may be degraded and replaced with collagen, which is a much stiffer fiber and restricts stretching of the vessel wall. The implication of this arterial stiffening is that the pressure pulses exerted by the heart on every heartbeat are not absorbed by stretching of the blood vessel walls, also known as compliance. Thus, organs like the brain are exposed to a full-pressure pounding rather than the normal blood flow that is usually modulated by the compliant walls of the blood vessels leading to it. Over time, this can cause deleterious effects on these organs such as microscopic areas of damage in the brain or pressure waves that reflect from vessel branch points in the larger vessels that may impair the function of the heart. In diseases, the alteration of the arterial walls may accelerate, causing these harmful effects to appear earlier. This effect was summed up succinctly by William Osler, one of the founders of The Johns Hopkins Hospital, Baltimore, Maryland, "Man is only as old as his arteries" (O'Rourke and Hashimoto, 2007). With this assertion, developing noninvasive means for evaluating vascular stiffness to understand the state of one's health could be very useful.

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Ultrasound Imaging of the Vasculature

Medical ultrasound imaging uses high-frequency sound waves to form images of the internal structure of the human body. Because the sound speed in soft tissues, an average of 1,540 m/s, is very high, the echoes from the transmitted waves into the body return to the transducer in a short period that permits imaging of the tissue with real-time frame rates. This speed allows for imaging dynamic processes such as the beating heart, pulsation of the vasculature, and blood flow. Ultrasound imaging at frequencies ranging from 1 to 40 MHz is used to visualize vessels at different levels of the vascular tree (Ketterling and Silverman, 2017). Sensitive methods have been developed for visualizing flow in the smallest arteries, veins, and capillaries, often collectively referred to as the microvasculature, with and without bubbles that can be injected into the bloodstream to provide added ultrasound imaging sensitivity. These gas-filled bubbles reflect the ultrasound waves and return substantially large pressure amplitudes back to the transducer despite their small size, with diameters typically on the order of 1-6 μm, thereby improving the detectability of tiny vessels.

Due to these capabilities, ultrasound imaging of the cardiovascular system is widely used for diagnosis of many diseases and conditions. Significant applications of ultrasound to vessels are imaging of plaques or blood clots within vessels, narrowing of blood vessels (stenosis), abnormal widening of vessels (aneurysms), and leaky vessels. Ultrasound imaging also provides real-time imaging for gaining vascular access for an IV and assessing blood flow patterns (Ruoss et al., 2020). However, clinical evaluation of the mechanical properties of the vessel wall, outside of measuring dynamic diameter and thickness changes, has traditionally not been a focus.

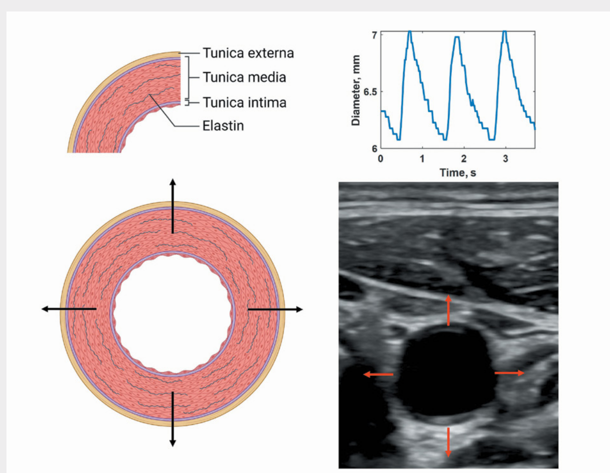
Ultrasound-Based Elastography

Over the last three decades, multiple research groups and medical-imaging vendors from around the world have worked toward developing and disseminating methods for measuring and creating images of the elastic properties of soft tissues using a method typically called shear wave elastography. Palpation has been used for centuries by physicians because abnormal tissues feel different than normal tissues. For example, breast cancer tumors feel like a "lump" in the tissue and indicate that something is not normal and may trigger having medical imaging and a biopsy performed. Despite being a fundamental part of the physical examination, palpation has several drawbacks. It is subjective and may depend on the proficiency of the examiner, and it may not be sensitive to deep abnormalities. To address these shortcomings, ultrasound elastographic methods allow measurement of the elastic modulus or the stiffness of a material in a quantitative manner.

Measuring Vascular Elasticity

Noninvasive measurement of the elastic modulus of the vasculature could be a useful biomarker for early and progressive disease in the arteries. The high temporal resolution of ultrasound allows for the measurement of dynamic activity of arterial wall motion caused by the pressure pulse transmitted by the blood flow. A straightforward approach is to measure the diameter change and quantify the minimum and maximum diameters (Laurent et al., 2006). As an example, an elastic vessel like the carotid artery in the neck is made up of three different layers that may have different amounts of elastin, collagen, and smooth muscle (**Figure 1**). As a composite material, the artery wall can be tracked with ultrasound to determine diameter changes over time. When combined with measurements of the diastolic and systolic blood pressures measured with a blood pressure cuff, the elastic modulus of a vessel can be evaluated. More

Figure 1. *Distension of elastic artery with three layers: tunica externa, tunica media, and tunica intima (**left**). Ultrasound has a sufficient frame rate to allow measurement of real-time motion and thus the diameter change over the cardiac cycle (**right**). Created with Biorender.com. See **Multimedia File 1** at acousticstoday.org/urbanmedia for a video of the pulsating vessel.*

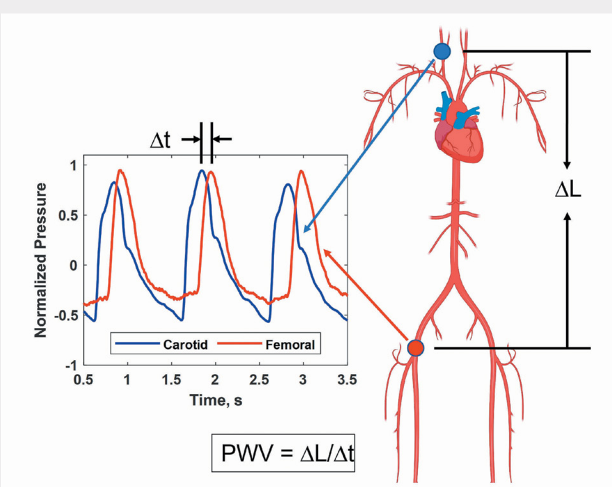


accurate blood pressure measurements would require a catheter in the blood vessel, which is invasive and not routinely considered.

Others have developed methods that utilize the artery's pulsatile motion to quantify the strain of the vessel wall (de Korte et al., 2002). The general assumption in using these methods is that a compliant vessel will undergo more strain than a stiff vessel. However, this method does not consider the vessel's pressure levels, which directly affect the amount of strain produced.

A widely used method for determining vascular elasticity is applanation tonometry to measure the vascular system's pulse wave velocity (PWV), or the rate at which the pressure pulse generated by the heart travels through the vessels (Laurent et al., 2006). Tonometry uses a pen-like probe with a pressure-sensing transducer. The probe is used to deform the vessel of interest to measure the pressure pulsation within the vessel, something that is like putting your fingers on your neck to feel your pulse. The most common application is to make simultaneous measurements in the carotid artery in the neck with the probe (**Figure 2,** *blue circle*) and femoral artery in the upper leg with a blood pressure cuff (**Figure 2,** *red circle*) and examine the time difference (Δt) between the waveforms (**Figure 2**). Using the length over the body surface (ΔL) made with a measuring tape the PWV is calculated using PWV = $\Delta L/\Delta t$. However, the length measurement accuracy is limited by measuring over the skin surface instead of the actual internal pathway. Additionally, the wave originates in the heart. It moves in opposite directions, upward to the carotid artery in the neck and downward to the femoral artery in the upper leg. Hence, the wave measured is not moving from one of the measurement locations to the other (carotid to femoral artery or vice versa). The PWV is more related to the central or aortic stiffness and is not localized to a particular vessel. Despite these limitations, many studies have shown that the PWV increases with age and in patients with cardiovascular disease (CVD) (O'Rourke and Hashimoto, 2007). The PWV is related to Young's modulus (E), wall thickness (h), inner radius (R), and density of the blood (ρ_b) by the Moens-Korteweg equation (PWV= $\sqrt{Eh/2R\rho_b}$) (Nichols and O'Rourke, 2005). This equation highlights that the mechanical properties and geometry are essential in determining the PWV.

