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Candidacy Expansion and Improved Outcomes in Cochlear Implant Surgery

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Presenter: Daniel Zeitler, MD, FACS

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- [Moderator] At this time it is my pleasure to introduce Doctor Daniel Zeitler who will be presenting: Candidacy Expansion and Improved Outcomes in Cochlear Implant Surgery. Doctor Zeitler is a board-certified neurotologist and school-based surgeon in the Department of Otolaryngology Head of Neck Surgery at Virginia Mason Medical Center in Seattle, Washington. He graduated from Northwestern University and earned his MD with honors from NYU. He completed his residency at NYU and a fellowship at the University of Miami Ear Institute. Doctor Zeitler has engaged in a variety of clinical and basic science research projects, has published over 40 articles and book chapters, and has presented his work at national and international meetings. We welcome back Doctor Zeitler today, and at this time, I'll hand the mic over to you.

- And I appreciate the introduction. I just want to mention that some of this work was supported by a grant from the NIH. Today I wanna talk to you about candidacy expansion and improved outcomes in cochlear implant surgery, one of my most favorites surgeries that I get to do on a weekly basis here at Virginia Mason. Just a quick picture to show you where I am, in the upper left corner of the United States, beautiful city of Seattle. It doesn't always rain, and this is a picture of one of those days I suppose where it wasn't raining, but we welcome anybody who wants to come visit us here anytime. The objectives for today are: to discuss the advances in surgical technique and electrode design that have allowed us to improve patient outcomes following cochlear implantation, we wanna discuss the use of cochlear implantation as a rehabilitative option for patients with single-sided deafness and we'll talk about why that's especially apropos in light of recent announcements in the past several weeks, and lastly to review the use of objective tools to determine the subjective sound quality of a cochlear implant. So I think we all know as audiologists here, this is an audiogram of a patient who used to show up to our door for a cochlear implantation. This is an audiogram of a patient with bilateral severe to profound sensorineural hearing loss and I think all of us in this chat room would know that this patient certainly meets criteria for cochlear implantation, but I think more and more now it's this patient who's walking into our office asking about the possibility of cochlear implantation and I think a lot of us may not consider this patient to be a good candidate for cochlear implantation. I hope that by the end of today's lecture you will understand that this patient with significant amount of low-frequency hearing is just as good a candidate, potentially even better as the patient I showed you previously, but in order for that to happen, we have to keep that low-frequency hearing or at least we have to try to keep some of it after cochlear implant surgery and that's because we know fairly well from objective research that low-frequency hearing preservation after cochlear implantation is incredibly beneficial to these patients, objectively speaking, in addition to subjective benefits. We know that acoustic electric hearing in patients with low-frequency preserved hearing can improve localization of sound, it can improve things like melody and pitch recognition in listening to music, it can make hearing-in-noise objective outcomes better, and it can even in some papers, although there is some around this, can allow for improved speech recognition, although certainly this is very much in the air as far as the results of hearing preservation on speech outcomes, but what are the requirements for hearing?

So if we know that it's important to do, how can we do it? Well, in my opinion, there are two ways that we can make hearing preservation successful after cochlear implant surgery. We can either make the surgery better, in which case me and the other cochlear implant surgeons have to do our job well, but we can also remove the blame off of our shoulders and say that it has to be the design of the electrode that determines the outcomes of hearing preservation. So we're gonna talk a little bit about these individually. First of all, let's talk about advances in surgical technique. So the whole idea of soft surgical technique, vis-a-vis hearing preservation, efforts first came about around the mid-1990s in Germany by a cochlear implant surgeon by the name of Ernst Lehnhardt and he stated that in order to do very atraumatic and soft surgery there were four key components to doing that well. The first was to minimize drilling on the cochlea, which makes total sense. The second would be to treat the cochlea like a very very sacred fluid chamber so you don't want to open the cochlea for the implant until you're absolutely ready to put the electrode in. This sort of encompasses the idea of not wanting blood or bone dust or other foreign materials from the surgical field getting into the cochlea as there are some people that believe that inflammation in the cochlea may be facilitated by some of these foreign objects getting into the cochlea. We want to avoid suctioning of the perilymph out of the cochlea. This is the same technique we use when we do stapes surgery. We do not want to remove the fluid out of the cochlea as this has significant effects on the homeostasis and electrical conduction of the cochlea, and then lastly you can use a lubricant of some sort. Some people have talked about glycerol or hyaluronic acid, which does two things. It lubricates the electrode, so it reduces surface tension going in, but it also has a density that is greater than blood and bone dust and so it allows those things to float out of the cochlea if they have sneaked in. In doing these soft surgical techniques the idea would be that you minimize trauma and thereby improve objective outcomes. So why should that be the case? Well certainly we know that all of the mechanical hardware of the cochlea travels through the osseous spiral lamina as it enters into modiolus, the neurons of the hair cells go through the osseous spiral lamina so you don't want to fracture that. That's the highway of these neurons getting into the modiolus. Similarly as important, you do not wanna injure the modiolus.

