Feedback Management in Hearing Aid Technology

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- [Andrea] Welcome everyone. I am Dr. Andrea Hannan-Dawkes and I'm a member of the education and training team at Starkey Hearing Technologies. It's my pleasure to be meeting with you today to discuss feedback management and hearing aid technology. Before we get started, there are few housekeeping items to cover. I am talking now, so hopefully you can hear me. If you have any technical difficulties, please stay logged on and call Audiology Online at 1-800-753-2160. They'll be able to troubleshoot whatever issues you might be having. I do know and can tell you that the most common cause for technical problems is having other software or applications running at the same time that you're trying to watch this class. So you might wanna take a minute to close down any other programs you're running. But again, if you continue to have any technical difficulties, please contact Audiology Online so you can fully participate in today's session. This session is available for one CEU hour or .1 CEUs. In order to get credit, you must stay logged on for the entire session. Attendance is monitored and then complete a short quiz comprised of 10 multiple choice questions. For reference, the quiz is available 15 minutes after a live course presentation. Simply log into your AO account and the quiz can be accessed under your pending courses. You have seven days to complete the quiz when viewing live courses, and 30 days when viewing recorded courses. A PDF of this presentation is available in the File Share pod found in the bottom left corner of your viewing area. Feel free to download that if you're interested in having a copy of the slides today. The chat box on the left may be used for questions. I will stop periodically to answer them. And you can use the icon in the top right corner of the screen with the four arrows heading out in different directions to enlarge your viewing area.

Course objectives for this class, attendees will know what acoustic feedback is and why it occurs. Attendees will be able to discuss the consequences of acoustic feedback on a listener. And attendees will understand the approaches to feedback management available in hearing aid technology today. And with that we are ready to get started. So let's begin by defining feedback. Acoustic feedback has been described as whistling, howling, screeching, screaming, squealing, whining, ringing, humming, buzzing, oscillating and the list goes on. There are a variety of other terms we or our patients have used to describe acoustic feedback. These sounds can certainly be irritating for both patients and anyone nearby and can significantly impact the gain that's available in a fitting and the sound quality of amplification. Feedback can actually make or break the patient's willingness to use amplification and their satisfaction with it.

So it's important for us to understand what it is and how to manage it. To that end, this course has been designed to provide an understanding of what feedback is and why it happens. Information on the strategies for managing feedback including acoustic options, gain reduction and feedback cancellation and a variety of clinical tips to assist you in the office with patients. There are actually three types of feedback that can occur in hearing aids. Acoustic feedback happens when the output of the receiver leaks out of the ear canal, enters the microphone and is reamplified. It's essentially a circle of amplification where amplified sound is continuously reamplified to the point where an audible sound is heard. This is the most common form of feedback in hearing aid technology. But there are two other types that are worth mentioning. Mechanical feedback occurs when physical vibrations of the receiver diaphragm are transmitted back to the microphone diaphragm through contact with the hearing aid casing. And then electronic feedback is the third type, and this type is caused by a malfunction in the device's circuitry. We'll spend most of our time today discussing acoustic feedback, but I do wanna touch on both mechanical and electronic briefly.

There are two forms of mechanical feedback that can occur in hearing aids. One occurs when the receiver comes physically into contact with the hearing aid case and the microphone housing or the circuit components inside the hearing aid case which transmits mechanical vibrations to the microphone through direct mechanical interaction. Another is when the receiver is not touching other internal components but vibrations from the receiver cause vibrations in the case wall that result in acoustic radiation that leaks back to the microphone and initiates feedback. Mechanical feedback can occur in any hearing aid but it's more common in custom hearing aids than it is in standard products. Custom devices are constructed of course with the receiver and microphone within the same housing and in close proximity to one another which creates a pathway for the structural transmission of sound energy.

With BTEs and especially RICs, there is greater separation between the hearing aid components. In RICs of course, the receiver is moved completely out of the hearing aid case which decreases the points of contact between the microphone, the shell or the case and the receiver. If mechanical feedback occurs, it usually comes into play following modifications to a hearing aid or if the instrument has been dropped or damaged. This type of feedback should only be corrected by the manufacturer because it usually involves changing the placement or positioning of the receiver. Electronic feedback can occur when there's an issue or malfunction in the electrical components of the hearing aid. The solution for this involves opening the case of the device to determine the source of the problem and then possibly replacing components in the hearing aid.

