Implications and Techniques for Individualize Mapping

Recorded May 4, 2020

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AudiologyOnline.com Course #34745

- All right, thanks, my name is Brendan O'Connell. I want to thank the American Cochlear Implant Alliance for the opportunity to present, and the organizing committee for the invitation to do this remotely. The topic that I'm gonna focus on is Frequency-to-Place Mismatch in Adult Cochlear Implant Recipients. I want to start by acknowledging the large team of people that we have at UNC. As you can see here there's lots of members that contribute to our research, and in particular I want to highlight the efforts of Meg Dillon, Emily Buss and Mike Canfarotta, who were instrumental in accomplishing the data presented herein.

So to begin, I think most of us recognize and know that default implant mapping capitalizes on the natural tonotopic organization of the cochlea, such that low-frequency information is delivered to the apex, and higher frequency information is delivered to the base of the cochlea. Frequency-to-place mismatch is essentially the result of a discrepancy between frequency filter assignments and natural acoustic place of transduction within the cochlea. And for CI-alone users, so non-electric-acoustic stimulation users, variability in electric position is the primary factor that drives mismatch, which can impact the spectral cues that are delivered to the patient. And two things, so in CI-alone users, two factors primarily effect that mismatch or effect the electrode position, and the first of those electric characteristics. So length of the electrode. As you can imagine a longer electrode is gonna sit at a different position than a shorter electrode. And I highlighted here differences in the Flex series for an array in terms of length. So the FLEXSOFT is 31.5 millimeters. The 28 and the 24, are 28 and 24 millimeters respectively. So the second factor is patient specific cochlear geometry. And the primary thing that contributes to differences in electrode position related to geometry is the cochlear duct length. And what we've shown here, courtesy of Vanderbilt, is the 3D reconstruction of two cochleas. The one on the left has a relatively average, just below average cochlear duct plane at 33 millimeters than the one on the right is a large cochlear, almost 38 millimeter cochlear duct length. And that's the same electrode, FLEX28 electrode inserted into both of those cochleas. You can see just in terms of relative position the differences that would be present, largely due to the difference in cochlear size between the two. For electric-acoustic stimulation users, the frequency filters are fixed but rather they vary as a function of the residual acoustic hearing. So just to recap in a patient, so this would be a patient that's been implanted in the left ear. The cut off frequency is identified where the unaided threshold exceeds 65 decibel, so here it would be about 300 hertz. Everything less than 300 hertz would be delivered and amplified acoustically, and the remaining frequency information would be logarithmically distributed across all 12 electrode contacts. And this adds one more dimension and variable to the concept of mismatch in EIS users. It individualizes frequency filter assignments but it's based off the audiogram, not based off the electrode position.

So in terms of the objectives in the outline, we're first gonna investigate variability in insertion depth, angular insertion depth, and a large cohort of lateral wall arrays. Secondly, we're gonna review the associated frequency-to-place mismatch for CI-alone, and EAS users who are mapped with default frequency filter assignments. We're then gonna move on and go through some data which look at the impact that frequency-to-place mismatch has on speech recognition performance in electric-only condition. And then lastly, assess whether the speech benefit conferred by decreased mismatch could be mediated by improved spectral resolution. So just starting with angular insertion depth, we enrolled 111 adult recipients, all were recipients of metal electrode arrays to maintain consistency and design programming, Electric contacts and spacing. All patients underwent post-operative CT imaging, this is an example of a post-operative CT. Here oriented in the cochlear view. The round window is marked by the green dot in the lower right where the electrode enters the cochlea. The red dot marks the center of the medullas. A line is drawn through these, and that essentially is your zero degree access, and then anything in the first turn is gonna be 360 degrees obviously, and the second turn then up to 720 degrees. The contacts are then identified in an angular insertion depth for each contact is calculated. And then that angular insertion depth is used to approximate the place frequency, the cochlear place frequency based off of previously described average spiral ganglion maps. So these are our data that plot on the X-axis the different arrays that were included. So 25, 24, 28 and 31.5 millimeters arrays. And on the left y-axis you can see the angular insertion depth of the most typical contact. And on the right y-axis you can see the associated spiral ganglion place frequency with that insertion depth. And first off, just on average, as you would expect, the angular insertion depths increase with increasing length of electrodes on average the FLEX24 group electrode contact one was sitting in a region of about 400 degrees on average. FLEX28 maybe 550 degrees on average. And then the FLEXSOFT the standard group about 630 degrees. And these corresponded to place frequencies of respectively moving from 24 to 28 to standard place frequencies of 600 degrees on average for the FLEX24, or sorry, 600 hertz. Roughly 300 hertz for the FLEX28, and about 150 or 160 hertz for the FLEXSOFT. And that number is relatively important, because that often times is very close to what the center frequency of what the electrode is in CI-alone users. The other thing is worth mentioning and highlighting is the variability that you see within individuals within the same electrode group, and that is most pronounced for the FLEX28, and you can just see a very wide spread of angular insertion depth.