Figure 2. *Pulse wave velocity (PWV) is measured from tonometer pressure signals at the carotid artery in the neck (**blue circle** and **blue trace**) and femoral artery in the upper leg (**red circle** and **red trace**). The time difference (Δt) between the pressure signals can be measured. The distance (ΔL) between the measurement sites (**circles**) can be measured over the body surface to be used for calculation of the PWV. Created with Biorender.com.*



Over the last 15 years, efforts have been directed toward measuring the local PWV using fast ultrasound imaging of a vessel like an aorta or carotid artery in a method called pulse wave imaging (PWI) (Konofagou et al., 2011). An example of PWI is shown in **Figure 3** where ultrasound imaging of a vessel is performed to measure how the wall deformation caused by the pressure pulse travels within the imaging plane (x-z plane). The PWV typically ranges between 4 and 15 m/s depending on the state of the vessel. However, the view of an ultrasound transducer for an artery may only be a few centimeters of the arterial length. For example, for an ultrasound transducer with a 4-cm-wide field of view (FOV), the time difference for a wave to pass from one end of the image to the other may be only 10 ms for a vessel with a PWV of 4 m/s. Although conventional ultrasound imaging is in real time (30 frames per second), a single ultrasound image frame may take 33 ms to acquire and would miss the pulse wave traveling in the ultrasound image, so ultrafast imaging methods are needed to capture the motion of the wave traveling across the image.

Acquisitions of a limited number of imaging lines with focused transmissions can be performed at high frame

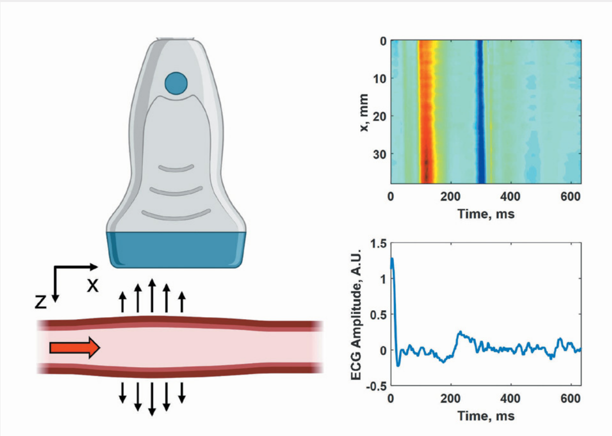


Figure 3. *Pulse wave imaging (PWI) as the pulse travels from left to right (+x direction;* ***left, red arrow****) passes through the imaging plane (x-z plane) and the distension motion is captured by the ultrasound transducer (****left, black arrows****). A diagram of the wall velocity as a function of distance (x direction) along a human carotid artery is shown (****top right****), with the corresponding electrocardiogram (ECG) trace (****bottom right****). The time axes are the same for both plots.* ***Top right, red:*** *motion toward the transducer;* ***blue****, motion away from the transducer. The PWV is determined by tracking the time of arrival of the wave peak (****red****) or another feature at each position along the length of the artery (x direction). In this case, the PWV is 5.01 m/s. Created with Biorender.com.*

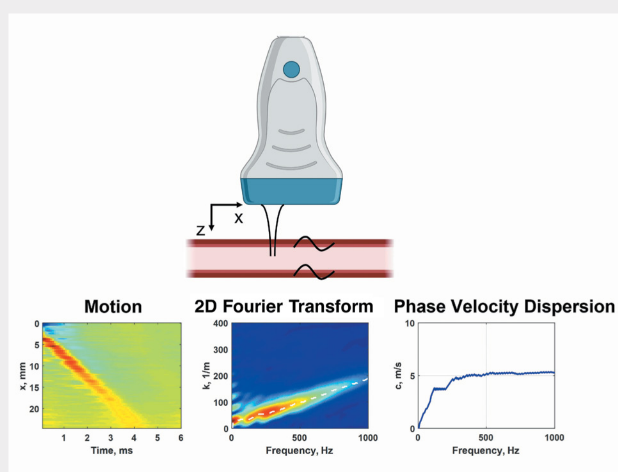
rates and, when synchronized, produce a complete FOV visualization of the wave propagation throughout several heartbeats. Alternatively, an unfocused transmission can insonify a large region, and the imaging rate is only limited by the time it takes for the ultrasound echoes to return from a prescribed depth. This plane wave imaging can yield frame rates of thousands of frames per second (Montaldo et al., 2009). Compounding several angled plane waves can improve the signal-to-noise ratio of the acquired ultrasound data. Using PWI methods can provide 1 or 2 measurements over the course of a cardiac cycle related to the ejection of blood from the left ventricle of the heart (Luo et al., 2012). The frequency content of the pulse wave is low, around 1-10 Hz.

Induced Waves and Computational Approaches

Although the previously described methods use the endogenous pulsatile motion of the artery as an excitation source, we and other groups have used methods to induce waves in the arterial wall to make measurements of the arterial elastic modulus. This "tapping" involves using focused ultrasound beams to generate small deformations on the order of a few micrometers in the arterial wall (**Figure 4**). The focused ultrasound generates an acoustic radiation force (ARF) that lasts on the order of 200-400 µs. This "tap" creates a series of waves propagating along the length of the artery and around its circumference (Couade et al., 2008). The wave motion is measured with the same plane wave compounding methods used in PWI to achieve ultrafast frame rates and measure the waves propagating at 4-20 m/s. These waves typically have a frequency content of 200-1,500 Hz. With the fast transit times of the waves through the FOV, measurements can be completed within 10-20 ms at different points throughout the cardiac cycle. This unlocks the ability to evaluate dynamic arterial elastic properties under different physiological conditions while the pressure pulse is traveling through the artery and stretching the vessel.

The motion that we measure in the space-time (x-t) domain could be used to match to simulation models, but another approach is using methods in the frequency

Figure 4. *Measurement with acoustic radiation force (ARF) excitation of propagating waves in the x direction in the human carotid artery while imaging in the x-z plane with the ultrasound transducer (****top****). The ARF "tap" causes the wave motion from the top wall of the artery (****bottom left****). We apply a two-dimensional Fourier transform and examine the magnitude distribution (****bottom enter****). The peaks in the magnitude distribution are identified for each frequency to estimate the phase velocity dispersion curve (****bottom right****). Created with Biorender.com.*



domain. Instead of examining the velocity of the whole wave packet, we can measure the wave velocity at certain frequencies and its variations, which is referred to as dispersion.

The main approach we follow is to estimate the elastic modulus of the arterial wall by matching the measured and computed dispersion characteristics of the wave propagating along the artery. Measured dispersion characteristics can be quantified by applying a two-dimensional Fourier transform to the wave motion in the space-time domain and using sophisticated signal-processing techniques to extract the dispersion curves related to different propagation modes (see **Figure 4**) (Bernal et al., 2011). Using the measured values of artery wall thickness and diameter made with B-mode ultrasound images and the induced wave motion, we can match the measured dispersion curves with those predicted using analytical or computational models.