So this type of feedback should also be managed by the manufacturer. It is possible for us as professionals to test for internal feedback by sealing off the receiver with putty or a fingertip and then holding the hearing aid up the ear to listen for any kind of sound or signal. Any whistling would verify internal feedback and a listening tube may also be used as well. But keep in mind though that it can be tricky to completely seal the receiver, which may lead to some false alarms. Do know that mechanical and electronic stability are verified during production by the manufacturer using a specific setup. So generally speaking, we don't really see mechanical or electronic feedback very much today. Now let's shift our attention to acoustic feedback, which is what we'll be focusing on today given that it's the primary form of feedback that occurs in hearing aid technology. Acoustic feedback occurs when sound from the hearing aid receiver leaks back into the microphone. The amplified signal gets reamplified, which can create undesired oscillations in the hearing aid, which can make the system unstable. The result of instability is what we call feedback, that loud or unpleasant sound. Many times acoustic feedback isn't audible, but when the output in the ear canal, okay, of that amplified sound, exceeds the attenuation that's offered by the shell, the dome or the earmold, it can become audible. And this can happen when the gain of the hearing instrument is sufficiently high, when a larger than necessary size vent is used, or there is less than optimal coupling to the ear. This schematic shows the process for acoustic feedback in a really simple and straightforward way.

Let's look at the gray path first. The incoming signal goes to the microphone, then on to the amplifier. The amplified signal is then delivered to the ear via the receiver. Acoustic feedback is generated when some of the amplified sound from the receiver is reintroduced to the hearing aid microphone, so now look at the blue path. The amplified signal gets reamplified and then gets mixed with the original signal. If sound reentering the microphone is softer than the original sound entering the microphone, there's minimal risk of feedback. For those of you who have or will read up on this topic, you'll see this referenced in the literature as negative loop gain. If the sound reentering the microphone is more intense than the original sound, feedback may occur. And this is referenced in the literature as positive loop gain. This can occur with power fittings and very high gain, or even with an open fitting when a lot of gain is needed at that high frequencies for example, with a steeply sloping hearing loss.

There are a variety of environmental factors that can contribute to feedback as well. So let me show you a video that provides a simple but effective representation of acoustic feedback. So here we can see the custom device in the ear. We've got the input signal coming into the microphone. The output signal going into the ear canal. And now we can see some leakage of that amplified sound that redirects that signal to the microphone. And now if you look at the ear canal area, you can see that yellow sine wave indicating that feedback is now present for the listener. Now let's take a look or consider some of the factors that are, that play a role in influencing the feedback path that pertain to the amplification system in general.

So venting of course. A loose fit or poor coupling to the ear. A cracked or damaged earmold or shell. Improper alignment of the receiver. And hearing aid gain can all contribute to the leakage of amplified sound from the ear. Generally speaking, feedback is more common in linear fittings. Compression, of course, reduces the gain as the signal intensity increases and therefore can improve the stability of the system and reduce the severity of acoustic feedback. But of course it can certainly occur with all hearing aid technology. In addition, there are several other considerations that pertain to the patient's physical state, movement or environment. So factors like these, cerumen, hats, scarves and other head coverings, jaw and head movements, hugs, coughing, chewing, sneezing, yawning, talking, positioning of an object near the ear like maybe the classic example of that is a telephone.

And even the hands near the ear, when the patient is inserting or removing the hearing aids. Acoustic feedback poses a major problem to hearing aid users for a variety of reasons. And I've got them listed here. So it can create loudness discomfort. The feedback signal can certainly be annoying, that ringing, buzzing, humming sound that they hear or others hear. It can introduce distortion and impact sound quality and that's a really big deal. Feedback can reduce speech understanding and perceived benefit of amplification. The goal in most hearing aid fittings is to achieve the target frequency response for a given hearing loss. But if feedback is present in the hearing aid, it may not be possible to reach the necessary amount of amplification, and speech intelligibility may suffer. Feedback can also facilitate the stigma that hearing aids don't word well. It can be embarrassing and it can lead to hearing aid rejection. So here we see some data from the MarkeTrak Nine study in 2015 related to hearing aid rejection.

The study tells us that the most common reasons people stop wearing or return their hearing aids are because the device is physically uncomfortable or does not perform as well as expected. And performance falls short of expectations when there's too much background noise, too much feedback, and/or poor sound quality. For those of you who are not familiar with MarkeTrak, it's a longitudinal study of the consumer journey that's conducted by the hearing industry's association that provides some really unique data on hearing difficulty, hearing aid usage and adoption rates. And their research over the past 30 years is focused on examining the trends in hearing healthcare, providing professionals with a better understanding of the consumer journey and assisting, even assisting consumers in their quest for treatment of their hearing impairment.