So these are all complete insertions are plotted here so none of these are partial insertions, all electrodes have all 12 contacts within the cochlea. And you could see that the FLEX28 varied from as much as 430 degrees, all the way up to almost 700 degrees, and again, that's driven by differences in individual patient geometry of their cochlea. So moving on to looking at frequency-to-place mismatch, again focusing initially on CI-alone condition. So this graph here plus the mean angular insertion depth of feature electrode contact as a function of the default frequency filters. Each electrode group, or each electrode is plotted separately according to the different colors. And we've also plotted the spiral ganglion frequency to place function in the dark black line. And this is for all 80 users that were listed in the CI-alone condition. As you can see moving from left to right, From low-frequency to high-frequency, each symbol represents a contact, so that first group of symbols on the left, around 150 hertz represents E1, and all electrodes on E1 receive the same center frequency, 150, 149 hertz. And you can see that they in general on average are gonna lie at an insertion depth that basal or proximal to the associated place frequency. Of 149 hertz, and obviously that's most pronounced, that difference between the spiral ganglion frequency map and the frequency filter assignment for each electrode is most pronounced, most different for the shallowest insertions. This now plots the same data with the same convention, just showing each individual patient. The dotted lines now represent, we got it on partial insertion you can see as you would assume the partial insertions are gonna be shallower than complete insertions, that's logical. But overall there were only four partial insertions, and I think it's worth noting that there were only two partial insertions out of a large number, out of 46 and 31.5 millimeter electric cohort, and that just goes to show that in our experience we don't have an issue with any electrode being too long, we certainly don't have high rates of partial insertion With longer electrodes. And this data also demonstrates the marked variability within electrode arrays, so within the FLEXSOFT 28 group, within that 31.5 millimeter group, of how they differ in terms of position within the cochlea in relation to the spiral ganglion place map. This now plots mismatch on the y-axis, so plots mismatch in semitones between the default center frequency and the place frequency of that contact as a function of insertion depth, and it does that for each electrode.

So if you look at, let's take the left half of the graph from 0 to 270 degrees, so within the first turn of the cochlear. If there was no mismatch all the symbols on average, all the average symbols would lineup right on the zero line. But if you look in that first 270 degrees you can see that the 28 and 31.5 millimeter electrodes lived about six semitones away from no mismatch. So to review, six semitones is half an octave, so the 28 and 31.5 millimeters electrodes were deviated by about half an octave below the spiral ganglion place frequency in the first term. Whereas the 24 millimeter electrode deviated by an octave in that first turn. And then you really see things start to diverge beyond 270 degrees. So looking to the right of 270 degrees, you can see that the FLEXSOFT and standard group maintained about half an octave deviation from place frequency through the second turn in the cochlea. In that same region the

FLEX28 now is deviating by about an octave, and the FLEX24 deviates by up to two octaves in that late part of the first term, and early part of the second term. So in order to assess the impact that frequency-to-place mismatch has on performance, we need to do it in a way that easily quantify what mismatch was. So we chose to measure absolute mismatch in terms of semitones deviation at 270 degrees insertion, which response to the 1500 hertz region of the cochlea. This has been an important region, has been identified as an important region for frequency alignment in prior vocoder simulations, also corresponds to the approximate spectral center of speech information required for recognition. And this graph over here plots that metric, so absolute semitone deviation at 1500 hertz for each electrode. And as you would expect, you can see the greatest deviation, greatest mismatch for the FLEX24 group. And then less as the electrode is getting longer, and those differences between electrode groups were significant.

But this is more important and this now plots the absolute mismatch on the x-axis in semitones against the CNC performance on the y-axis. And what you can see is that less mismatch, so further to the left of the graph was associated with better CNC word performance. And you may look at this and may notice that perhaps these correlations are primarily driven by the poor performers that live in the bottom right of each of those graphs, the one month and six months time points, and that brings up the question, and we can't answer with these data, but it brings up the question of whether or not there's a criterion threshold for which mismatch becomes notably detrimental. And looking here, anything with less then six semitone mismatch looks more or less like a cloud, and you get beyond six semitones, and there's not a ton of patients that live in that area, but beyond half an octave of mismatch and performance clearly start to decline. So something that we could look at in the future there. So up to this point I've showed data that support the notion that a shift in the spectral queue, so mismatch is what could impact performance in the CI-alone condition. Both really at short term time points and acutely at six months. But because electrodes and CI-alone conditions, because programming uses default filters over a fixed frequency range, and because the contacts are also fixed, a change in the length of the electrode, which inherently changes the spacing between the 12 contacts could impact spectral resolution. So as longer electrodes generally decrease mismatch, and also have larger contact spacing or outcomes that we previously presented could be confounded. So we wanted to look a bit more into this idea of spectral resolution, so as a proxy for spectral resolution we measured the angular distance between contacts on that same region of the cochlea that we assessed mismatch. So for contacts sitting between one and two kilohertz we measured the angular distance between them and then plotted that against CNC words, and again at the same time points, so here we have one month and six months and you can see that the greater distance between contacts, the better performance in CNC score. Suggesting that there could be better spectral resolution by spacing out the frequency information a bit more which confers benefit. We hypothesize that electrode spacing would be highly correlated with mismatch for the same reasons that I discussed before. And this demonstrates those same concepts.

So on the left we have what you would perceive to be a potentially ideal scenario, you have a small cochlea, a long electrode. So a long electrode reaches all the way into the apex, it minimizes mismatch which is marked by the green, and that's in that region of 1500 hertz, that's where we've marked that. And the spacing between contacts is roughly 60 degrees in that scenario, so that's favorable to both the mismatch and the spacing are favorable. Now we're gonna move in another direction, so let's take the same electrode and a larger cochlea. Mismatch is not worse, so marked by red. And angular spacing is now worse, because it curves to a lesser degree, or less steeply. And that now is moving both things in the wrong direction and the same goes for okay, and even a bit worse, you take a shorter electrode in that same large cochlea, and mismatches again even worse, it's spacing is even worse. But what we found was interesting in that spectral resolution did not directly correlate with mismatch, and this is why, it's really due to differences in basal insertion depth. So you can take that same long electrode and a large cochlea now, and you can, whether you want to call it over-inserted or not, you can push it in further, perhaps all the way to the stopper marker, and now you've actually reduced mismatch. So you've made mismatch again favorable, but still the contact spacing is a little bit less favorable than it would be in a small cochlea, so now the two have moved in opposite directions, and for this reason the two did not correlate. And in a regression model we found that both mismatch and greater spacing between electrodes were independently associated with better CNC performance post-operatively. So switching gears a bit to electric-acoustic stimulation. As I mentioned before, there's another variable at play here, and that's the residual acoustic hearing which determines the cut-off frequency, which determines frequency allocation. And that's all done irrespective of electrode positioning in the cochlea. So this is like one of those initial graphs I presented for electric-only patients this is individual patient data with angular insertion depth plotted as a function of frequency filter assignments for EAS users, and you can just see that things are kinda all over the place here, each electrode has a different color, you can see that some patients line up very nicely with the spiral ganglia map, others are below, some are above the spiral ganglia map, and this then plots it similarly to the graph in terms of the prior graph that showed mismatch in semitones.