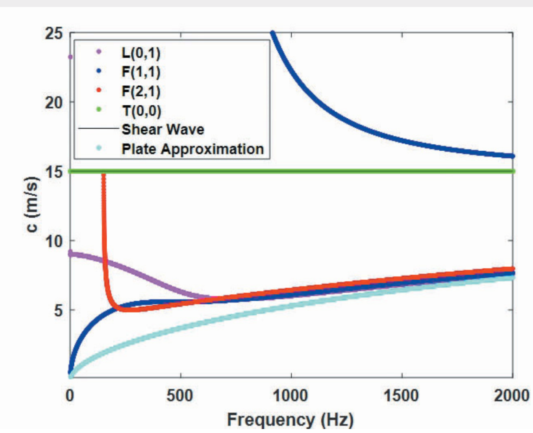
Initial approaches to estimate dispersion curves for artery-mimicking tubes and arteries used a simple plate (Lamb wave) model, where the arterial wall is approximated as a plate (Maksuti et al., 2016). However, this plate model was not able to capture the effect of the curvature of the tube wall, which has a significant effect given that the radius is of a similar order as the wavelengths being considered.

We observe multiple wave modes induced by the application of the ARF in the arterial wall due to the cylindrical shape and the nature of the excitation. Theoretical models describing the modes propagating in a cylinder of known diameter, wall thickness, and elastic modulus have been described, starting with Gazis (1959). These models have been instrumental for the nondestructive testing of pipes and other structures. However, we can apply the same underlying physics to the soft "pipes" within the human body (Zhang et al., 2005).

Simple closed-form solutions of these models do not exist, especially for thick-walled tubes such as large arteries, so computational approaches to obtain the mode shapes and other features have been used. Specifically, the dispersion can be calculated and used to compare with measured data. For example, the dispersion curves for a cylindrical vessel made of a material with a shear modulus of 225 kPa (shear wave velocity of 15 m/s, assuming a density of 1,000 kg/m^3), an outer diameter of 8 mm, and a wall thickness of 1 mm are shown in **Figure 5**. In addition, Lamb wave or plate wave model dispersion curves for zeroth-order asymmetrical and symmetrical modes are also shown for a 1-mm-thick plate of the same material.

One can construct the computational models with several different approaches, including finite-difference models and finite-element modeling (Treeby et al., 2019). We use a semi-analytical finite element (SAFE) approach that captures the behavior of the three-dimensional model but at a significantly reduced computational expense (Roy and Guddati 2022). The model that we are using (see **Figure 6**) assumes a hollow cylinder of infinite length that has fluid on the outside and inside and has a uniform thickness and diameter. The cylinder is stimulated by a force that has a specific spatiotemporal definition, which provides a high degree of flexibility in adapting to different configurations of ARF excitation, which can also be determined using simulations (Treeby et al., 2019). The solution is written in terms of harmonic modes in time and spatially configured along the axial (x) or length direction and in the azimuthal direction

Figure 5. *Mode dispersion curves for a cylindrical vessel made of a material with a shear modulus of 225 kPa (shear wave velocity of 15 m/s, assuming a density of 1,000 kg/m^3), an outer diameter of 8 mm, and a wall thickness of 1 mm. Longitudinal [L(0,1)], flexural [F(1,1) and F(2,1)], and torsional [T(0,0)] dispersion curves are shown. Shown in addition, the shear wave velocity and zeroth-order asymmetrical and symmetrical mode dispersion curves for the plate approximation with Lamb waves. These are the possible velocities that can occur in this cylindrical vessel, but depending on the ARF excitation, only certain modes may be stimulated.*



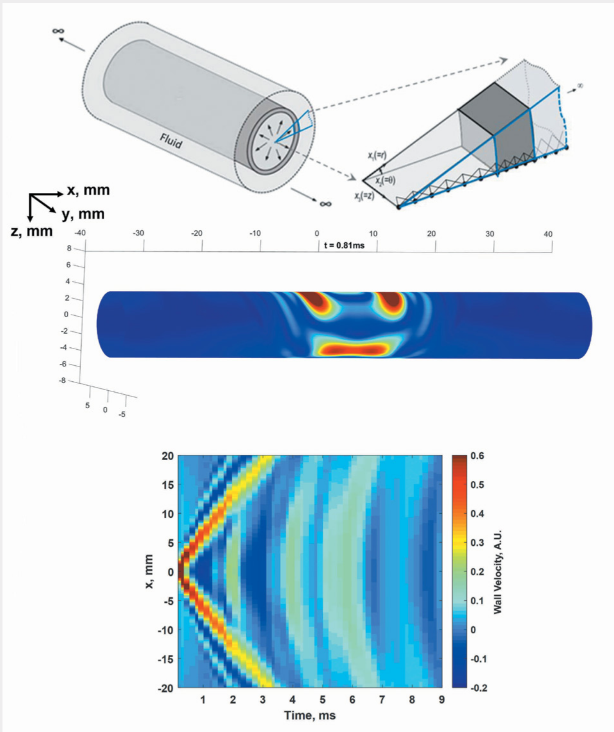


Figure 6. ***Top:*** *semi-analytical finite element (SAFE) model simplifying a three-dimensional (3D) infinite length cylindrical vessel into a one-dimensional waveguide model. The simplification allows for efficient computation without sacrificing fidelity to the underlying physics.* ***Center:*** *simulated 3D motion at* t = *0.81 ms after the ARF stimulation at the top wall in the center of the cylinder. The snapshot shows waves propagating down the length of the vessel in both directions as well as a wave traveling around the circumference of the vessel. See* ***Multimedia File 2*** *acousticstoday.org/urbanmedia for a video of the simulated propagating waves.* ***Bottom:*** *motion isolated from a line along the top wall corresponding to measurements that can be made in an artery with an ultrasound transducer. Reproduced from Roy et al. (2021), with permission of IOP Publishing Ltd., © Institute of Physics and Engineering in Medicine, all rights reserved.*

(θ) in polar coordinates (**Figure 6,** *top*). The response of each of these modes is then solved with the help of a high-order one-dimensional finite-element discretization that is highly efficient (**Figure 6**). We emphasize that the method accurately captures the fully three-dimensional (3D) wave propagation phenomenon as well as coupling with interstitial and surrounding fluid. In fact, the responses of each of these modes can be synthesized to obtain the full 3D response of the artery (see **Figure 6**). Computation of the 3D response takes less than four seconds, in contrast to several hours needed for direct finite-element simulation.

This "waveguide" model provides the opportunity to quickly obtain the motion and the dispersion curves for a given configuration (geometry and elastic modulus). Estimates of the elastic modulus from dispersion curves, using common optimization approaches, can be quickly determined. The presence of multiple modes appears as a complicating factor, but information from multiple modes could also be used to estimate the elastic properties of the artery (Roy et al., 2021).

Our group and others use these methods to estimate the elastic properties of human arteries for evaluating patients with different conditions such as high blood pressure and other diseases that are known to affect vessel function (Pruijssen et al., 2020). Shear wave elastography is typically applied, with a few underlying assumptions such as the organ is locally homogeneous and large with respect to the wavelengths of the waves generated in the organ. These assumptions are not valid in the case of the arterial wall where the wall is thin with respect to the wavelengths produced by the ARF excitation and the cylindrical shape creates complicated waves. Therefore, the full physical behavior must be accounted for, using guided-wave models, in estimating the elastic mechanical properties of the artery.

Figure 7 shows an example of an in vivo measurement and comparison with results from the computational model. The measured motion in the arterial wall is shown along with the dispersion curve extracted from analysis of the motion signal (**Figure 7**, *blue solid curve*). The simulated motion from the model described in **Figure 6** is also shown along with the corresponding dispersion curve (**Figure 7**, *red dashed curve*). It is notable that the data match well in the time domain (motion) and the frequency domain (dispersion curves). The simulation contains information about the geometry of the measured artery and captures the complicated motion that is exhibited in the experiment.