The MarkeTrak 10 study published this year from data collected in 2018, shows us that these percentages are coming down. That's not surprising given the advances in noise reduction and overall signal processing, but there's less of a change to feedback being the primary contributor to hearing aid rejection. So it's still a significant issue that we need to understand and be able to address. Now that we've discussed what feedback is, how and why it occurs and why it's problematic, let's shift our focus to feedback management strategies. We'll discuss what we can do and what the signal processing in the hearing aids can do. The goals of feedback management are summarized here. A better physical fit and comfort for the listener. Make soft sounds more audible. Increase speech understanding. Improve sound quality and provide overall better performance for the listener in all environments. The solutions to managing feedback fall into three broad categories, acoustic adjustments, these are the things that we can do to improve the physical fit and performance of the hearing aid or earmold, gain reduction, feedback can be managed by decreasing hearing aid gain. And feedback cancellation, signal processing algorithms designed to cancel or eliminate the feedback signal. Let's start with acoustic adjustments.

There are several things we can do to control feedback by reducing the leakage of amplified sound from the ear with regard to the physical fit and general characteristics of the hearing aid or earmold. The more we can attenuate leaked sound, the smaller the risk of feedback. One of the things we can do is manage the vent diameter. Typically in the case of feedback issue, that relates to decreasing the vent size. We can increase the diameter of the first bend portion of the earmold or hearing aid for a snugger fit and better acoustic seal. And we can use thick or double-wall tubing in earmolds to help reduce acoustic feedback in high-gain hearing aid fittings. Receiver in the canal hearing aids are still the most popular style fit today. The MarkeTrak 10 study just released found out or identified that the vast majority of hearing aid owners have a hearing aid that sits behind the ear, 73% of study participants. And 60% of those were RICs. So when it comes to RICs, we can change the dome size for a better fit.

Custom earmolds for RICs are a great option. They really provide the ultimate for proper fit, retention and receiver orientation in the ear and of course we can consider stock earmolds for RICs. If the expensive custom earmolds is prohibitive in any way or you know, that's a consideration. Many if not all companies offer these and they typically provide a much better fit than domes or earbuds. And earmold material should be added to this list. In the case of more significant hearing losses where higher gain will be needed, the use of a softer material can often provide a better acoustic seal of the ear and will be more absorptive rather than reflective of sound. In addition, a softer material is recommended for patients with a harder or firmer ear texture to optimize the fit and acoustic seal. Sometimes we know there are trade offs to constructing a snugger fit for the hearing aid or earmold in the ear. For example there may be a decrease in the flow of natural low frequencies through the vent, which can sometimes result in the perception or of the poor sound quality and increase perception of occlusion during vocalization. So it's definitely a balancing act. The best defense for feedback, fit and sound quality problems is a good offense.

So if we can optimize the fit and characteristics of the hearing aid or earmold out of the gate, we'll have fewer issues to address down the road. So over the course of the next few slides, we'll discuss how to optimize ear impressions, coupling to the ear, device or earmold alignment, gain selection and venting. Effective choices in these areas really will help ensure that the hearing aid user is given the best opportunity to utilize the available gain in the hearing instrument regardless of the availability of any feedback cancellation algorithms in the hearing instrument. So let's take a look at ear impressions first. When it comes to custom products or earmolds, good ear impressions are key to a proper and acceptable fit. A couple of suggestions, thoughts and ideas for you. Use cotton otoblocks. They take up less space and you can capture more of the ear canal. When you take your impression, capture the full concha bowl and helix for proper alignment of the hearing aid or earmold in the ear. Of course, be sure to take deep impressions if you're gonna be ordering a CIC or an IIC style device for the patient. And definitely send new impressions with each order.

Yes, they are kept on file by the manufacturer for a period of time. But anatomy can change at any time. So do that as well. So the images on this slide, you can see some examples of incomplete impressions along the right-hand side, and some good ear impressions along the bottom. So we've all heard of the need for good or complete, and/or complete ear impressions. But I thought it would be helpful to show you why it makes a difference. So here's an example of the impact of an incomplete impression. So along the left side of the slide, you can see a good impression highlighted by the blue boxes. On the top is an image of the impression and below along the bottom, we've got the hearing aid superimposed on the impression, the resulting ITE there. And then in the orange boxes, along the top we can see an incomplete impression and then we can see the resulting ITE that was created using that incomplete impression. So again, along the bottom they're superimposed over the impressions. And on the right, here are some of those main points. So if we look here towards the top, a complete impression, you know an accurate canal helix any tragus, is gonna help yield better retention of the instrument in the ear.