So this is mismatch in semitones between the default center frequency for each specific patient according to that patients audiogram, and the spiral ganglia place frequency as a function of insertion depth. And it demonstrates just the high degree of variability and mismatch. Really it shows us three different scenarios, the first scenario would be one, so if you take all the patients above the zero line that's one in which the insertion depth extended into the cochlea region, which is being aided acoustically. So you're delivering frequency information, higher frequency information to lower frequency region of the cochlea, which has also been amplified acoustically with a hearing aid. And as you imagine this could be detrimental, in a sense that it could cause peripheral electrical and acoustic masking. The second scenario would be one in which the insertion depth meets the cut-off frequency, and that would be insertions typically on the far right of the graph, insertions that are around that zero line, where the depth is just so happened to meet the edge frequency of electric hearing and mismatch is minimized in that scenario. And then the third scenario as all those insertions that are below the zero line, in which the insertion depth is proximal and it did not meet the acoustic region and that causes negative mismatch as we saw in the electric only group. And it's just worth noting that the majority of cases fell into this negative mismatch category. And the take-home from this is for me is 55 to 60% of EAS cases demonstrated mismatch by greater than half an octave, and it goes back to the concept of if we think half in octave is important, in over half of cases here half of patient's listening with EAS are outside of that range, then perhaps this could also impact outcomes, and that needs to be looked at in the future. So in conclusion, these data demonstrate significant variability in angular insertion depth across recipients, even for those with the same electrode array, and that's due to individual differences in cochlear size and geometry. Variability in insertion depth results in mismatch in both CI-alone and EAS device users, who listen with default frequency filters. And when you look at the CI-alone condition, both reduced mismatch and greater spacing between electrode contacts are independently associated with better speech recognition in that electric only condition. Thanks for your time.

- Hi, I'm Margaret Dillon from the University of North Carolina at Chapel Hill. And this is the second part of our decision on Individualizing Electric Frequency Filters for Cochlear Implant and Electric-Acoustic Stimulation Devices. As Dr. O'Connell just laid out, we have seen variability in angular insertion depth of electrode arrays, and we think incorporating where the cochlear implant is within an individual's cochlea can help us improve their outcomes when we are considering how we should map these devices. I would first like to acknowledge our team at the University of North Carolina, we are spoiled rotten to have such amazing physicians, researchers, clinicians and students that work with us to advance our patient care. My collaborators on this particular project are Dr's O'Connell, Buss, Canfarotta, and Hopfinger. So as Dr. O'Connell just reviewed, we have seen large variability in the angular insertion depth of electrode arrays, both across and within different electrode array types. We'll talk a little bit first about the default mapping procedures for cochlear implant alone and electric-acoustic stimulation devices, propose our place-based mapping procedure that incorporates the angular insertion depth of individual electrodes. And then review some pilot data that we have collected for simulations of CI-alone and EAS device users showing the superiority of the place-based mapping procedure as compared to current default procedures. What we currently know is that insertion depth and where we are in the cochlear can influence a patient's speech perception with the cochlear implant, and we have seen evidence of this in cochlear implant users of longer lateral wall arrays demonstrating better speech recognition than those with shorter lateral wall electrode arrays. And we've also seen this in a simulation work, but then also with cochlear implant recipients where we have seen a closer alignment between the electric frequency filters and the cochlear place frequency supports better more monaural and binaural hearing.

As Dr. O'Connell just showed you, we have seen that within a given device there is wide variability in where the electrode array ends up in relation to the cochlear place frequency. What we have here is individual recipients of the FLEX24, the FLEX28, and then the FLEXSOFT electrode that all differ in electrode array length. And here we have the Apical AID, or the Apical electrode ID of where it is within the cochlea. And on this side we have the predicted spiral ganglion place frequency. And what we can see within a given electrode array, that if we look particularly at the FLEX28 there is wide variability of where that Apical electrode array ends up relative to the cochlear place frequency. So we could be stimulating a cochlear place frequency anywhere between 750 hertz, all the way up to around 125 hertz. However, this information is not currently being incorporated into the way that we program a cochlear implant. So for CI-alone devices, the aim is to provide the full speech frequency range, and for an example a default range may be 100 to 8500 hertz, and the way this is done is that for each individual electrode the frequency information is divided up and logarithmically distributed across the electrodes. And this is an example of that where we have our most Apical electrode here is electrode one, all the way up to electrode 12, and we can see how that low-frequency information all the way up to that high frequency information is being distributed for each of those individual electrodes. But again, this is not taking into account where we are within the cochlear. For EAS devices the aim is the same of wanting to provide the full speech frequency range. However, now we need to make the decision of where to divide that frequency information between acoustic and electric simulation. And we have an example audiogram here of the patient that was implanted in the left ear and the default procedure for mapping EAS devices is to 1st identify the region of aidable acoustic hearing, and that we can see that here highlighted in blue. And from that point on we logarithmically distribute the remaining frequency information across those active electrodes. And again, we are not considering where we are with the electrodes within the patient's cochlear.