Future Opportunities

We would be remiss if we did not acknowledge the collaborative work that combines the in vivo wave motion measurements in arteries and the evaluation of the inverse problem associated with estimating the elas-

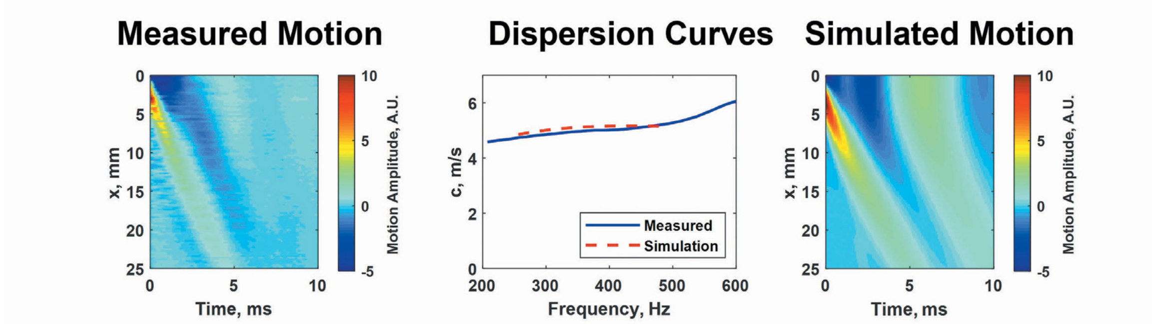


Figure 7. ***Left:*** *measured motion from the left carotid artery of a human research subject).* ***Center:*** *dispersion curve from analysis of the measured motion data (**blue solid curve**) is shown along with the dispersion curve from 250 to 500 Hz (**red dashed curve**) from the simulated model (**right**) for a shear modulus of 254 kPa and viscosity of 45.7 Pa·s. The images of the motion look similar as do the dispersion curves, indicating good agreement between the measured wave and the waves simulated from the SAFE model.*

tic mechanical properties. Combining the necessary expertise of ultrasound engineers and computational mechanics has brought the prospects of accurately evaluating the elastic properties of the arterial wall. Continued development opens the doors for evaluating additional mechanical properties such as anisotropy, nonlinearity, and viscoelasticity of the artery.

At this stage, we are assuming that the artery is a homogeneous and isotropic cylinder; the underlying layered structure of the artery makes the mechanical properties anisotropic in the length or axial direction and the circumferential direction. With different propagating modes in the axial and circumferential directions (**Figure 6**), we may be able to discern the properties in these different directions.

The high temporal resolution of measurements throughout the cardiac cycle allows for the opportunity to explore the behavior of the artery exposed to different internal pressures (Marais et al., 2019). The elastin and collagen fibers that compose the arterial wall have different mechanical behaviors. The elastin fibers stretch linearly at low pressures (or low-stress states). At a certain point of applied stress, the elastin fibers reach a point of maximum stretch and the contribution of the collagen fibers increases. However, collagen fibers exhibit a nonlinear relationship to applied stress. As a result, the composite stress-strain curve has a linear region at low pressures and a nonlinear increase as the pressure or stress increases. We can make several measurements of the elastic modulus along the stress-strain curve to characterize the nonlinear relationship of the artery. Additionally, combining aspects related to the low-frequency distension due to the pulse wave and the high-frequency-induced waves could provide opportunities for developing new biomarkers.

Last, the artery, like many soft tissues, can be viscoelastic. That is, the tissue has a time-dependent behavior that involves the dissipation of energy due to viscous components in the tissue. Previous work related to the evaluation of the hysteresis of the distension of arteries has identified that the combined elastic and viscous components could help characterize the arteries of different patient cohorts (Armentano et al., 1998). Using wave-based techniques, we can fit dispersion curves using a viscoelastic material model (**Figure 7**) or attempt to measure the attenuation of the waves as they propagate to understand the viscous nature of the arterial wall.

In conclusion, using wave-based physics applied to biomedical ultrasound and modal analysis of structures has provided new ways to examine the human vasculature. New biomarkers could provide insight into disease processes and assist in identifying cardiovascular disease at earlier stages, which would have profound effects on earlier interventions and improved patient outcomes. These developments could provide for the measurement of the physiological "age" of a person's arteries in line with Osler's previous assertion.

Acknowledgments

We thank Sierra Slade for study coordination of our human studies. We thank all participating sonographers for their expertise in acquiring the ultrasound and arterial healthy assessment data. We thank Charles B. Capron and Hyungkyi Lee for assistance with the studies. The measurements shown in **Figures 1-4** and **7** were acquired under protocols approved by the Mayo Clinic Institutional Review Board. Research subjects provided written informed consent. This work was supported in part by Grant R01 HL145268 from the National Heart, Lung, and Blood Institute (NHLBI), National Institutes of Health (NIH), Bethesda, Maryland. The content is solely the responsibility of the authors and does not necessarily represent the official views of the NHLBI or the NIH.

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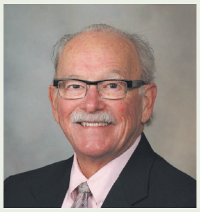

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SOUND PERSPECTIVES

Recent Acoustical Society of America Awards and Prizes

Acoustics Today is pleased to present the names of the recipients of the various awards and prizes given out by the Acoustical Society of America. After the recipients are approved by the Executive Council of the Society at each semiannual meeting, their names are published in the next issue of *Acoustics Today*.

Congratulations to the following recipients of Acoustical Society of America medals, awards, prizes, and fellowships, who will be formally recognized at the Spring 2023 Plenary Session. For more information on the accolades, please see acousticstoday.org/asa-awards, acousticalsociety.org/prizes, and acousticstoday.org/fellowships.

Gold Medal
Mark F. Hamilton
(University of Texas at Austin)
for contributions to theoretical nonlinear acoustics and education and for service to and leadership of the Society

Helmholtz-Rayleigh Interdisciplinary Silver Medal in Biomedical Acoustics and Physical Acoustics
Vera Khokhlova
(University of Washington, Seattle, and M. V. Lomonosov Moscow State University, Moscow, Russia)
for contributions to the application of nonlinear acoustics to medical ultrasound

Medwin Prize in Acoustical Oceanography
David Barclay
(Dalhousie University, Halifax, Nova Scotia, Canada) for contributions to the fundamental understanding of ocean ambient sound

R. Bruce Lindsay Award
Julianna Simon
(Pennsylvania State University, University Park, Pennsylvania) for contributions to the understanding of ultrasound-induced mechanical bioeffects and their clinical applications

Hartmann Prize in Auditory Neuroscience
Bertrand Delgutte
(Harvard University, Cambridge, Massachusetts)

Congratulations also to the following members who were elected Fellows in the Acoustical Society of America in Spring 2023.

- **Kevin Haworth**
(College of Medicine, University of Cincinnati, Cincinnati, Ohio) for contributions to the development of passive cavitation imaging and therapeutic ultrasound methods
- **Tracianne Neilsen**
(Brigham Young University, Provo, Utah) for applications of machine learning to inverse problems in ocean acoustics
- **Bogdan Popa**
(University of Michigan, Ann Arbor)
for contributions to active acoustic metamaterials
- **Sarah Verhulst**
(Ghent University, Zwijnaarde, Belguim) for contributions to computational modeling of the normal and impaired auditory system
- **Robert White**
(Tufts University, Medford, Massachusetts)
for advancement in the field of acoustic microelectromechanical systems

Conversation with a Colleague: Ruth Litovsky

Ruth Litovsky
Conversation with a Colleague Editor:
Micheal L. Dent

Meet Ruth Litovsky

Ruth Litovsky is the next acoustician of our "Sound Perspectives" essay series "Conversation with a Colleague." Ruth is Associate Dean, professor, and Oros Family Chair of Communication Sciences and Disorders at the University of Wisconsin-Madison, with a joint appointment in surgery/otolaryngology (see bhsl.waisman.wisc.edu). Ruth received bachelor's and master's degrees from Washington University, St. Louis, Missouri, and her PhD from the University of Massachusetts-Amherst. She completed her postdoctoral training at the University of Wisconsin. Ruth received the Silver Medal in Psychological and Physiological Acoustics from the Acoustical Society of America (ASA), the first woman to receive this award. She is a Fellow of the ASA and served as an associate editor of *The Journal of the Acoustical Society of America* for seven years. We asked Ruth to give us her elevator pitch and then to elaborate on her inspirations, contributions, and hopes for the future.