So you can see now the ear impressions, you can see the resulting ITEs that were created using those impressions. And now of course, those are superimposed on top of each other. So it helps us see the impact that a good complete impression can have. So better retention of course. If we go to the side here, with an incomplete impression, we're gonna end up with a product that protrudes more out of the ear. So that's a consideration and every patient of course, wants the best fitting optimal size, cosmetic element possible. And then certainly very importantly, as we move to the right here, the orientation of the receiver in the vent. So that can be impacted by an incomplete impression. So again, just wanted to show you why and how good impressions are important.

So open fittings are the most popular type of hearing aid fitting today. So our RIC style devices and open fittings. But they of course are the most susceptible to feedback. So it's important to understand which form of coupling is most appropriate for a patient. For a RIC or even an open BTE device, the threshold at 500 hertz is the primary indicator. So in order to provide optimal amplification with natural sound quality, all the time or all the while avoiding feedback, an open dome should be considered when the threshold at 500 hertz is 20 dB or better. An occluded dome should be considered when that threshold falls between 20 dB and 40 dB. And then a custom RIC earmold should be used when the threshold at 500 hertz is poorer than 40 dB. Manufacturers should be able to provide specific guidance with regard to optimal earmold options. This chart comes from Starkey and shows the best RIC earmold choices as a function of hearing loss. You see some venting elements incorporated there as well. Remember that custom earmolds are always the best option for comfort, retention and receiver positioning in the ear canal.

And sometimes of course the cost of a custom earmold is prohibitive, so stock earmolds are an excellent choice over domes or earbuds. This chart shows the stock earmold options as a function of hearing loss. So you can actually see the earbud options on there as well as the stock earmold options as a function of hearing loss. An important consideration for us as professionals to consider is when to replace earmolds or domes to prohibit the possibility of feedback. You wanna do that certainly if a patient's weight has changed, if their thresholds have changed, if the ear canal tissue has stretched due to earmold usage. Sometimes that occurs of course. If an earmold is damaged, you wanna replace it. In the case of children, they grow of course, so the ear has grown.

So in that instance, of course we wanna make a change. And a mold needs to be replaced when it feels loose or if frequent acoustic feedback occurs. And that's pretty straightforward and logical for us. But keep some of these things in mind by way of when to replace earmolds or domes in earbuds. We would all agree that selecting the proper hearing aid gain and output is crucial for a successful fitting. Hearing aid gain is technically the difference between the input level and the output level in dB SPL. Pragmatically however, it's better defined in my opinion, as the amplification that allows a person with hearing loss to hear, communicate and participate more fully in daily activities. So how do we determine the most appropriate hearing aid gain for a fitting? When choosing the gain for an instrument, 2,000 hertz is the key frequency to consider. It takes more energy to reach the high frequencies than the low frequencies. And the peak response of a receiver is typically at 2,000 or 3,000 hertz.

So you wanna base your decision for the gain of a hearing aid matrix on the threshold at 2,000 hertz. So if for example it falls between 25 and 55 dB, a 40 gain receiver will be sufficient. Another important consideration when it comes to the strength of the receiver are the high-frequency thresholds. Poor high-frequency thresholds should not be part of the equation in determining hearing aid gain when you're considering the matrix you wanna choose. You don't want, or we don't want the high-frequency gain to overpower the low frequencies and introduce distortion that will impact sound quality. Frequency lowering is usually the best option for patients with precipitous or significant high-frequency hearing loss. So keep that in mind. You would be amazed at the number of 70 gain receivers that get ordered for hearing losses like this when the threshold at 2,000 hertz is 35. You definitely wanna fit for today and not for a potential threshold change tomorrow. Another helpful tool is to know that 750 hertz is the most important frequency for vent selection. Be sure to test 750 hertz or at least interpolate or average the thresholds at 500 hertz and 1,000 hertz when selecting a vent. Sometimes we get so concerned about occlusion that we think a bigger vent is always better. But bigger isn't better if there's too much sound leakage and feedback occurs.

This table shows you vent size is a function of the threshold at 750 hertz. A three vent for example, refers to a three millimeter vent. So that would be the right choice for thresholds of 30 or 35 dB at 750 hertz. The number of hearing-impaired individuals supplied with open fitting hearing aids has certainly been steadily increasing over the last how many years. I mean it is the most popular type of fitting. And of course those devices are really nice for alleviating problems related to the occlusion effect. But open fittings of course are especially susceptible to acoustic feedback. So it really keeps, we have to keep this in the forefront of our mind as we're making these decisions about the fitting. I wanted to share a couple of great resources with you. The Microsonic Custom Earmold Manual is available to professionals by visiting their website and signing up with your email address. It provides a wealth of information on everything from taking ear impressions to choosing earmold styles, to acoustic considerations. And the Starkey Modification Guide is a wonderful tool for guidance on all aspects of modifying the hearing aid. And it spans from ear impressions to buffing to patches, to managing occlusion.