So this idea of thinking about place of simulation is not new, early work thinking about cochlear implant patients and the way to program them showed that when you were assigning the electric frequency filters closer to the estimated cochlear place that patients and those listening to simulations of cochlear implant devices perform better on speech recognition tasks than if that electric frequency information was shifted. Also more recently we have seen the use of post-operative CT scans in order to determine where an individual's electrode is within their cochlea, and we have seen work from Vanderbilt where they have identified electrodes that have had scaler displacement And figuring out when to deactivate particular electrodes and seeing if that is providing patients with better speech recognition if we are individualizing the mapping of these devices. So with our place-based mapping procedure, we are using the post-operative CT scan to calculate that cochlear place frequency. And then we assign the electric frequency filters for individual electrodes to match the cochlear place frequency up to at least 3000 hertz. There are some considerations for CI-alone and EAS device users when we were applying a place-based mapping procedure. For CI-alone devices, you could be limiting the amount of low-frequency information that's available to the user. For instance, if we pay attention to this FLEX24 electrode array group and we are applying a strict place-based map, it could be that these listeners do not have low-frequency information below 500 hertz, and by limiting the amount of low-frequency information that is available to the listener, this could be detrimental for their speech recognition. For EAS devices we can have a situation where we are creating an overlap between the frequency information that is being represented acoustically and electrically. Here we have an electrode array recipient of a long electrode where the two Apical electrodes our within that region of aidable acoustic hearing. And so in this scenario we would be representing that low-frequency information both acoustically and electrically if applying a place-based map. The way that we can resolve this situation so that we are not masking any of the benefits if acoustic low-frequency hearing is that we can turn down the stimulation levels of these most Apical electrodes to allow that frequency information to be represented acoustically while still having the place-based map on the remaining electrodes. We can also have a situation where we are creating a gap in frequency information, and so now we have the same audiogram but only a short electro array recipient, and we can see that the electrode does not extend into that region of acoustic edible hearing, however there is this gap where frequency information is being represented if we're doing a strict place-based map. And we have seen from previous work that having a gap of frequency information in electric acoustic devices is detrimental for speech recognition.

So this is something that could also impact negatively speech recognition when using an EAS device with a place-based map. So our question was is there a difference in acute speech recognition when listening with the place-based map, as compared when listening with a default map for CI-alone and EAS devices. So we first piloted this with some simulations of CI-alone and EAS devices for some normal hearing listeners to see whether or not this would be an effective approach. And we based our simulation off of the FLEX24 array recipients, so the shorter array recipients we were talking about earlier to see somewhat worst-case scenario, if we had someone with a high low-frequency filter because of that strict place-based map. Would that be detrimental for CI-alone users, and with that the detrimental for an EAS user. So we took one of the FLEX24 array recipients from that earlier plot and calculated the cochlear place frequency using the spiral ganglion frequency place function as defined by Stakhovskaya et al. in 2007. And we had 22 normal hearing young adults who were randomized to listen to either a stimulation of a CI-alone device or an EAS device that was mapped with either a default or a place-based map based off of this particular patient's cochlear place. For the CI-alone simulation the default frequency filters were 70 to 8500 hertz. For the place-based map which took into account where the electrode array was for that individual FLEX24 electrode array recipient. The low-frequency filter for the place-based map was defined as 550 hertz and we decided to use the same high frequency filter as the default condition. For the EAS simulation, the default mapping procedure assigned 250 hertz at the low-frequency filter of electric simulation considering the patient's unaided acoustic hearing. For the place-based map the frequency filters are the same as what we would have in the CI-alone condition, and we based the simulation of the acoustic output as the same as what was provided in the default condition.

And what we can see here is by doing that we are introducing a gap in acoustic and electric represented frequency information, which is what we had known up to now it should be detrimental for speech recognition. The test battery was the AzBio sentences and a 10-talker masker. And the procedure was a repeated stimulus, ascending signal-to-noise ratio task, where the masker was fixed at 60 dB SPL, and the target sets intensity was increased in two dB steps until the subject understood the sentence 100% correctly or reached the maximum signal to noise ratio, which was 19 dB SNR. What we have here are the results in the CI-alone simulation, first for the default condition. On the Y-axis we have proportion correct, and on the X-axis we have the range of dB SNR that was provided to the listener. Each of these individual lines are the results from the 10 subjects that listened in this condition. And if we think about what we do clinically, we typically present AzBio sentences at a 10 dB SNR, so to give you a gauge of where we are in the clinic, this is the range that we typically see for default listeners at 10 dB SNR for the AzBio sentences. And so we can see from this plot there was poor performance at those more challenging SNRs and that that started to improve as the SNR became more favorable, but there is this variability in the speech recognition performance across these normal hearing listeners listening to CI default condition. Interestingly with the play space condition we can see that these listeners, again we have 10 subjects in this group. Achieved better speech recognition overall at these more challenging signal-to-noise ratios. So if we pay attention again to the 10 dB SNR, we can see overall the speech recognition was better in this condition and at these more favorable SNRs they were ending up with a better outcome than what they were with the default condition. And to remind you the CI-place condition, the low-frequency filter was 550 hertz, so these listeners do not have access to low-frequency information below that. For the EAS default and EAS place conditions, again we can see wide variability at that 10 dB SNR.