This is where the spiral ganglion cells live and so injuring the modiolus can rupture the input to the auditory nerve. You certainly don't wanna compress or tear he microvasculature as this is where the battery essentially of the cochlea lives, and lastly we know that if you have what's called interscalar excursion or the electrode goes from the Scala Tympani to the Scala Vestibuli, that's also gonna do significant damage and compromise hearing preservation. To show that this is a project I did as a resident at NYU. We took a cochlea out of a cadaver and we shaved it down so we were just holding the cochlea in that, in the clamp here that you can see, if my pointer's working. Here is the clamp. We did three different sort of angles of insertion and looked at them under fluoroscopy. You can see that with very subtle changes in the direction of the electrode, you can go, on that first picture on the left, really right towards the modiolus on that picture on the right sort of go away and towards the lateral wall, and then in that second middle picture you're really going right down the lumen. So it's the subtle changes that are important because if you look at your physics, if you remember physics, there's forces that are derived from insertion of the electrode. So here you can see the electrode in the Scala Tympani right here. As you put that electrode in, there's a force that travels towards the lateral wall as it goes in, that then generates a force from the lateral wall against the electrode and the resultant force, F3, goes up towards this basilar membrane seen right here. That's important because if you don't get the angle right and you have significant force upwards, what you end up with is a picture like this where you can see the electrode is coming in. Here, this shows up well on your screen, is the basilar membrane, and here you can see this electrode has gone right up through the basilar membrane and is now sitting in the Scala Vestibuli. We know that there are a number of counterproductive factors when this happens. So because of all of these thoughts, the idea originally was that we should make a cochleostomy to put these electrodes in. In other words, we should make a hole into the cochlea so we know that we're putting in the electrode in the correct orientation. This theoretically improved visualization down the cochlear lumen, as well as ensured a mid-scalar trajectory.

This is a really beautiful picture taken from a friend of mine, Peter Rowland, at the University of Texas Southwestern, and here you can see that exact thing. So here's the round window in this cochlea. Here you can see we've made a cochleostomy and here's the electrode going right down the lumen of the Scala Tympani. So this is an ideal situation. If you then compare that to this drawing, here is now the same or similar picture, but now instead we have the electrode going through the round window right here. In the previous picture the cochleostomy would've been up here. Here you can see by the dotted line is a region of the cochlea called the hook region or the crista terminalis. What that hook region does is it forces the electrode away from the scala and up towards the modiolus. So the problem is that even though, sorry the thought was that by using the cochleostomy we could avoid this problem. The difference between these electrodes in 2007 and the electrodes now is that the electrodes now

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are much softer and thinner and they're actually made specifically to improve the ability to go through the round window. So these pictures really were relevant many years ago, but now with the changes in the electrodes it may not be so relevant. The other important thing to consider as we talk about cochleostomy is that we as surgeons aren't as good as we think we are and I don't encourage any of you to tell us that ever, but we can look at our own data and admit it because here's a study that was done at the American Neurotology Society in 2007. They showed this picture to all of the cochlear implant surgeons in the room and asked us where we would make the cochleostomy. As you can see, this picture is number one through 14, and from the graph on the right, every single dot on that picture, other than number eight and number I guess, yeah, other than number eight, every single dot had someone who felt like that was the correct placement of the cochleostomy. What I think is most interesting is if you look at those two red dots, those two reds dots are on exact and opposite sides of the cochlea.

So a percentage of us, and I hope I wasn't one of them, didn't even know which ear this picture was representing. So it seems as though we aren't quite as good at making cochleostomies as we think we are. So what we learned from that is that the cochleostomy, while it was sort of originally the dogma of electrode placement, probably had a significantly high rate of electrode placement outside of the scala. The problem with that is that it allowed for all of those traumatic events to occur like I just mentioned. So in the mid-2000s there became sort of a cry for help if you will and a renewed interest in round window insertion of the electrode to reduce trauma and improve accuracy. This is a beautiful study by the folks at Vanderbilt in 2016 where they looked at the three different surgical approaches. They have round window on the left, cochleostomy on the right and what they call extended round window, which is an insertion still through the round window, but instead you sort of drill down that crista terminalis area that I showed you before. What you can see here in black are all of the Scala Tympani insertions. They looked at the placement of the electrode after insertion. On the gray is the Scala Vestibuli. You can see that with round window, and slightly less so with the extended round window, we're getting the electrode in the Scala Tympani about 2/3 or more of the time, and this is significantly better, statistically, than where we get it with a cochleostomy because as you can see half or even more of the electrodes in the cochleostomy end up in the Scala Vestibuli. So this was really a telling sort of revelation and it went against a lot of the dogma that had been sort of proposed previously. That's also important not because we wanna pat ourselves on the back and say we got the electrode in the right tube, but it does seem to make a difference. There was a lot of data out of WashU previously that showed that Scala Tympani insertion probably improves speech outcomes and that is represented by the reference to Skinner et al in 2008, and then O'Connell again in that same study showed similarly that when you have the electrode in the Scala Tympani, represented in black, you can see that both CNC and AzBio scores are significantly better than they are if the electrode ends up in the Scala Vestibuli.