So that one is available by reaching out to your Starkey sales representative. I know this is hard to see, but I wanted to try to share some of those topic areas or kind of expand on those topic areas in both of these resources. So here we see the Microsonic Custom Earmold Manual topics. And to give you just a little bit more on that, it covers hearing aid fitting concepts, speech acoustics, impressions, earmold materials, style options, acoustic options, occlusion and earmold counseling even. And then if we expand just a bit, the Starkey Modification Guide, there are sections on good impressions, buffing, difficult or tight insertion, occlusion, modifications, feedback, loose fit, wax protection, vent identification and various modification tools. So check those resources out when you have a chance.

So let's move from acoustic adjustments for managing feedback into gain reduction. Gain reduction provides a simple solution and essentially always works to manage feedback. But the loss of amplification may also reduce the audibility of speech and impact word recognition ability. So this has been used a lot, and it's still used today in the industry in a couple of different ways. Gain can be reduced equally over all frequencies. It can be reduced for the lowest input level. The lowest input level, of course, has the most gain applied in non-linear wide dynamic range compression fittings. And it can be applied or reduced in critical frequency regions where feedback is expected to occur. We refer to that as notch filtering. And an example of notch filtering where the gain is reduced in narrow frequency bands around a critical frequency. The system is made more stable, reducing the potential for whistling, but gain reduction may also reduce intelligibility. So keep in mind that gain reduction options can reduce or impact the audibility of speech, as well as word recognition ability. And typically there's more than one frequency where the instability occurs.

So in the case of notch filtering, suppressing one frequency may create feedback at another frequency. Let's take a closer look. So a notch filter is designed to reduce the gain around a specific frequency region. The name comes from the attempt to quote, notch out a single frequency from the input signal. Multiple notch filters can be employed if feedback occurs at more than one frequency. If the feedback signal changes in its frequency composition, then the notch filters can adapt to this change by correspondingly changing the location of the dip frequency. In this image, you can see a digital notch filter tuned to 2,500 hertz. There are a couple of challenges with the gain reduction and notch filters. Typically there's more than one frequency where the instability occurs. Suppressing one frequency may create another or create feedback at another frequency, and mentioned that already. While notch filters can adapt, reducing gain of course can affect the input signal and may impact audibility. This is especially significant if the bandwidth of the notch filter is wide and is further compounded when multiple notch filters are used.

So gain reduction can make the system more stable and reduce the potential for feedback. But the gain reduction can also of course impact speech. So keep that in mind. The possibility of reduced intelligibility and word recognition ability. The third option for managing feedback is the use of feedback cancellation algorithms. These feedback algorithms use the frequency in phase response of the feedback initialization process to model the feedback path. The general premise behind feedback cancellation algorithms is similar to that of noise canceling headphones. You create a copy of the feedback component and then you add it out of phase to the input signal. These algorithms work very well and most manufacturers in the big six use some form of feedback cancellation strategy. The algorithms however, are proprietary. So while general descriptions of the strategies are available, the details are not. Feedback cancellation algorithms should provide as much gain as possible over a wide range while minimizing or eliminating feedback. They should preserve the audibility of speech, speech intelligibility, sound quality and loudness. They should not introduced processing artifacts that could degrade sound quality. They should have low susceptibility to tonal signals and entrainments, and they should quickly adjust to feedback path changes to minimize instability for the listener.

So how does feedback cancellation work? Here you can see a schematic representation of the principle of feedback cancellation. So the feedback path is modeled mathematically and subtracted from the microphone signal which cancels the feedback. As a result, there's no audible oscillations at the output of the hearing aid. So you saw some of this earlier. If we look at where the signal is mixed with feedback, okay let me engage the arrow here, we see and look at where the signal is mixed with feedback. We can see now that the digital signal processor creates a model of the feedback signal that is then subtracted from the microphone input. So rather than manipulating the gain, feedback cancellation algorithms introduce an additional signal to cancel out the acoustical leakage and the feedback that results. Let's take a closer look at how cancellation of the feedback signal works.

So to do this, we need to consider frequency and phase relationships. If leaked sound represented here by the light blue sine wave, is fed back in phase with the sound being amplified, the medium blue waveform on the left side, the sounds reinforce each other and become larger in amplitude or louder. And that's the sine wave that you see on the right-hand side, that dark blue one. As the leaked signal is fed back and amplified several times, the two signals continue to add together until eventually the signal amplitude is so great that oscillation occurs which produces that characteristic audible squeal. If however the sound leaks back, the sound that leaks back is introduced out of phase with the sound being amplified, the two sounds will partially or completely cancel each other, and the resulting sound will be reduced or canceled. There are different approaches to feedback management that have been introduced in hearing aid technology over the years. But the most successful approaches to date have involved the use of feedback phase inversion.