Give your "elevator speech" about the thrust(s) of your scholarly work over your career.

We spend much of our lives in environments where our brains receive a barrage of sounds and echoes. Yet, somehow, individuals with typical ("normal") hearing are very good at locating the sources of sounds around us. Moreover, in a noisy restaurant, we can focus on what one person is saying despite a cacophony of clatter in the background. Throughout my research career, I have been passionate about understanding how our brain uses binaural information to compute sound locations, suppress echoes, and enhance speech understanding in noisy environments. Moreover, I study how we can use this science to guide clinical practices in listeners with hearing loss. My laboratory has shown that for children and adults who are deaf, bilateral cochlear implants can provide significant advantages over single implants, especially in noisy environments. However, patients face daily challenges because current cochlear implant technology strips out of the sound much of the information that the brain uses to build a three-dimensional picture of the auditory world. For example, perception of space is limited to some left-right localization, with little sense of distance or elevation, and pitch perception can be fairly "flat." To get at this problem, we use reverse engineering approaches to conduct studies on how to best coordinate information between the two implants to ultimately provide patients with better binaural hearing. Our ultimate goal is to improve patients' quality of life through better spatial hearing in noisy settings. This also means that patients can expend less cognitive resources as they learn, socialize, and communicate in their daily lives.

What inspired you to work in this area of scholarship?

When I began my PhD in 1987, I sat with my advisor Rachel (Clifton) Keen in the anechoic chamber and experienced the compelling auditory illusion known as the precedence effect. This phenomenon instructs our brain to weaken the weight assigned to information arriving from echoes so that we can accurately localize sound sources in our environment. The precedence effect is absent at birth and emerges with maturation of auditory cortical mechanisms. My PhD dissertation focused on how spatial hearing, including the processing of echoes, emerges during early childhood. During my postdoctoral training (1991–1994) with Tom Yin, I sought to understand the neural mechanisms underpinning spatial hearing.

https://doi.org/10.1121/AT.2023.19.1.55

By recording responses of neurons in the midbrain of cats, I gained insight into the fundamental auditory processes that support mammalian binaural and spatial hearing.

After gaining training that combined psychophysical and physiological acoustics, I was fortunate to work in two outstanding environments in Boston, Massachusetts: Steve Colburn's laboratory at Boston University and Bertrand Delgutte's laboratory at the Eaton-Peabody Laboratories at the Massachusetts Eye and Ear Infirmary. The role of the binaural system in human perception became the focus of studies with my students and collaborators. Since my arrival at the University of Wisconsin-Madison in 2001, I shifted focus to the field of cochlear implants, with a commitment to studying how we can provide better binaural and spatial hearing to patients who are deaf and receive two (bilateral) cochlear implants.

Of all your contributions during your career, which are you most proud of and why?

Choosing the field of hearing science meant learning how to adopt different behavioral techniques to extract meaningful data from human subjects, including very young children. The challenge came with delightful rewards, discovering that the young auditory system adapts to ongoing changes in sensory inputs and that these changes are driven by both biological maturation and the response to the environment. The spatial hearing system offered opportunities to probe development of perceptual mechanisms that are extremely important for everyday function. I had anticipated discovering that children's spatial hearing abilities would be rather poor during the early years of development. I had not imagined that our work would demonstrate how capable children would be at localizing sounds and separating speech from noise by the early age of two to three years. Note that auditory development is incomplete in early childhood. Indeed, emergence of sophisticated spatial hearing mechanisms depends on whether the auditory system receives binaural cues with fidelity, especially early in life. In children who are deaf, it is important that cochlear implant processors be able to capture binaural cues and provide these cues to a child's binaural system. If children have access to binaural cues during development, there is a greater likelihood that they will be able to have good spatial hearing abilities.

When my laboratory pivoted to investigating the effects of bilateral cochlear implants on spatial hearing, we learned that children with a unilateral device do not perceive the auditory world as emerging from specific locations in space, a perceptual capacity that most people with normal hearing take for granted. By working closely with children who are deaf, my students, trainees, and I gained long-lasting insights into the everyday challenges and triumphs experienced by cochlear implant users. We studied the emergence of spatial hearing after activation of bilateral implants, with a focus on how psychophysical methods can inform best practices in the medical field. Although bilateral cochlear implants were shown to provide a benefit over a single implant, we found that none of the implantees were able to localize sound or separate speech from background noise as well as their normal-hearing peers. The problem is that cochlear implants are not designed to function in bilateral modes and preserve binaural cues that are so naturally captured by the normal auditory system.

The issue of auditory plasticity became an important consideration in our research questions. Over time, the auditory system of children who hear through uncoordinated bilateral devices loses the ability to process and use binaural cues, in particular interaural differences in time (ITDs). For this reason, our laboratory took a deep dive into the world of reverse engineering, whereby we use research processors to design novel stimulation strategies to test ideas about how to best capture and restore binaural hearing to cochlear implant patients. To conduct this work, we have built interdisciplinary teams in the laboratory and collaborated with many engineers and scientists across the globe, all fascinated by what it takes to improve spatial hearing abilities of people who are deaf and rely on cochlear implants. Importantly, when research participants spend time in my laboratory, our team makes an effort to learn about their experiences and perceptions. We have come to know children as they grow up and learn about how they adapt to new challenges and experiences. My laboratory has forged bonds with our research participants because they are more than just research subjects; they have become part of the laboratory's larger family.

An important part of continuing to grow as a scientist and to bring new ideas to the field has also been the commitment to remain nimble in embracing newer research tools to expand our discovery of auditory perceptual mechanisms, for example, by using eye tracking and pupillometry to study the complex nature of decision making and effortful listening that participants undergo when engaging in our auditory tests. We embraced functional imaging to study how different brain regions engage during auditory tasks and to understand the benefits of hearing through two ears versus one ear.

It is impossible to describe my contributions without expressing my gratitude to my mentors, students, and colleagues. I was very fortunate to have received outstanding mentoring early in my career and to have forged deep friendships with collaborators and colleagues in the field of auditory science. As I advanced in my career, I focused on creating a sense of "family," not only in my laboratory but also with the larger scientific community. I will be forever grateful for the intellectual and personal connections that I have forged and that provided motivation, excitement, challenge, and sustenance over the decades. I am extremely fortunate to be in a position of loving the work that I do, in part because I encounter unanticipated challenges and always feel that there are more questions than answers. What I find most rewarding is not only the discovery of factors that drive human perception and communication but also the process of going about the route of scientific discovery and determination of what new tools and approaches should be harnessed.

What are some of the other areas in which you feel you made substantive contributions over your career?

As a woman in the field of acoustics entering the subfield of binaural hearing, I had to accept the fact that this discipline was dominated by White male scientists. I clung to the belief that being accepted by an existing group means participating fully, focusing on contributing interesting ideas and findings and discovering a community of like-minded colleagues and friends. The mentors that accepted me into their laboratories and gave me life-long advice became important anchors in my attempt to forge ahead as an independent investigator and to shift my research questions into novel and somewhat risky directions.

As I began to extend mentoring to students and postdocs beyond the immediate network of my laboratory and institution, I learned that trainees are hungry for open conversation about how to navigate careers, publications, grant writing, and life. Over the years, I've loved being able to offer mentoring opportunities through formal avenues such as workshops at conferences. These began as conversations for women in science/engineering and clinical domains. We moved beyond holding women-only events as it became clear that everyone is searching for mentoring relationships.