So we really came full circle here. Now you ask, well how can we determine where these electrodes are in patients who have cochlear implants? Well the answer used to be something complicated and very rudimentary like this where we would take an x-ray. We would do all kinds of complicated mathematical equations. You'd have to draw lines that were perpendicular to one thing and parallel and tangential to the other. It just didn't make sense and it was extremely difficult to have any kind of significant accuracy with where the electrode was. But now what we can do is we can take a patient, we can put the cochlear implant into their head and in real time, with the electrode inside, we can get a CT scan. We send that CT scan to my colleagues at the Vanderbilt University and they can reconstruct the scan with the electrode inside and it allows us to have beautiful data that's computer generated, such as if you look at each electrode contact there, one through 16, this is an Advanced Phonics device, and you can see that it can calculate through the computer things like the distance from the modiolus, which we'll talk about, the insertion depth, the frequency along the cochlea where each electrode is theoretically placed, the location of the electrode. You can see the electrode is entirely beneath the green, which is the representation of the basilar membrane. You can even in incredibly cool experiments use this map, use the CT scan to turn off electrodes that may have significant cross talk with nearby electrodes, and that's what's represented by that active and inactive. This data is fairly immature, but there are many many patients who can have improved quality of sound and speech outcomes if we turn off redundant electrodes. So really, really exciting. So we talked about surgical technique, now let's talk about advances in electrode design. So similarly, I showed you before that the type of placement in the Scala Tympani or Vestibuli could have an effect, but so too can the type of electrode. So this is a really nice study again done out of Vanderbilt University where they looked at different electrodes. They looked at lateral wall electrodes compared to perimodiolar electrodes. You can see here that it varies highly statistically significant number of electrodes ended up in the Scala Tympani when their lateral wall electrodes versus perimodiolar electrodes. Now before we start saying that we should not use perimodiolar electrodes ever in our life, it's important to note that this study was done with the older perimodiolar electrodes that were typically bigger and longer and stiffer.

So I think that this study would benefit from sort of a rehash of some of the data, but certainly you can see that at least with the older stiffer electrodes, lateral wall devices really stay in the Scala Tympani much, much better. Similarly you can see that if you look at those same two or three types of electrodes here, perimodiolar, lateral wall and mid-scala, in terms of hearing preservation, you can use the perimodiolar electrode as the reference and you can see that both lateral wall electrodes and mid-scala electrodes have highly significantly better hearing preservation rates than the perimodiolar electrodes. Again it's important to remember that these perimodiolar electrode are some of the older generations. There are some data coming out with the new perimodiolar electrodes that the hearing preservation is better, but we don't yet know how it compares. This is just a wonderful video to show you sort of exactly what I'm talking about where we have the force of the electrode going in, it hits the lateral wall and it wants to stay underneath the basilar membrane. So if we could play the video please. So here you can see the electrode going in here. You're gonna start to see it coming down here. And here, if we can pause the video, you can see that it's now just starting to contact the lateral, if I can pause, you can see that it's just now starting to contact the lateral wall. Here is the basilar membrane right here, demonstrated by this sort of thin clearer shell structure. Now remember the picture I showed you before. In the past this electrode that was stiff and wide would hit this lateral wall and probably want to bounce up due to that third force or F3. But here, as I continue to advance the video, you'll see that this electrode stays beautifully around the lateral wall rather than bouncing up through the basilar membrane here. You'll see that as it curls up and continues to curl up, it stays entirely within the Scala Tympani. This is the new slim J or lateral wall electrode from Advance Phonics. This video was used with their permission. You can see as it's going up, again just a beautiful lateral wall placement with absolutely no impingement onto the basilar membrane. This is really where electrode design has made significant strides. If we go back to the slideshow please. Technology is just amazing.