However, better speech recognition now with the addition of the acoustic component than what we saw in the CI default condition, which is what we have learned to expect from EAS device users with the addition of acoustic low-frequency information provides a performance benefit, particularly in noise as compared to performance with the CI-alone. But what was interesting with the EAS place condition is we also see better speech recognition at that 10 dB SNR if we pay attention to our clinical familiar point here, and that again they are ending up with better speech recognition at these more favorable SNRs. Here we have the results from each of the four listening conditions that we can compare performance against each other. So first we have EAS place-based map, CI-alone place-based map, EAS default and CI-default. And we have the results here and rationalize our sign units where a higher value indicates better performance. And we have taken the individual performance from that most favorable signal-to-noise ratio, so 19 dB SNR. Each of the individuals are represented by a green star overlaid on the box plot, and what we can first see is when we look at the EAS place-based map, compared to the EAS default map that we see that superior speech recognition observed with the EAS place-based map, as compared to the default map. And this again is interesting, because the EAS place-based map is introducing a gap between that acoustic and electric output, which what we have known till now, should be detrimental for speech recognition, so it could very well be that aligning the frequency information, the electric frequency information to cochlear place, provides the patient with better speech recognition performance than observed when we provide the full speech frequency range, as we currently do with the default mapping procedures. Next, as we've seen before we have the CI-alone place-based map, compared to the CI-alone default condition where we see that better speech recognition despite not providing low-frequency information below 550 hertz. However, what's interesting about plotting all these together, is we can now see that the listeners, the CI-alone simulation with the play space map outperformed those of the EAS default listeners. And this is particularly interesting, because again, we are not providing that low-frequency information electrically below 550 hertz with this CI-alone play space condition, and the EAS default condition has acoustic and electrically represented, or electrically stimulated information available to the listener.

So this was surprising that we would see better speech recognition with the CI-alone place-based condition as compared to the EAS default condition. And it could be that early speech recognition is supported by aligning this electric information to the cochlear place frequency, as opposed to having to acclimate to a shifted frequency representation. In summary, we see from our simulation data that there was better mask sentence recognition with the play space map, as compared to the default map from both the CI-alone and EAS simulations. What was particularly interesting is that we saw there was better performance with the play space map observed in that EAS condition, even in the presence of a gap in frequency information, which challenges what we currently think of as the optimal way to program these EAS devices. This work has led us into a prospective randomized investigation of performance between CI-alone and EAS device users, and we are randomizing them to listen to either a default or a play space map at activation of their device, and following their performance during the first year of listening experience to see whether aligning to cochlear place benefits to those listening with this place-based map within the initial months of speech recognition, and then to determine whether the default map recipients will catch up at later intervals to that of the play space map recipients. And we look forward to sharing this data with you at a future meeting. Thank you.

- Hello, I'm sorry we didn't have a chance to meet in sunny Florida unfortunately, but I'm really grateful for the chance to share our results with the community in this form. Today I wanted to talk about auditory plasticity, acoustic mounts of cochlear implants and single sided deaf patients. First let me start by thanking my collaborators, there's a lot of people at NYU who did a lot of work for this study, as well as our colleagues at Vanderbilt University in Rene Gifford's group, and at the World Hearing Center in Poland, Artur Lorens' group. Of course I have to acknowledge the support of NIH/NIDCD, the support of Cochlear Americas, Med-El and Advanced Bionics. And the collaboration of our colleagues at the Cochlear Implant Center, Tom Roland, Susan Waltzman and Bill Shapiro. These are the three questions we're gonna handle today, what does the cochlear implant sound like? Acoustic models of cochlear implants, are they valid? And the big question that goes well beyond cochlear implants, how plastic is the human brain?

So the three questions may seem unrelated, but as you will see we answer them using the same datasets, the same task and all of them will come together at the end. What does a cochlear implant sound like to post-implant deaf adults, and does this change with experience? We've all talked to patients who have made comments about it. I'm gonna start again, I don't know what I did. Thank you very much for the opportunity to present our results in this form. Although I'm sorry we didn't have a chance to see each other in person in Florida. Today we're gonna talk about auditory plasticity in cochlear implant users, and how that relates to electrode location and experience. This is a study done in single sided deaf patients. Many collaborators made important contributions to the study, including all these folks at NYU, as well as Rene Gifford's team at Vanderbilt University and Artur Lorens' team at the World Hearing Center in Poland. I'd like to thank the support of NIH/NIDCD, as well as Cochlear Americas, Med-El and Advanced Bionics. And the assistance of my colleagues at the NYU

Cochlear Implant Center, Tom Roland, Susan Waltzman and Bill Shapiro. The three questions we are trying to answer today may sound completely disparate to you, at least at the beginning. What does a cochlear implant sound like to post-implant deaf adults? Acoustic models of cochlear implants, are they valid? And how plastic is the human brain? The last question seems to come out of left field, and it's certainly a question that's about human nature, it's much more general in cochlear implants. But as you will see we will use the same data set, the same task to get answers to all these three questions. The first one, what does a cochlear implant sound like? I'm sure we've all had conversations with patients about this topic. These on the right are actual comments from social media, somebody asks whether anyone had to deal with Darth Vader or Mickey Mouse voices upon initial stimulation. And yeah that's common, somebody heard Minnie Mouse for two months but then it went away. Another one heard them for nine months, post-activation and still hears them.

Now this is interesting and provocative, but what does it mean? In the past we had to rely on comments, but now we can explore this question systematically with the help of SSD CI users. Acoustic mounts of cochlear implants, we have used them for many years, there are dozens if not hundreds of studies using noise vocoders or tone vocoders in place of cochlear implants, but we don't know how valid they are and it's a basic principle that all models must be validated. In this example from the New York Times on the left that reports on a study showing that mice happened to be very imperfect models for many human illnesses, specifically for three major killers, sepsis, burns and trauma. So something that was found that worked in mice. Not only didn't work in humans, but sometimes even had negative effects. So the bottom line is all models have to be validated. Standard acoustic models of cochlear implants use the same signal processing is a cochlear implant and the resulting speech perception scores are in the same ballpark, that's nice, it's a beginning, but it's not enough. There are some indications that speech perception by normal hearing users using a standard acoustic model can be much better than that obtained by average CI users even after months of experience. And other results regarding pitch shows that there are differences between acoustic models an actual CIs. The third question, how plastic is the human brain, we're not gonna answer the question in general, we're gonna answer it in one specific case, which is that of adaptation to tonotopic mismatch in most link wooly deaf cochlear implant users. We're gonna explore how well they adapt in the time course of that adaptation that will tell us about the extent of the limitations of human auditory plasticity. Our working hypotheses are with respect to each question, number one that what to cochlear implant sounds like will depend on electrode location and CI experience will be different from one patient to the next. Standard acoustic models that do not incorporate tonotopic mismatch are generally not valid. In that human listeners do adapt to tonotopic mismatch, but some of them may not adapt completely. The talk is going to have five parts, the first two are introductory, first we're gonna go over and signal processing in cochlear implants and in acoustic models. We'll explain what an acoustic model is.