Part of the mentoring process led me to advocate for our support of trainees, in particular focusing on individuals from underrepresented minorities. Choosing to be a scientist can be both the best and hardest career decision; there are so many opportunities to succeed and take joy in our work and there are equally many times when we can be crushed by rejection or failure. Opening opportunities for discussion, support, and mentoring was not only a way for me to give back but also a place where I could reveal my inner worries and discuss the never-ending "imposter syndrome."

Most of all, I am proudest of my personal collaboration with my husband David Baum, an evolutionary biologist and botanist. As a dual-career couple, we concentrated on making decisions to honor our wishes as individuals and as a family unit. As we raised our three amazing children, we juggled combinations of fun and challenging commitments and opportunities. Finally, my family and I share a commitment to look outward and to be mindful of our responsibility to our extended families and communities around us.

What do you think are the most pressing open questions that you would like to focus on over the next 5-10 years?

Harnessing my experience in binaural hearing to understand compromised communication in special populations, including individuals with Down syndrome (a common genetic cause of intellectual and developmental disability) whose high incidence of hearing loss is underdiagnosed and appears to be related to cognitive and language delays. Similarly, the role of binaural hearing in the normal aging process. There is growing evidence to suggest that active and effortful listening is "costly" to cognitive function. Gradual declines in hearing may contribute to exacerbated dementia (loss of memory, attention, executive function). I feel compelled to apply my experience toward better diagnoses of auditory decline that might help improve communication and quality of life in one's later years.

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International Student Challenge Problem in Acoustic Signal Processing 2023

Brian G. Ferguson, R. Lee Culver, and Kay L. Gemba

The Acoustical Society of America (ASA) Technical Committee on Signal Processing poses international student challenge problems in the discipline of acoustic signal processing (Ferguson and Culver, 2014; Ferguson et al., 2019). The International Student Challenge Problem for 2023 involves the student (or team of students) processing real acoustic sensor data to extract information about the source from the sound that it radiates.

For the present problem, the acoustic sensors are three hydrophones, N, O, and P, located 1 m above the seafloor in water 20 m deep. The hydrophones are distributed along a straight line, with a separation distance of 14 m between adjacent hydrophones (i.e., the uniform interelement spacing of the three-element horizontal line array is 14 m). Hydrophone O is the middle sensor at the center of the array. The output of each hydrophone is sampled at the rate of 250,000 samples per second (i.e., the sampling period is 4 μs). The sampled data time series for the three hydrophones are recorded in Waveform Audio File (WAV) format. The files are Hyd N.wav, Hyd O.wav, and Hyd P.wav and can be downloaded as .wav files at acousticstoday.org/iscpasp2023.

The source is an open-circuit scuba diver swimming at constant speed and altitude along a straight-line trajectory (i.e., a line vertically above and parallel to the axis of the horizontal line array). The acoustic signature of an open-circuit scuba diver consists of a sequence of regularly spaced broadband-pulsed acoustic emissions linked to the inhaling phase of the diver's breathing cycle. The pulses are generated by the scuba equipment's high-pressure regulator where expansion of the compressed air from the tank produces turbulent airflow pressure fluctuations that excite structural vibrations of the regulator's valve and channels (Donskoy et al., 2008; Gemba et al., 2014). The student is invited to undertake two tasks.

Task 1

(a) Display the output spectrogram (frequency versus time) for one of the hydrophones (e.g., the middle hydrophone O). Comment on the spectral properties of the scuba diver's acoustic signature.

(b) Estimate the breathing rate of the diver in hertz.

Task 2

Assume that the isospeed of sound travel in the underwater environment is 1,520 m/s.

(a) Estimate the time (in seconds) when the diver is at the closest point of approach to the middle hydrophone O.

(b) Estimate the diver's altitude (i.e., the distance vertically above hydrophone O, when the diver is at the closest point of approach).

(c) Estimate the diver's swimming speed in meters per seconds.

Your solution should detail your approach, signal-processing methods, and reasoning to solve the problem as well as your best estimates of the above parameters.

The deadline for student submissions is October 31, 2023. Submit your solutions, along with your contact details and proof of student status, to asa@aip.org with the subject line "Entry for International Student Challenge Problem in Acoustic Signal Processing 2023." The finalists and prize winners (monetary prizes: first place, $500; second, $300; and third, $200) will be announced by November 30, 2023.

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Reaching Reporters, Teachers, and Bosses: Lay Language Papers

L. Keeta Jones

For over 25 years, the Acoustical Society of America (ASA) has used a Public Relations and Media outlet (see www.acoustics.org) to provide access to the latest acoustics research by way of lay language papers (LLPs). The LLP program emerged to provide efficient dissemination of plain-spoken information regarding the field of acoustics to the news media, science writers, and other interested parties. If you have ever presented at an ASA meeting, you may have been approached to write an LLP. But why should anyone submit an LLP? In this essay, I explain what an LLP is, discuss the benefits of writing LLPs, and provide guidance on writing LLPs so that they will be of interest to science reporters and a more lay audience in general.

What Is a Lay Language Paper?

Readers may have heard of *Astrobites* (see astrobites.org), which "disseminate high-quality, jargon-light educational blog posts […] that explain findings from cutting-edge research for an audience of interested undergraduates and nonscientists." LLPs function in much the same way, but instead of focusing on published research, LLPs are approximately 500-word common speech summaries of research presented at ASA meetings. These "bite-sized" papers are meant to be digested by readers in a few minutes because they might not have the background, time, ability, or access to read entire research articles. This includes reporters, teachers, and even funding decision makers.

A distinguishing factor of LLPs is that the acousticians responsible for the research are also the ones writing the summaries, ensuring that the scientific and technical content is conveyed accurately. For promptness, submissions are only reviewed for clarity and grammar before being posted online, which means that the media has the most rapid access to newly announced and cutting-edge research presented at ASA meetings. Authors can request additional feedback from myself and the Public Relations (PR) Committee and resubmit at their own discretion.

Although every ASA meeting presenter can submit an LLP, the ASA PR Committee collaborates with the American Institute of Physics (AIP) media services to pre-identify meeting abstracts that may garner media attention and invites those authors to write LLPs. These LLPs are typically posted before the meeting and are used, along with press releases written by AIP media services, to promote the meeting. Current and past LLPs are also used to encourage engagement between meetings through social media.

Why Should I Write a Lay Language Paper?

Writing LLPs allows researchers to foster the acoustics community, reach people outside of their fields, and develop science communication skills. Just by writing LLPs, authors contribute to the translation of complex acoustics topics, making the field more approachable to a lay audience. As previously mentioned, LLPs are more likely to gain media attention than more technical material. LLPs can also help interested readers to find journal publications and learn about the ongoing work or research of LLP authors and potentially connect them to funding opportunities. Based on requests for information from the press and even social media interactions, we know that LLPs are well received by internet users and promote further conversation in and beyond the acoustics community.

Another reason to write an LLP is that it can act as a convenient digital space to host multimedia content like audio files, videos, or images that can be referenced in other published work or presentations. For example, in a 2012 article in *The Journal of the Acoustical Society of America* entitled, "The tones of the *kalimba* (African thumb piano)" (see doi.org/10.1121/1.3651090), author

https://doi.org/10.1121/AT.2023.19.1.60

David M. F. Chapman (2012) tells readers to listen to audio examples of the instrument by visiting the LLP he wrote for the 155th ASA Meeting (see ow.ly/lW6V50LpVVl).

How Do I Write a Lay Language Paper?