So there was a really interesting article in 2008 that was written here out of the University of California, San Francisco, and they sort of talked about the three primary goals as they saw them for future electrode design. It's almost like these revelations of Marty McFly in Back to the Future have come true, but they talked about reduced intra-cochlear trauma, they talked about deeper insertion to access low-frequency neurons in the apex, and they talked about greater operating efficiency. So this was their wish list, and interestingly, all of these things have happened and we're gonna talk about that. So we've already sort of showed you that electrode location matters. I showed you that there is a significant correlation between the CNC word and AzBio scores when it comes to where the electrode is in the scala. The Scala Tympani as I showed you has a much higher benefit for speech outcomes. Now we're gonna talk about these other two things, which are insertion depth and proximity to modiolus. So as we think about cochlear depth and how it might relate to outcomes, it's important to remember that everybody's cochlea is different. If you look at a graph of different cochlear sizes of the cochlear duct, you can see that there is certainly a bell curve and a uniform distribution. The majority of cochlear duct lengths are somewhere between about 29 and 33 to 34 millimeters, but you can see there are some patients down in the 25 to 26 millimeter range and there are a handful patients around the 34 to 36 millimeter range. So I think, again, in the past, we've sort of used a one-size-fits-all theory, the idea being that if we have an electrode that fits in the cochlea, at least most people's cochlea, it's gonna do well enough, but I think more and more companies now are starting to use this idea of variations in cochlear duct length. In fact one of the companies now has electrodes that span all the way from 31 and a half millimeters to 28 to 26 to 24 to 20, so a huge sort of portfolio of electrode sizes with the idea being in the future we can more accurately measure people's cochlear duct lengths and pick sort of a customized electrode for that patient. But as insertion depth or angular insertion depth relates to speech perception outcomes , while we don't yet have customized electrodes, we do know that speech perception may be affected by insertion depth, and this talk was really perfectly timed.

There was just this month or last month a systematic review in the journal Otology Neurotology where they looked at seven studies and correlated angular insertion depth toward scores, and in fact only one study that was done well. These studies included patients only that had one year's worth of follow-up. They included only adult postlingual patients and they included only those patients that had had CT imaging to confirm the location of the electrode, but as you can see only that study from 2016, the O'Connell study that I've referenced previously, showed any benefit or, sorry, any relationship. In fact, what they showed was quite interesting. They showed that for every 10 degrees of insertion depth, or angular insertion depth as we call it, so basically 360 degrees angular insertion would be one full turn. 720 degrees angular insertion will be two full turns. So for every 10 degrees of angular insertion depth, they got a 0.6 bump in CNC or essentially for every 15 degrees of angular insertion, they got a 1% change in CNC. What's interesting is this doesn't sound like a lot, but in a patient who had a significantly deep insertion, you could get somewhere between 12 and 15% increase, theoretically, over someone that had a shallow insertion. Now this correlation was even stronger in patients without preserved hearing, again sort of highlighting the fact that if you don't have low-frequency preservation, you want to cover the entire cochlea, and I think that's what they showed here. There were a few studies that were excluded from the systematic review due to less than one year of follow-up, but these studies did have correlations that were starting to develop. So it may be that these relationships between insertion depth and speech perception really are manifest by the speed at which people start to perform well, rather than the long-term performance, i.e. maybe people who have deeper insertions do well faster, but at the end the asymptote of all patients' performances is basically the same. It is important to note that for that O'Connell study only the lateral wall and the straight-array electrode showed this relationship between insertion depth and CNC. For the perimodiolar arrays, it did not, and actually those arrays showed that shallower insertion actually had better performance. We could talk about that at the end, but it probably is due to the fact that if you use a perimodiolar array and you insert it too deeply, you're gonna miss some of those basal-most spiral ganglion cells for activation.

There is also a trade-off right between angular insertion depth and trauma. You can see the line at the top there that as the Scala Tympani goes from basal to apical location, the diameter of the Scala decreases. We know that as you put the electrode in, there's gonna be, as that Scala diameter gets smaller and smaller, at some point you're gonna reach sort of the cutoff point whereby increasing depth is gonna start to also be correlated with increasing trauma. That probably seems to happen around 24 to 25 millimeters at least when it's a lateral wall electrode. I think the important thing to remember here is that maybe what this means is we just need to make smaller, narrower electrodes. But the other question that a lot of us have and one really knows the answer to is: does the insertion depth regardless of trauma have a bigger representation in outcomes than does reduction in trauma, but shallow insertions? I think this is sort of the Holy Grail that no one really knows the answer to . So last thing we're gonna talk about: increased operating efficiency, so again sort of that wish list of the three things that the folks from UCSF wanted. They mentioned increased operating efficiency, and that's in the form of what we call electrode-modiolar distance. So in other words, it is exactly what it sounds like, how far is the electrode from the modiolus from those spiral ganglion cells that need to be activated? There have been a number of studies that have shown that reducing the electrode-modiolar distance causes a number of positive benefits, including decreased excitational spread, lower stim currents, lower psychosocial thresholds and sea levels, as well as improved speech recognition. This is a really nice study again out of WashU where they looked at electrode-modiolar distance and they did it in the form of something called a wrapping factor, in other words, how tightly wrapped is the electrode to the modiolus? So you can see that a lower wrapping factor is a better more tightly wound electrode than a higher wrapping factor. This is a computational number that's derived from a mathematical equation, which I don't have here, but suffice it to say you can see that there is a very very clear negative and very statistically significant negative trend between the distance from the modiolus and the CNC word scores with those patients that had more medially and more tightly wrapped electrodes showing increased CNC scores.