We'll explain tonotopic mismatch. And then we'll go through methods, results and discussion to answer the three questions. This shows a block diagram of signal processing in cochlear implants. The signal is picked up by a microphone, we use a bank of filters from low to high frequency, and then we use different mechanisms to obtain the envelope of the energy coming out of each filter. That envelope is used to modulate pulse trains that are now simultaneous. Each pulse train is delivered to an electrode inside the cochlear with lower frequency channels associated with more Apical electrodes, to mimic the specificity that takes place in a normal cochlea. In this example we show SA, it would be seen at the inputs of the cochlear implant. This is the output of each filter, the high frequency filter only has energy for S, the long frequency filter is for the vowel. And here we show the stimulation pattern that results. Now the signal processing for an acoustic model at the front end is identical to that in cochlear implants, but the thing is that the outputs we don't have electrodes, so instead we use bands of noise or tones. So if we have say the word SA. I'm sorry, the word SA.

- [Computer] SA.

- Here we show it broken down into four channels, and this is the output of each one of the four channels. These are bands of noise, when we put them all together it sounds like this. Which is a reasonable reproduction of the original sound. These traditional acoustic models are frequency matched, they make the assumption that CI users do not experience tonotopic mismatch, and as we will see, this assumption may be wrong. We are making the assumption that if we have a filter with an analysis filter band of 188 to 313 hertz, that when we stimulate the corresponding electrode, the most typical one, it sounds like a noise band of exactly that frequency range. Like this. But does it, or does it sound like a noise band with higher frequency, 500 to 900? Or even higher frequency? A priori, we don't know, in studies with electric-acoustic pitch matching, such as that this hypothesis made by classic standard acoustic models are not correct.

So why might patients hear things that are at higher frequency then the analysis filters? Because of tonotopic mismatch. Here we show an electrode inside the cochlea, and these numbers in blue represents a characteristic frequency of the neurons that are close to each one of the electrodes. Starting at 1000 hertz, 5000 and so on and so forth. Electrodes don't reach all the way to the tip of the cochlea, so the only go down to a certain frequency and no further. And the analysis filters shown in red associated with each one of the electrodes may have these frequencies. So what may happen is that these neurons that were stimulated by 1000 hertz information when the patient had normal hearing, we're talking about post-lingual deaf patients here. Now were stimulated in response to much lower frequencies and this results in things sounding higher pitched, like Mini Mouse, that's why patients report that. This is another way to demonstrate tonotopic mismatch. This shows that a given location in the cochlea, shown but the angle of insertion going from there wrong window. This angle, 270 degrees is associated with stimulation when the frequency of the input is 800 hertz or so. However, that location in the cochlea, in the normal human cochlea that we like is associated with a much higher frequency. This is a study that Dave Landsberger and

I've published in 2015. So let's go over the methods, the subjects were 53 single sided deaf CI users, who were tested over several sessions. Some of them were tested only once, a few of them were tested repeatedly, some shortly after initial stimulation, others a few months later, and others years after initial stimulation. This is the test that we used, so we're gonna dwell for a couple of minutes here, because this is essential to the talk. Remember these are single sided deaf patients, they have a cochlea implant in one ear and they have perfect hearing like most of us in the other ear. First we present a sentence like big dogs can be dangerous through the speech processor direct on your inputs. Then a short pause, then the same sentence is processed by an acoustic model and presented to the acoustic ear. This acoustic model is adjustable, we wrote the software so that the patients could adjust the acoustic model until it sounds as similar as possible to the cochlear implant. So in a way by obtaining that information from listeners, that tells us what each one of them are hearing, what the cochlear implant sounds like to them. The three parameters that are adjusted are the low and the high-frequency edge of the noise bands that are used in the acoustic model, and the amount of channel interaction. This shows the graphical user interface that patients used in the experiment, each square represents a different acoustic model. So they explored this whole space to find the model that sounds most similar to the implant. Let me play a few of them for you, you'll see that they sound very different from each other.

- [Computer] The player lost a shoe. The player lost a shoe. The player lost a shoe. The player lost a shoe.

- Okay, so in these acoustic models the input filter bank for each subject remains constant and it's identical to the one used in their speech processor in the other ear. Same number of channels, same frequency range, same exact frequency range for each channel. The changes that are made in the acoustic model are made to the noise bands or the tones by moving up and down in this domain will change the low-frequency edge of the noise bands. Moving left right will change the high-frequency edge, and by moving a slider not shown will change the amount of channel interaction among the noise bands or tones, that's illustrated here. Let's explain how we obtain estimates of tonotopic mismatch when using these models. This shows a traditional acoustic model, this example is frequency matched, because the analysis filters and the noise bands are exactly the same frequency range. This shows the low-frequency edge, 188, the high-frequency edge, and this is what it sounds like.

- [Computer] Big dogs can be dangerous.

- In this case we have zero tonotopic mismatch, because the noise bands the filters are the same. Another patient may select a different acoustic model with these noise bands. And it sounds like this.

- [Computer] Big dogs can be dangerous.