Authors do not have to be a professionally skilled science writers, but keep in mind that LLPs are not like typical research articles. Unlike research articles, LLPs should start with the most newsworthy information and end with background information. The basic structure of the paper should follow the inverted pyramid of journalism (**Figure 1**) that shows what information should be prioritized from top to bottom. Authors should start with their main takeaway message and then briefly explain how they got there; don't bury the lead because readers might never get there! Another option is to tell a good story with a beginning, middle, and end.

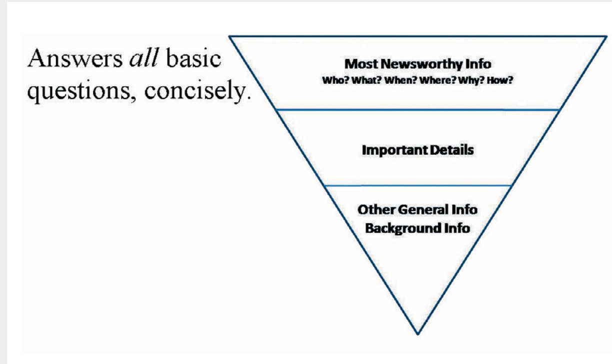

Figure 1. *The inverted pyramid of journalism structure. The widest part at the top represents the most interesting and important information and should lead the paper while the lower sections show what information should follow in order of importance and decreasing space. Figure by Svetlana Tkachenko, CC BY-SA 4.0, via Wikimedia Commons. Modified.*

Start by setting up a problem that needs to be solved. Then move on to how it was solved or how solving is being attempted. Finally, end with the lessons learned or insights gained.

Whether an author takes more of an inverted pyramid or story approach, keep the language simple. Many readers will not be familiar with technical terms. LLP titles tend to be shorter and have a more casual tone such as "Saving Lives During Disasters by Using Drones" (see ow.ly/UAuY50KYBwe) that is based on the abstract "Bearing estimation of screams using a volumetric microphone array mounted on a UAV" (see doi.org/10.1121/10.0004448). Authors can avoid field specific-jargon by not overloading the paper with too many scientific concepts. This De-Jargonizer program (see scienceandpublic.com) can provide insights into which words occur in everyday media. For more about the ASA LLP style requirements and even more tips, visit the LLP style guide (see ow.ly/rBbp50LpWgn).

What Do the Experts Say?

Sometimes it is best to hear directly from acoustics science communicators. Check out what these experts have to say when it comes to acoustics lay language writing. Allison Coffin, *Acoustics Today* contributor (see ow.ly/F9Bv50LpZBs), ASA member, associate professor at Washington State University Vancouver, and president of the Association of Science Communicators (see associationofsciencecommunicators.org) wrote in an email:

> "Writing for science reporters is different than writing for non-technical lay audiences. The reporter wants to know why the work is potentially important—why will their audience care, and why should they contact you for an interview? For reporters, best to hit the "so what" right away, and even talk about the people who could benefit from your work.
>
> For non-technical readers who are just interested in science, they are often drawn in by a story. For example, if the research is about retrofitting a concert hall to improve the acoustics, take the reader through the experience of being in that concert hall—before, with echoes—and after, with an amazing listening experience as they enjoy their favorite music. Make it real!
>
> To me, one of the biggest benefits of writing for non-technical audiences is that I'm reminded why I do the work. So often as scientists we get lost in the details and forget the bigger picture. I also see it was a public imperative, particularly for research funded on tax money. Finally, it's fun! I can be more creative with my wording. I sometimes wish that we could write all of our papers in a more relaxed style—still accurate, but more story."

As the AIP Press Officer and former sciencewriter for *Scilights* (see aip.scitation.org/journal/sci), Ashley Piccone regularly summarizes newly published acoustics research for a broad scientific audience (see ow.ly/nZoB50LpZFn). Via email, Ashley recommended that LLP authors:

> "Relate the science to the everyday. Use terms and ideas that would make sense to someone you'd chat with in a bar. And I love using a good analogy to explain a complicated topic!
> Focus on what makes your science important and interesting. Is it an important application? A unique technique? An unintuitive result? Emphasize it, and emphasize it early."

And if there is space at the end of an LLP draft or for something longer like an *Acoustics Today* article, Avery Thompson, another science writer for *Scilights* (see ow.ly/8yLQ50LpZMr), said this in an email correspondence about conclusions:

> "One of my favorite things about talking with scientists is how passionate they are about their research area. Find the things that excite you the most about your work and share those with your readers. Why did you choose to study this topic in the first place? Why do you feel your research is important? What excites you about the future of your field? What do the results of your research mean for that future? The answers to these questions can provide a great concluding takeaway for readers."

I hope you now understand why the ASA maintains the LLP program and that you are encouraged, empowered, and excited to submit your own paper. If you have or will be presenting at an ASA meeting, visit ow.ly/rBbp50LpWgn to learn more and to submit a LLP!

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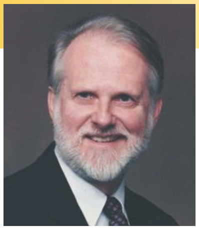
Obituary
James W. Beauchamp
1937–2022



James W. (Jim) Beauchamp, a Fellow of the Acoustical Society of America and of the Audio Engineering Society and professor emeritus of music and electrical engineering at the University of Illinois Urbana-Champaign (UIUC), died on May 5, 2022, at the age of 84.

Jim grew up in Michigan. He studied and played jazz trumpet at Albion College, Albion, Michigan (1955–1957) and went on to earn his BS (1960) and MS (1961) in electrical engineering from the University of Michigan, Ann Arbor. He pursued doctoral research at the University of Illinois, earning his PhD in electrical engineering in 1965.

Jim's doctoral dissertation, *Electronic Music Instrumentation for the Synthesis, Control, and Analysis of Harmonic Musical Tones*, was highly influenced by composition faculty member Lejaren A. Hiller Jr., and other members of the UIUC Experimental Music Studios. The dissertation described one of the first practical additive voltage-controlled electronic music synthesizers, known as the Harmonic Tone Generator (HTG). The HTG synthesized six exact harmonics with variable fundamental frequency and independent amplitude control. Jim's voltage-controlled synthesis work was contemporary with that of Robert Moog. In fact, Beauchamp and Moog independently presented their first analog synthesis papers at the Audio Engineering Society Convention in 1964, but unlike Moog, Beauchamp's muse was academic research and collaboration, not commercialization. His work with the HTG resulted in a flexible platform for studio experimentation, providing sounds for influential electronic music compositions such as Salvatore Martirano's piece "Underworld." The HTG is now preserved in the UIUC Library's Sousa Archives and Center for American Music.

When Jim joined the UIUC electrical engineering faculty in 1965, his technical focus moved from analog electronics to digital audio software. In 1968, he spent a year working on automatic speech recognition at the Artificial Intelligence Laboratory at Stanford University, Stanford, California, using formant-tracing software he developed. Returning to UIUC in 1969, Jim began a unique joint appointment between the schools of music and electrical engineering, attracting students interested in cross-disciplinary work between the two programs.

Jim's research soon encompassed time-varying spectral analysis and synthesis of musical sounds via computer. One of his key technical contributions was experimental software to calculate the time-varying spectral centroid, or *brightness*, of musical instrument tones played at different volume levels. He utilized these empirical observations to control additive synthesis techniques mimicking the natural spectral evolution of brass instruments with a variety of musical timbres.

In the 1980s, Jim and his students developed an extensive set of digital audio and music signal-processing software routines, the sound analysis package (SNDAN). During his years leading the UIUC Computer Music Project (1984–1993), he also led the development of Music 4C (M4C), a comprehensive computer music synthesis package. Moreover, Jim's music analysis/synthesis research contributed vital technical insights for fundamental frequency tracking algorithms, musical vibrato models, and nonlinear audio processing.

Jim retired from the UIUC faculty in 1997 but remained active in the musical acoustics field, including organizing sessions at many meetings of the Acoustical Society of America.