So this has been the reason truthfully why people have been really pushing back towards perimodiolar electrodes despite the fact that the older ones like I showed were stiff and big and long, and probably cause more trauma. There is a renewed interest, specifically by Cochlear Corporation with their new 632 device, to try to get the electrode in the perimodiolar location to increase wrapping factor and possibly outcomes. The one question you might ask is, well, the wrapping factor's great, but how do we know that the electrode is staying in the Scala Tympani? In other words, what's more important, the Scala Tympani or the wrapping factor? And the answer was really nicely shown in the same study that if you take away all of the electrodes that were not in the Scala Tympani, so now we're just looking at Scala Tympani placement, there is still a very very strong negative correlation between wrapping factor and CNC score. In other words, those patients who had better wrapping factors had better CNC scores. Whereas those with larger wrapping factors had poor CNC scores. So again it does seem as though Scala Tympani insertion is important, but even still it also seems that the wrapping factor or the distance to the modiolus is similarly important. We talked about spread of excitation and this is just a picture, just kind of demonstrate that graphically. You can see that in the lateral wall electrode on the right there can be significant spread of excitation. Whereas placing the electrode closer to the modiolus really concentrates the spread of excitation around the spiral ganglion cells that are more closely approximated to the filter center frequency of the device itself . So that sort of finishes up our topic on the device and the surgical, and now let's talk about advances in surgical candidacy, and specifically let's start with early implantation and cortical neuroplasticity. So we know that the juvenile brain has a great capacity for plasticity and there have been a number of authors who have talked about something called a sensitive period which is basically thought to be stages with high neuronal plasticity. In other words, these neurons can sort of be told what to do. We've seen studies where we looked at patient's brains and even the old wives' tale where someone that can't hear very well say they can smell better and people who can see say they can hear better.

There may really be some logic to these old wive's tales, that the brain utilizes parts of the cortex that are not in high demand and it donates these things to other senses that may be in more high demand, but the problem is that these sensitive periods also seem to have an end point at which learning is probably compromised, in other words the neurons are no longer highly plastic and the cortical delegations for tasks have been more definitively assigned. This endpoint seems to happen probably around four years where the neurons kind of rapidly proliferate for the first three and a half years and then those neurons that aren't being used much, like you would to prune your hedge, are sort of cut back and potentially not only cut back but maybe even donated to other cortical regions. So it makes sense that if you have early lack of auditory stimulation, you're gonna have a lack of cortical development. So this has been sort of the push behind the thoughts about getting patients implanted earlier than 12 months. So as we all know, the FDA says that we are supposed to implant patients 12 months

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and older, but many many of us have been doing patients younger than 12 months off label for a number of years and we aren't doing this to be cowboys or to prove how great we are as surgeons. We're doing this because the data actually seems to be very impressively positive. We know that children implanted under 12 months show improved comprehension and expressive communication compared to their peers implanted later. We know that they have improved word learning. They have reduced language delay which is equal to their chronological age and this gap is closed much sooner and they also are able to increase their sentence complexity compared to their peers who are implanted later. This is an incredibly busy slide and I don't expect you to understand this, but I wanna make a few points here. This is worked on by Anu Sharma at the University of Colorado Boulder who I've done some of my research with, and this is basically a graph. This is a graph of a bunch of cortical-evoked auditory potentials. What we see here, in each color is a patient who or patients who are implanted at different times of deafness. So you can see half or six months to one and a half years, one half years to two and a half, et cetera, et cetera. And these tracings down here in the middle are the evoked potential tracings. Specifically we're looking at P1 because the P1 latency is a really good marker for electrical maturity of the auditory pathway.

So here, using this CAEP , we can look all the way to the primary auditory cortex. You can see that here in green, those patients who are implanted between six months and one and a half, their P1 latency, which should be between 50 and 300 here, as you can see, milliseconds, these P1 latencies come right back down into this normal range, which is the space between these graphs. You can see kind of going along as you go from purple to black to light blue, and light blue is the three and a half to four and a half year old age group, you can see that once these patients are implanted their P1 latencies come back to pretty normal, but there's a stark sort of division line here as the colors start to turn purple, which are those patients which have four and a half to five and a half years of deafness before implantation. Now you can see a lot of the purple. Almost all of the yellow and all of the fuchsia or pink, which are patients implanted over the age of six and a half, never ever returned to this normal P1 latency standards, So this is an electrical study that sort of confirms what we've always thought with behavioral studies. So still moving on. Now, so even more recently, so we've talked about those patients with low frequency hearing loss coming into our office who want a cochlear implant, now we have patients who have audiograms like this: single-sided deafness or severely asymmetric hearing loss. I always have said that people have strangest ways of sort of having epiphanies about what they wanna do in medicine. This is Graeme Clark, Professor Clark who is basically credited with developing the multichannel electrode at Cochlear. This is me. I had the pleasure of meeting him in Australia. As the story goes, Graeme , was walking down the beach and he picked up a conch shell and he said, "Gee, this looks like a cochlea," and he took up a piece of grass or some kind of weed on the beach and slowly thread the weed through the cochlea and said, "Wow, I can get an electrode," or, "I can get a piece of wire into the cochlea "by threading it up through the lumen," and that was his epiphany for the multichannel electrode. Now unfortunately my story is not quite as beautiful and romantic.