So I've got another video for you that provides a helpful visual on how this works in hearing aids. So here we can see the feedback represented by the yellow sine wave superimposed over the hearing aid output. When we take that signal, we model it mathematically, we invert it and then re add it to the feedback signal. You get this nice cancellation of the feedback signal. So it's eliminated for the listener. Go back to the presentation. I've got a fun fact for you on the topic of phase inversion. The Grateful Dead's wall of sound prevented feedback by having two microphones for each vocalist with one of the mics 180 degrees out of phase of the other.

So when both mics were mixed on the same channel, the only information that wasn't canceled was the voice. Pretty neat. For reference, the wall of sound was this enormous public address system designed specifically for the Grateful Dead's live performances in 1974 to provide a distortion-free sound system that could also serve as its own monitoring system. I thought that was interesting and a nice example of the use of phase inversion. Since feedback cancellation algorithms simply cancel out unwanted feedback, there's no gain reduction associated with eliminating feedback. They can easily improve the stability of the hearing aid and allow an additional 10 to 15 dB or more of additional gain over an instrument or hearing aid setting that does not use feedback cancellation. So feedback cancellation is very effective for managing feedback in open fits with large vents and just overall in general a great strategy. Let's talk just a little bit about a few of the variables related to feedback cancellation. Let's touch on filters, artifacts and entrainment. A static filter is a single filter applied to the signal. The initialization process identifies where the highest feedback potential exists and one filter is applied. This is very useful for feedback paths that won't change where the environment is stable. There's no movement. Very useful to address entrainment artifacts or entrainments I should say. And some people end up liking the sound quality better with a static filter because there's no artifact from output phase modulation that is a natural result of the phase inversion strategy that can be used or that is used with adaptive filters.

Adaptive feedback cancellation filters are used to accommodate changing feedback paths. The filter is always changing to address changes to the feedback path. The feedback canceler sensitivity settings regulate the speed of adaptation to the new signal. Faster changes are helpful to address the changing feedback path, but artifacts can result. So as a result, the more aggressive the feedback canceler is, the more potential there is for artifacts which may impact sound quality for the listener. Let's touch on that just a little bit. We are likely familiar with two of these potential artifacts. Warble, or that talking in a fan sound, and chirping.

Adaptive feedback cancellation is very effective at eliminating feedback. Phase shifts of course are what allow it to work so well. We talked about that. When the signal with the shifted phase is combined with the original signal, output phase modulation occurs. It's just a natural result. If the feedback canceler's sensitivity is aggressive, there's a larger phase shift. When this happens, the patient may notice a warbley sound quality typically in response to their own voice, but sometimes also for other sounds. When that happens, more artifact reduction is needed. But artifact reduction can cause chirping. So think of artifact reduction as the engine that figures out the high risk for feedback and when to allow the parameters of the system to adapt. It's simply the smart way of turning on or off the feedback cancellation and of managing the filter coefficients. So that's when and how the adaptive filter should change to successfully track changes to the feedback path. These variables are what create the proprietary nature of feedback cancellation algorithms and effective feedback cancellation systems have to find the right balance of engagement and aggressiveness to address feedback without impacting sound quality.

Another important consideration for feedback cancellation systems using phase inversion is entrainment. So this is an artifact that occurs when the feedback canceler mistakenly attempts to cancel a tonal input to the hearing aid, resulting in the patient reporting any of the following. Audibility of the tone, feedback after the original sound has stopped, a modulation type distortion of the sound and distortion. One example of entrainment would be instead of hearing the microwave ding once when it's done, the patient hears ding, ding. They hear the additional tone. The feedback canceler thought that the microwave signal was feedback, so it sent out, it sent an out-of-phase signal to cancel it. But it really wasn't feedback and now that tone is audible to the listener. Entrainment can also distort the sound quality or the quality of the sound and may cause continued feedback once the desired signal has stopped. None of this of course is desirable for any listener and could prove especially problematic in an environment like the operating room where there's a lot of beeping equipment. That is probably one of the last places we would like to have a listener experience any form of distortion or have any kind of issue.