- You see it's still intelligible, the sentence is still big dogs can be dangerous, but it's a bit higher pitched.

- [Computer] Big dogs can be dangerous.

- The tonotopic mismatch at the low-frequency edge in this case is 250 hertz, the noise bands are a bit higher frequency than the analysis filters. Let me show you an example with much more pronounced tonotopic mismatch, now the noise bands are a lot higher, 1625 hertz higher, and this is what it sounds like. The quality is a lot poorer to the extent that it's really not intelligible. You can have the opposite effect as in this example four right here where the noise bands are actually lower in frequency then the analysis filters, that results in negative tonotopic mismatch and it sounds like.

- [Computer] Big dogs can be dangerous.

- See, a little bit like.

- [Computer] Big dogs can be dangerous.

- Not like Mini Mouse but like Darth Vader. And this is also possible, to have a situation where noise bands are compressed with respect to the analysis filters, this may happen for example in someone with a very large cochlea. The other parameters that patients could adjust is this slider down here, where each one of the settings represent a different amount of channel interaction. Now after finding a self-selected acoustic model for each subject as we described before, we also evaluated that self-selected model and four other models that were traditional types. All of them were frequency matched, all of them assumed no tonotopic mismatch. Two of the models had six channels, two other models used all channels that the patient had in the speech processor. We used tone and noise vocoders, so we got five types of models at work evaluated to compare their validity. The validation measurements that were used were of two types, first, overall similarity using this scale shown here, the patient had to give us a number from one to nine, saying the sound I hear through my un-implanted ear is either not at all similar or somewhat similar, very similar or identical to what they hear through the cochlear implant. We also evaluated other qualities in addition to overall similarity, and we did speech testing for all five acoustic models, and for the cochlear implant.

So if we had a model that was perfect then patients would select identical, this sounds identical to the cochlear implant. And when we measure the speech perception results will be identical with the CI and with the acoustic model. We also measured electro insertion depth using either CT scans or x-rays. So let's go through results, and before I show you the overall results, let me remind you that our three hypotheses were that what a cochlear implant sounds like will depend on electrode location and CI experience. That standard models are generally not valid, and we will find that human listeners are indeed plastic and adaptable, but some listeners may not adapt completely to tonotopic mismatch. Some of the questions are well how much tonotopic mismatch is there shortly after implantation? Does it depend on electro insertion depth? Experience? Does it go away? So let me show you this one example, in this plot we're showing the user interface that the patient saw. And I'm gonna play you a couple of examples obtained, first just a couple of days after the initial stimulation, .03 years. And then a year and a half later. This as the subject who initially showed very little tonotopic mismatch, I say because this gold star indicates a selection that's the traditional acoustic model with zero tonotopic mismatch. The patient selected this which is actually very close. Oops, let me play this for you.

- [Computer] Read verse out loud for pleasure.

- This is the original sound.

- [Woman] Read verse out loud for pleasure.

- [Computer] Read verse out loud for pleasure. Read verse out loud for pleasure.

- So these two sounds I just played, these two locations in the grid represent the models selected by this subject very shortly after initial stimulation and a year and a half later. There was a little mismatch in the beginning, and there was no change essentially. Compare that to this subject, who showed a large amount of tonotopic mismatch initially. Over 1000 hertz. So initially the cochlear implants sounded like this to her. You can't even understand that, this is the sentence.

- [Man] Take the match and stroke it against your shoe.

- Even when you know what the sentences, is very hard to understand it.

- [Computer] Take the match and strike it against your shoe.

- Now one year after the initial stimulation this is what the patient heard in response to the same stimulus.

- [Computer] Take the match and strike it against your shoe.

- You can see it's not perfect, but it's a lot better the tonotopic mismatch hasn't disappeared completely. So this is an example of initial tonotopic mismatch, with almost full adaptation over the course of a year. The insertion depth in this case was 337 degrees, which is not very deep. This is another example. Insertion depth is better, but there was still initial tonotopic mismatch. Let me play that for you. A few months later tonotopic mismatch decreased, the selection made by the subject was up here closer to the gold star, but not all the way there.

- So it still sounds rather Mini Mouse-y, it doesn't sound normal, there is still some tonotopic mismatch. So this is an example of a patient who shows the initial mismatch had only partial adaptation. And this one is probably the unluckiest patient, there's a lot of mismatch.

- [Computer] The paper box is full of thumbtacks.

- That's harder to understand than the original.

- [Man] The paper box is full of thumbtacks.

- So that was just a month or two after initial stimulation, and this is a year and 1/2 later.

- [Computer] The paper box is full of thumbtacks.

- Still sounds Minnie Mouse-y, there's been no change in the acoustic model selected by this subject, so this is a case of initial mismatch without any evidence of adaptation. So let me show you the data from all patients. This is an important graphic, if you're going to remember only three slides from this presentation, this is one of them. On the x-axis we show the location of the most Apical electrodes obtained from x-rays for each patient. In the y-axis we show the amount of low-frequency tonotopic mismatch, and we can see that there is a clear trend For shallower insertions being more likely to show tonotopic mismatch. The deeper and deeper you go the less likely it is that you will find high levels of tonotopic mismatch. The different colors represent different devices, yellow for cochlea, blue for advanced bionics, and read for Med-El of course. And the different symbols show earlier later points. The bottom line of this slide then is that shallower electrode insertions result in acoustic models that tell us there's more tonotopic mismatch in the low frequencies. Now, does this change over time? Remember that some of these data points were from the same subjects obtained at different points in time.