My story instead starts when I was in Denver for four years studying single-sided deaf patients. I went to a little brewery just outside of Denver and they had a beer called One Ear and I said, well, there we go. This is my epiphany. As all good things happen with alcohol, so too did my desire to study patients with single-sided deafness and thus was born my research interest in patients with unilateral hearing loss. This talk really comes on the heels of what is a remarkable announcement that the FDA has just approved two weeks ago the use of cochlear implants for single-sided deafness and asymmetric hearing loss. This is an incredible breakthrough as many of us have been trying to do this for many many years and we now finally have the opportunity to do so. So I think, it's sort of a great quote that I've sort of modified, that it's not only movement that creates new starting points but sometimes all it takes is a subtle shift in perspective or a new route to see new options. We've been studying cochlear implants for years, in fact, decades, but it's now the single-sided deaf patient population that has allowed us to sort of change our perspective about how we study these patients and gives us a window of opportunities into doing some new things. So as you study these patients with single-sided deafness, there's sort of two schools of thought. The pessimist or the person who is kind of the naysayer would say, Well if you give a patient that has an excellent signal in their normal ear and you give them what is sure to be a poor signal in their implant ear, they're gonna attend to the better signal. The poor signal's gonna suffer neglect. They're gonna have a slow acquisition of recognition and their asymptotic performance is gonna be low and they're probably not gonna do well in the binaural condition. They're also probably gonna always compare their CI ear to their normal ear and they're gonna tell you it sounds awful. The optimist is gonna say exactly the opposite, that maybe if you have a normal hearing ear, the brain can use this signal as the correct signal or kind of an anchoring purpose, which is really the optimal condition for learning.

Therefore, the acquisition of speech should be rapid. The performance should be better than average. The binaural function should be good and the subjective quality should be good because the normal ear can actually teach the deaf ear of what sound sounds like. So this has sort of been the million-dollar question as we've started to study these patients and we're slowly and surely getting some answers. This is a study that we did in 2016, myself and my colleagues from the Mayo Clinic, we looked at our first 23 subjects with single-sided deafness who had been implanted. You can see there about 2/3 adults, 1/3 children. The duration of deafness, you can see, most of our patients had idiopathic hearing loss. What we found as you can see is that preoperative, the mean is there in red on CNC and AzBio and you can see at three months, the mean score improved significantly, which is to say that these patients are learning quite quickly how to use their implant. Interestingly, from three months to six months, these scores did not change statistically. So maybe this is sort of the optimist's view coming through here and showing that learning is quick but that asymptotic performance happens early and may not get a whole lot better over time. We're continuing study these patients and we're gonna try to see how they do up to a year. Similarly if you put these people in a sound localization task, you can see that we have normative data from Arizona State University, which is where my collaborator Doctor Michael Dorman has his lab. You can see that if you put patients into a sound field and ask them to estimate where they heard the sound amongst a 13-speaker array, they can do that with about six to eight degrees of accuracy. If you have a patient with bilateral cochlear implants, you can see that their mean is there, about 30 or 31. In our patients with single-sided deafness, rather than chance, which you would expect that they only have one ear, now that we give them that CI back, they're doing as well as these patients with bilateral cochlear implants. Now why aren't they doing better? We don't know. It probably has something to do with the compression of the processing in the implant compared to the normal hearing ear and the loss of latency and timing cues, but what is interesting is that a handful these patients do really really well and in fact approximate the 95th percentile of the patients with normal hearing.

So this was exciting. We also specifically looked at our children that had SSD and this was written up in a separate paper that was published just this year earlier when we looked at children and adolescents who had been implanted for single-sided deafness. These are our patients and you can see that the majority of them again had idiopathic congenital hearing loss. You can see that the mean length of deafness was about four years, but there were some outliers, so the median was about three years, and here are their scores. So you can see that in the preop to three-month condition, again, there was a significant improvement, but you can see just, I don't have the means marked here in red, but you can see just sort of using your sort of mind's eye that the mean probably didn't change a whole lot from three to six months and from six to 12 months when the data becomes a little sparse as these patients haven't been followed, all of them up to a year. Again this sort of shows that maybe the single-sided deaf patients' brains are sort of primed to learn quickly by their normal hearing ear. If you then compare these pediatric patients to the adult patients which are in gray, you can see that they look to do better, they look to do a little bit better at three months and maybe especially at six months, but the problem is again we have a small number of subjects.