So entrainment artifacts can be eliminated by using an non-adaptive or static feedback cancellation filter. Quite often for example, feedback cancellation is set less aggressively or is turned off all together for music signals. Now let's discuss how dynamic feedback cancellation systems are configured and optimized for each individual patient. The professional performs an initialization process in the office using the fitting software. And the hearing aids, with the hearing aids of course, in the patient's ears. The specific environment surrounding the fitting is included in the measurement including the individual pinna, ear canal, the fit of the hearing aid in the ear and all of the other individual wearer characteristics that would or could affect the feedback path. A broadband noise with a known spectrum, a white noise, is played through the hearing aid which creates a buzzing sound. Potential feedback paths are measured to improve the effectiveness of the canceler. And this is done by comparing the frequency response of the signal at the source to the response at the microphone of the hearing aid.

The potential feedback paths are measured by identifying the frequency regions and which feedback is most likely to pose a problem. And of course it's important to account for the individual anatomy and fitting of each patient. Initialization must be performed in a quiet environment. But we've all had the patient who lets us know that they can hear the sound. But ideally of course we need to run that or rerun that in a quiet environment. The purpose of initialization is to measure potential feedback paths in order to set a starting point for dynamic adaptation in response to feedback conditions. There are two measurements that are commonly used to determine the benefit of feedback cancellation algorithms. Maximum stable gain is the first. MSG is the maximum amount of gain that can be provided without risk of audible feedback or degraded sound quality due to feedback oscillation. Maximum stable gain is often measured as the gain at the peak of the response regardless of the specific frequency at which it occurs. It varies as a function of frequency. More gain should be available with the feedback cancellation enabled versus disabled.

So in the image on this slide, you can see an example of the maximum stable gain at each frequency with the feedback canceler disabled represented by the red line or the red curve. And then enabled, you can see at the top there it's a green curve. So the maximum stable gain is the upper level of amplification that can be applied if the system is required to remain stable. Added stable gain is the second. Added stable gain is defined as the amount of additional stable gain that can provided by adaptive feedback cancellation. In this image, maximum stable gain with feedback cancellation off is shown by the gray line. Maximum stable gain with feedback cancellation on is indicated by the blue line. And the added stable gain is the gray area between the two lines. Feedback cancellation algorithms should provide more gain or should make more gain available to the listener. The goal is to be able to meet target amplification and provide some headroom for volume changes. Added stable gain is important because operating a hearing aid close to its maximum stable gain can result or impact sound quality.

That said, feedback cancellation algorithms across manufacturers do not produce equivalent results. There are differences. Let me show you an example of gain margin. In this example that you see, the gain margin is shown by the red and blue bars for the right and left hearing aids as a function of hearing aid channel. So it represents the amount of gain available before feedback. Notice that there is less gain available for the right hearing aid via the red bars that you see, versus the blue bars. I intentionally altered the feedback path when I made this measurement to create a difference to show you.

Let's look now at the relevance of maximum stable gain and added stable gain in another way. So in this image, the solid blue line represents or indicates the gain prescribed by the NAL-NL1 fitting formula for an input of 50 dB. The blue dotted line shows maximum stable gain with feedback cancellation off. Notice that between 2,000 hertz and 4,000 hertz, the prescribed gain exceeds the maximum achievable feedback-free gain. So without feedback cancellation, the clinician may be forced to sacrifice audibility and decrease the gain of the hearing aid to eliminate feedback. Now let's look at this gray dashed line. This shows us the maximum stable gain with a strong feedback cancellation algorithm. The prescribed gain can easily be accommodated with room for adjustment. So you can see the nice advantage that's available using feedback cancellation. The difference between the blue dotted line and the gray dashed line represents the added stable gain, so this region here in between. High added stable gain is especially crucial for open fittings where there's a greater risk for feedback, and as mentioned earlier, good sound quality is retained or facilitated by ensuring that we don't operate the hearing aid close to its maximum stable gain. Now let's take a look at some additional clinical considerations for managing feedback. Although feedback reduction techniques have become common in digital hearing aids, there's still no standardized objective procedure for evaluating them.

That said, there are a couple of probe mic measures that can be done to evaluate the quality of feedback cancellation systems. The first one is referred to as added gain before feedback. So in this test, the gain of the hearing aid is programmed to a prescriptive target like NAL-NL2. The feedback suppression is turned off. The real ear-aided response is measured. The feedback reduction algorithm is then turned on, and the process is repeated. The difference between the two real-ear aided responses is the added gain before feedback. This test can measure how well the feedback cancellation prevents audible feedback. But if gain is stable without suppression on, with suppression off, without it engaged, the hearing aid might reach maximum output with feedback reduction on before feedback actually occurs which would prevent any assessment of added gain.