So let me show those data. The y-axis is still the same as before, it shows an amount of tonotopic mismatch. Now the x-axis is a logarithmic access showing time after initial stimulation, so this is one year, this is .1 years, that's 37 days, this is just four days. And this is essentially around initial stimulation. Now the colors encode insertion depth, insertion angle. We used the rainbow, so the red in the rainbow shows the shallower insertions, 300, 350 degrees cochlear insertion. Then orange, 350 to 400. Yellow, green and blue. So one thing we see as we go left to right is a function of experience. Tonotopic mismatch clearly disgraces, you see that there is one outlier here who goes up, But the bulk of these data show patients with less and less tonotopic mismatch over time. However, the other thing we see is that tonotopic mismatch doesn't go away completely for all CI users, even at the one-year point, after one year of CI experience. You see that there's quite a few data points up here show high levels of tonotopic mismatch. So the bottom line then is that the human auditory brain is indeed plastic, it changes in the right direction, but only so much. I will mention later that it may be possible to hack the brain to make it more plastic, but we'll get to that later. You may wonder whether tonotopic mismatch is associated with poor speech perception scores, and that is indeed the case, it's not a perfect correlation by all means, and obviously speech perception depends on many other factors. The lower the frequency mismatch, on the x-axis, the closer it gets to zero, the higher the levels of speech perception for either CMC 30 words or for AzBio sentences. This is clearly significant, it remains significant even when we remove any outliers. Now let's move on to validation of acoustic models. Here we are showing average speech recognition scores obtained with a cochlear implant in red, and with each type of acoustic model in different shades of blue. The self-selected model with tonotopic mismatch is this one, and as you can see both for words and sentences resulted in a decent match to the speech scores obtained with a CI, on average. We also see that six channel tradition models, without tonotopic mismatch also result in similar scores as the CI. At least for CMC words. Not so much for sentences.

So this is speech perception, we also evaluate similarity, and in that case results were extremely clear-cut. On average the self-selected models were rated 6.16. So that's between somewhat similar and very similar, close to very similar. So that's good. It's not a perfect model. But all the other models without tonotopic mismatch were deemed between not very similar and completely different. So traditional models sounded very different from the cochlear implant to these patients. Now let's combine these two datasets. So the similarity ratings are shown on the x-axis, speech perception on the y-axis. Each one of these symbols represents one individual listener, one individual listener, and this is how they rated the acoustic model in terms of similarity and in terms of speech perception differences between the cochlear implant and the acoustic model. So the perfect model would be rated nine, identical to the cochlear implant, and the difference in the scores and speech scores between the CI score and the acoustic model would be zero. So the perfect model is where the gold star is. Now, the five ovals represent the 95% confidence intervals for self-selected models in red, and for the traditional models in other colors. So we see that the traditional models with all channels not only are rated very different, so they are on the left side of this plot, but they are also on the top part of the graph, because speech perception with those all channel models is much better than with cochlear implants. When using the six channel traditional models speech perception is about the same, that's why the oval is around the zero line. But the similarity ratings are very different. In conclusion, the self-selected model on average was a much better representation of the cochlear implant, both in terms of speech perception and similarity than traditional acoustic models.

So in conclusion, what does a cochlear implant sound like? Well, it's different for different patients. It may sound like Darth Vader or Minnie Mouse, Minnie Mouse is much more frequent. Or like a traditional noise or tone vocoder. Minnie Mouse is more likely, especially early on, for some patients like that one we saw in social media saying that initially it sounded like Minnie Mouse, but then that went away. That indeed can change over time. But a Minnie Mouse percept is much less likely when electrodes insertion is deeper, it's more likely when electrode insertion is shallower. And it does become less pronounced over time, but not for all CI users. In terms of acoustic models, you'll find that traditional models with zero tonotopic mismatch even in cases when speech scores are close sound extremely different from what you hear with a CI in the same patient, just a different ear. The listener adjusted models with tonotopic mismatch provide a much better fit in terms of speech perception similarity. Last but not least in terms of brain plasticity, the good news is that the human auditory brain is indeed plastic and we knew this from many other datasets, including changes in electroacoustic pitch matching overtime. So the human auditory brain is plastic, it can overcome tonotopic mismatch, in some cases complete overcoming of that tonotopic mismatch after a few months. But in other cases the bad news is that some listeners do not achieve complete compensation of tonotopic mismatch. Patients with deeper electrode assertions may have little tonotopic mismatch to begin with making this type of plasticity unnecessary. So if there is tonotopic mismatch, many of you are clinicians, others may be electrode designers, may wonder what may be done to avoid or minimize tonotopic mismatch. One obvious possibility is to use longer electrodes, but there are caveats there of course. We don't want to affect human preservation, or vessel membrane integrity, because there are some indications that both those things may be negative for speech perception. Another possibility is to modify the frequency allocation tables, because we can do that with most cochlear implants. But that shouldn't be done at the expense of eliminating too much of the frequency information. Another possibility is training, providing additional behavioral rehabilitation for those patients who seem unable to overcome tonotopic mismatch. And last but not least, using neuromodulation, that's the brain hacking I was jokingly referring to in an earlier slide. Our students, Erin Lennon in post-doc, and Harry Haidt, working with my colleagues, Rob Frankie's lab, are investigating the use of neuromodulation, and have shown it is indeed possible to facilitate, enhance and accelerate, only through training in rats with cochlear implants by stimulation of the locus coeruleus But that's a conversation for another time.

Last but not least, somebody may see this presentation and say, maybe I can go a bit deeper with my electrode insertion, even at the expense of basal cochlear coverage I think that's a really bad idea, I say this because this has been done in a couple of cases historically with not very good results, so an electrode that has not been designed to go very deep into the cochlea should not go very deep into the cochlea. So this concludes my presentation thank you very much for the opportunity. And if you have any questions please feel free to reach out, I missed the give-and-take of the Q&A at the end of the presentation, so maybe we can do it over email, over Skype, over Zoom, and perhaps in person in the not too distant future. Thank you very much.