If you actually look statistically at those differences, while the pediatric patients do do better, these results were not statistically significant. So I think it's important to understand and what I tell my patients is you can expect your pediatric single-sided deaf patients to do at least as well as the adults. My hunch as the data becomes more mature is that these differences will become statistically significant, but that is purely speculation. Now last but not least, sort of what has driven a lot of my research over the last five to six years has been the question and I think all of us wanna know the answer to which is: what does a cochlear implant sound like? Now for many many years we've been unable to answer this question because we're relying on patients who have bilateral deafness, in some cases 30 to 40 years of bilateral deafness to try and remember what normal sound sounds like and compare that to their implant, and that, as you can imagine is essentially an impossible task, but now we have this incredible window into what a cochlear implant can sound like because we can put an implant on somebody's ear that has single-sided deafness and we now can compare the implant to a normal hearing ear, and this has been truly exciting.

How do we do that? Well it's actually this experimental design is really quite simple. We take the patient's implant, we plug in through a direct-connect cable into their processor and we play a signal, we play a speech, we play a sentence. We then play that exact same sentence in the opposite ear through a headphone and we ask the patient to compare the two. And as they compare the two, they use a computer setup here and you can see, if I make this a little bit bigger, that the computer setup, which is done through MATLAB in a custom sound booth, you can see that they can use a number of these different filters. They can change the pitch, they can change the formant, they can use a sign or a noise vocoder, they can use a higher or low pass band filter. What they're doing here is they are adjusting what they hear in their normal ear to sound like what they hear in their implant ear. So you can see that. So you can play the original to the CI, and then you can play the simulation and you can make adjustments in the simulation so that these two sound more and more identical. What do we find? Well it seems as though place-pitch match is probably the single most important thing that drives what the implant sounds like. So as you may or may not know, the cochlea has a very very topic specific or organization of the spiral ganglion cells in the hair cells, which is to say that each area of the cochlea does one very specific task as it relates to frequency. There's an equation, the Greenwood function, which has been updated recently by who has a somewhat more accurate equation, but the Greenwood function basically predicts that the position of the hair cells in the cochlea respond to a certain frequency along the spiral ganglion and this creates a pitch map. So ideally if you put energy into the cochlea, a speech signal, theoretically you'd want that energy along the array to be the same as the energy along the cochlea, and in a perfect scenario, that would happen. Unfortunately, the cochlea is not a perfect scenario. We know that there are non-radial trajectories of the spiral ganglion cells, especially as they reach the apex, that probably cause a failure of this alignment, and as I mentioned it probably gets worse as you go from the base to the apex. So realistically, the signals which are supposed to be matched up perfectly have some kind of pitch shift and in some cases it may be two or 400, and in some cases it may be quite significant at six or 800 hertz.

So again , using that information and using these beautiful scans that we can get from Vanderbilt, we can actually see where these electrodes are in the cochlea and try to match them up with a place-pitch match. So these are two different patients of ours. You can see that in this patient number one, we can match up the filter center frequency of the electrode, all 16 electrode contacts, and we can use that and estimate where that would be in the cochlea and you can see that there's an offset of about two times. So the filter center frequency of the electrode is about two times off what it should be at the nearest tissue. Now this was a little bit disturbing, so we decided to check with different electrodes. So the first was Advanced Phonics, the second was a , and again, we saw the exact same thing. So clearly it seems that there is about a two-time shift in pitch along the electrode array. Now what does that mean? What's the consequence of a shift of two times? Well if you can picture in your mind the sound that a Munchkin's voice would make , this is an exactly a two-times pitch shift mismatch. The Munchkins in the Wizard of Oz were not actually recorded from little people, the voices from little people. They were actually recorded in 1939 from normal-sized people and they were recorded at half speed and played back at two-times speed, which gave the impression of a much higher voice frequency than normal . So for this reason, many of the voices in the implants have what we have started to call a Munchkin quality. So just to play a few examples of this, if I could have the sound files . So if we play a sound, a sentence, and I hope you can all hear this, here's the original sentence.

- [Man] Do you like camping?

- Okay, so that's the original sentence, do you like camping? We can then use the software to upshift that pitch. So here's that same sentence at 20 hertz upshift.

- [Man] Do you like camping?

- 60 hertz upshift.

- [Man] Do you like camping?

- 40 hertz, I think I went out of order.

- [Man] Do you like camping?

- And lastly, 80 hertz.

- [Man] Do you like camping?

- Okay, so with a pure pitch shift, you don't really get that Munchkin quality. So this is the fundamental frequency shift. If we then go to the next slide, if I could have those sound files, now we're shifting the entire spectrum or what we call the formants of the original signal. So again, we'll play the original.

- [Man] Do you like camping?

- Now we're gonna shift the entire spectrum up 200 hertz.

- [Man] Do you like camping?

- 400.

- [Man] Do you like camping?