So in addition, keep in mind that while this can be a useful tool, it doesn't provide any information related to sound quality. The second probe mic measure is maximum real-ear insertion gain that's available with the feedback reduction algorithm on. So here the real-ear unaided response is subtracted from the real-ear aided response. It provides an indication of how much headroom is available for the fitting. It could be a nice tool for comparing hearing aids if you have the time to do that or in a situation where you'd like to do that. Or perhaps more practically for us, coupling options. We can see the impact of the coupling that we've chosen and potentially make changes based on the results that we see. Gain capping secondary to running the initialization process is common in the hearing aid industry. Four of the big six companies will limit the amount of gain you can access for the patient. So for anyone best fitting a hearing aid and not checking, you may be under target. Keep in mind that real ear and speech mapping are extremely beneficial to ensure the hearing aid response is appropriate. And it's important to rerun the feedback canceler initialization under the following conditions. I've listed here for you new fittings. If the wearer or the user reports feedback, if there are any changes to coupling that are made, if you make any changes to venting, and certainly following hearing aid repair.

So when you're refitting or reissuing the device, you want to rerun that feedback canceler initialization as well. So here we want to account for changes to the acoustic, you know the feedback path. We wanna account for any potential changes to the circuitry in the hearing aid, any potential anatomy elements as well. And remember keep in mind that the purpose of initialization is to measure feedback paths, so those potential paths in order to set a starting point for the dynamic adaptation and response to feedback conditions.

So much more optimal, much more on point for the patient to use that initialization process versus not using it. Feedback does not always occur in the high frequencies. It can happen in the low frequencies as well. Here you can see the region with the lowest gain margin I've got circled, or circled, boxed there in yellow for you. So in this example, the lowest gain margin is occurring at 1,100 hertz and below. If I were to raise the gain in the hearing aid and I heard feedback or the patient reported feedback, and my response was to reduce high frequency gain, which is actually a very common clinical go to for feedback, two things would occur.

One, I would reduce the audibility of the consonant sounds of speech that are centered in those higher frequencies that are so important for speech clarity and word recognition ability. And I wouldn't address the feedback. The issue is likely going to occur in the low frequencies. So one of the impacts of reducing high frequency gain is a significant impact on the listener with regard to speech understanding and word recognition ability and all of that. So we really wanna manage feedback with a cancellation strategy instead of a gain reduction strategy whenever possible. Power on delay can be a good tool. We can increase the power on delay for the patient to give them more time to get the hearing aids up and into their ears. This can be a very effective tool. We've already talked about custom RIC and BTE earmolds to ensure proper seal of the ear canal and alignment of the receiver in the ear with movement and to provide comfort as well.

And just another kinda plug for stock earmolds. Keep those in mind as well. Definitely a better option over domes or earbuds. Frequency lowering is a feature designed to improve high frequency audibility with precipitous high frequency hearing losses. In these strategies, the high frequency bandwidth is altered. There's little-to-no high frequency gain applied and so feedback can be less problematic with frequency lowering engaged. That said, this feature should only be used with the right patients. All forms of frequency lowering across the industry alters sound quality to some degree. So we don't want to just randomly use frequency lowering. We don't wanna use it as a tool to manage feedback. And of course behavioral validation is necessary to validate the benefit of frequency lowering when used. So keep that in mind with regards to frequency lowering algorithms.

For the BAHA sound processor, the bone-anchored hearing aids, the feedback source is generally broadband and can be of acoustic or mechanical origin. The source of the feedback is not solely related to leakage from the transducer back to the microphone and may actually relate to feedback originating from a mechanical source, skull radiation, soft tissue interference or other variables that are known to play a part in the feedback pathway for BAHA sound processors. So just a quick word or mention on those. And then another fun fact for you related to feedback. In I Feel Fine by the Beatles, that sound actually starts with a single percussive feedback note that was produced by Paul McCartney plucking a string on his base while John Lennon's guitar was leaning against McCartney's base amp. The feedback was picked up and amplified. So this actually turned out to be the first use of feedback on a rock record. So if you wanna check out that song like I did and listen to that, you will hear that feedback note at the start of the song.

And so to wrap up today, feedback management is an important tool for optimizing the patient journey with amplification. I hope everyone has a better understanding of feedback and feedback management and feels better prepared to assist patients with this issue. I definitely wanna encourage all of you to take the time to understand how feedback management works in the hearing aids you're fitting. Read the white papers published by the manufacturers. Understand the acoustic options for earmolds, venting and coupling to the ear. And definitely do real ear measurements and speech mapping to ensure optimal fittings. And with that, I thank you very much for joining me today. I really appreciate your time and I hope you have a great rest of the day.