Jim is survived by his wife of 40 years, Karen; his children Nathan, Kara, Warren, and Bryan Beauchamp; and several grandchildren.

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Obituary

Louis D. Braida, 1943–2022

Louis D. (Lou) Braida, a Fellow of the Acoustical Society of America, died on September 2, 2022, at the age of 79. Lou received his BS in electrical engineering (1964) from The Cooper Union, New York, New York, and his MS (1965) and PhD in electrical engineering (1969) from the Massachusetts Institute of Technology (MIT), Cambridge. He remained at MIT for his entire career as a professor of electrical engineering and computer science (EECS) and of health sciences and technology (HST). He was named to the Henry Ellis Warren Chair in EECS. Lou served for 15 years as director of the Speech and Hearing Sciences Training Program, a part of the Harvard-MIT HST Program, and retired as professor emeritus.

Conducting his research within the Research Laboratory of Electronics at MIT, Lou was internationally known for his work in the areas of intensity perception, the characterization of hearing impairments, and aids for the deaf. Using modern communication theory and signal-processing techniques, he worked to develop improved aids for people suffering from sensorineural hearing impairments, addressing many of the field's knottiest problems in the pursuit of improved performance.

Lou's work strongly enhanced the research community's analytical understanding of both the benefits and limitations of compression amplification in hearing aids. He also did rigorous research on approaches to frequency lowering for individuals with restricted useful auditory bandwidths, on characterizing the benefits of "clear speech" together with attempts to re-create the benefits via signal processing, and on applying automatic speech recognition to generate real-time "cued speech" as a speechreading supplement. Additionally, Lou sought to develop tactile aids that would serve as a substitute for hearing in the reception of speech and environmental sounds in people who are profoundly deaf or deaf-blind.

Lou worked for the long term. His work on intensity perception and loudness includes a series of 14 papers in *The Journal of the Acoustical Society of America*. That research exploited a unidimensional model of perception. He then went on to develop a generalized multidimensional framework that could explain several interesting features of multimodal (audio-visual) speech perception.

Beyond his quantitative approach to perceptual research, Lou had a deep fascination with computers and engineering for psychoacoustic research and in the early days could be seen with streams of punched paper tape hanging around his neck. He was a devoted mentor to all his students, promoting a congenial laboratory environment that was truly remarkable. Occasionally, he "over-reached." To ensure that fresh coffee was always available in the laboratory, he once brought back 25 pounds of green (unroasted) beans from Hawai'i (Acoustical Society of America Meeting of 1988) because they don't become stale. However, we learned quickly that roasting them in a hot-air popcorn maker was not a pleasurable olfactory experience.

Lou will be remembered by his many students and colleagues as an intellectual force who had an enormous impact on our personal and professional growth, and he will be greatly missed.

Selected Publications by Louis D. Braida

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Obituary
Hendrikus (Diek) Duifhuis
1943–2022

Hendrikus (Diek) Duifhuis passed away in July 2022 at the age of 79. Diek was a Fellow of the Acoustical Society of America (ASA). He studied physics at the Technical University in Eindhoven, The Netherlands. His PhD research was conducted at the Instituut voor Perceptie Onderzoek (IPO), also in Eindhoven, under the supervision of Jan Schouten. Diek's thesis work included psychoacoustics experiments and their theoretical description. In his first publication in *The Journal of the Acoustical Society of America* (1970), he described the effect that when a high harmonic is removed from the spectrum of a periodic pulse, a sine tone is heard to pop out of the perception; the sine tone has the pitch of the high harmonic. This phenomenon is now commonly referred to as the Duifhuis pitch (DP). It was a prelude to his later work that focused on the contribution of inner ear mechanics to perception.

In 1980, Diek moved to the University of Groningen, The Netherlands, to take a position as professor of auditory biophysics. There he started to work on cochlear mechanics. After the discovery of otoacoustic emissions, he specifically focused on active cochlear models. These models consisted of an array of coupled self-sustained active oscillators, such as the Van der Pol oscillator, which could account for both the frequency selectivity of the basilar membrane and its nonlinear properties. Similar models have later been used to describe the active mechanical processes in the ears of various non-mammalian species. Diek also applied these models to describe the specialized properties of the cochlea of the horseshoe bat.

In addition to the theoretical work, a line of experimental research was started to investigate the biophysics of the lateral line organ of fishes. This hair cell sensor is much easier to access for experimental study compared with that in the vertebrate cochlea. This work showed the tight coupling between the hydrodynamics of the cupula that covers the hair cells and the mechanical properties of the hair cell transduction channels. Later in his career, Diek studied the acoustical properties of MRI scanners, given that the noise produced by these machines interferes with auditory studies.

Diek was very active as lecturer and leader to shape the physics education at the University of Groningen. He added Biophysics of Hearing and Signal Analysis to the curriculum. He was the first director of the Research School for Behavioural and Cognitive Neuroscience (BCN), still one of the cornerstones of research and education in Groningen. Until shortly before his passing away, Diek remained an active participant of the Auditory Research Group at the University Medical Center, inspiring many young scientists.

Diek is survived by his wife Francien, their sons Hans and Peter, and four grandchildren.

Selected Publications of Hendrikus (Diek) Duifhuis

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Obituary
Oswald Jozef Leroy, 1936–2022

Oswald Jozef Leroy, Fellow of the Acoustical Society of America; Doctor Honoris Causa of the University of Gdansk, Poland; winner of the "Médaille Étrangère" of the French Acoustical Society; and emeritus professor of the Catholic University of Leuven, Belgium, passed away on September 7, 2022, at Ostend, Belgium, at the age of 86.

Born in Passendale, West Flanders, Belgium, on May 16, 1936, Oswald lived his entire life around Kortrijk in West Flanders. His work in theoretical acousto-optics earned him a reputation as a prominent figure in the field of mathematics in Belgium.

Oswald's most significant accomplishment was a theoretical investigation of the interaction of light with two neighboring ultrasonic beams under diverse situations in terms of beamform, frequency content, and intensity. This research was conducted under a variety of different circumstances. In the 1970s, when new acousto-optic devices were being created, mainly due to fresh breakthroughs in laser technology, it was crucial to have a solid understanding of this phenomenon. These devices made use of neighboring ultrasonic beams. Optical modulators, optical scanners, information processing, optical filtering, and frequency-spectrum analysis all used these devices. Before Oswald made his contribution, the sole known phenomenon was the interaction of light with a single ultrasonic beam. Since that time, acousto-optic devices have been used in various fields, including the military and the field of communications.

Diffraction of light by ultrasound, Oswald's dissertation for his doctoral work at Ghent University, Belgium, earned him the degree of Doctor of Philosophy. Between 1966 and 1972, he held the position of assistant professor at Ghent University. Since 1972, he was a professor at the Catholic University of Leuven (KULeuven). While a member of the Department of Astrophysics, he took a position as a professor at this university's satellite campus in Kortrijk (KULAK). Advances in laser physics provided the impetus for partnerships between his team and various other laboratories. He has been a visiting professor at the Paris Diderot University and the Université de Bordeaux, France; the University of Tennessee, Knoxville; and the Tokyo Institute of Technology, Japan. Furthermore, he has collaborated with the University of Gdansk, Georgetown University, Washington, DC, and the University of Houston, Texas. He retired in 2001.

Oswald received an honorary doctorate from the University of Gdansk in 1991 for his contributions to theoretical acousto-optics and to celebrate a collaboration with the team of Antoni Sliwinski at the Institute of Physics. In 2015, Oswald Leroy was presented with a token of gratitude from the International Congress on Ultrasonics, which was co-organized by the French Acoustical Society, for his illustrious career and, in particular, for the warmth and friendliness that he had always shared with the entire acoustics and ultrasonics communities.

Oswald is survived by his wife Agnes Laperre, three children, and eleven grandchildren.

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