- 600.

- [Man] Do you like camping?

- And 800.

- [Man] Do you like camping?

- And it's with this spectrum shift at 800 hertz that you really start to hear that Munchkin quality or that very very significantly upshift-ed voice. So if we go back, you can take away the sound files, if we go then back to that graft that or, sorry, that graph, that table, again I told you that all of these patients have a two-time shift, but there's one significant difference between these two electrodes, and that's right here, and you can see that that's angular insertion, so again, going all the way back to what we talked about at the beginning, angular insertion depth. So it seems that angular insertion may not only make a difference in speech outcomes, but we believe that angular insertion depth probably also makes a difference in speech quality because the deeper you can put the electrode, the closer you can get the filter frequency to the nearest tissue in the cochlea. Here on the top you can see that the filter center frequency is or, sorry, the nearest tissue in the cochlea and a shallower angular insertion is not gonna be anything higher than about 419 degrees and that's gonna be about 620 hertz. Whereas in the deeper insertion of 525 degrees, the closest tissue in the cochlea's 390 hertz, and this we think makes a difference. So if we now take a handful of patients, and these are just sort of experimental tests, these were patients who we played a signal into their cochlear implant and they told us, when they did the matching on the software, that they did not use any shift in pitch or formant. So these are patients, here the first example is a patient who had the frequency of their deepest electrode at 300 hertz.

- [Man] The sun is finally shining.

- Now that isn't a very clear signal, but you can see that there's certainly no Munchkin quality. Second is a patient who had the place frequency of their nearest first electrode at 440 hertz.

- [Man] The sun is finally shining.

- I mean that signal sounds almost like a normal person to me talking through a microphone, then if you take a couple of patients who did use the software to create an upward shift in pitch and/or formant, you can see that their place frequencies where the electrode started were significantly higher. So here's a patient with upward shift that has a first electrode at 620 hertz upshift.

- [Man] Do you like camping?

- And a patient with 780 hertz upshift.

- [Man] Do you like camping?

- And those two patients in my opinion could be on the Wizard of Oz. So really you see that there really starts to become a significant upshift in frequency because of a shallower insertion. So as we finish up, I just wanna take three patients. Now these are real patients of ours who, just to sort of put it all together, this first patient is a patient who had a cochlear implant. The tissue nearest their most apical electrode based on the CTs images was 390 hertz, and this is a patient who demonstrated no shift in formant frequencies to make their match.

- [Man] The sun is finally shining.

- Okay here's the next patient with a tissue nearest the apical electrode at 590 hertz, and they used a 250 shift.

- [Man] The sun is finally shining.

- So much more of that high-quality Munchkin voice, and then lastly a patient with a significantly shallower insertion at 720 hertz and they used a 400 hertz shift.

- [Man] The sun is finally shining.

- So what seems to be clear is that the brain, if you go back to the last slide, in the plasticity of the brain, it can make some adjustments for mildly upward shifted sound quality but at some point the frequency along the spiral ganglion is too different and too off-shifted compared to the electrode for the brain to be able to make sense of that. At that point we think is when the frequency shifts occur and the formant shifts occur and we get that Munchkin quality voice. So this is really fun stuff and we're doing a lot of work with these patients and I wish I could give a whole lecture about some of the stuff we've done with these patients. But to conclude, surgical techniques and electrode design advancement have certainly led to improved outcomes following implant surgery. We know that atraumatic insertion and Scala Tympani placement are absolutely paramount. There also seems to be a significant advantage to implanting children with bilateral deafness younger than 12 years. I hope I've convinced you of that. Regarding single-sided deafness, we know that cochlear implants are a wonderful rehabilitative tool for these patients, and now that we have FDA approval, we're really excited to start implanting more of these patients, and that place-pitch match does not seem to have to be precise. The system can normalize the offsets, but there does appear to be a limit to that normalization and at some offset there's gonna have to be a shift in pitch and that's probably most dependent on where the electrode is in the cochlea with deeper insertions, giving us less upshift. Thank you very much.

- [Moderator] We're gonna leave the floor open here just for another moment or two. Thank you so much, Doctor Zeitler, for being on with us today. I know it's a beautiful sunny day out here in the Pacific Northwest and we appreciate your time and your expertise and joining us and presenting to our membership.

- My pleasure. I know that in the past I think if any of the people listening here have questions after they get offline or they look over the handout and realize they forgot to ask something, Christie, I'm happy to have you put anybody in touch with me that has a question I can answer by email.

- [Christie] We can absolutely do that, Doctor Zeitler. And I'll tell you from my own experience, we actually had a member who took your last course in October of last year. They put a comment that they did reach out to you and you just graciously replied back to help them set up their clinic and so I know our members do appreciate--

- My pleasure.

- [Christie] You as a resource. Thank you so much, Doctor Zeitler, and thank you everyone for being with us today. Enjoy your day.