Benefits Afforded by Precurved Electrode Arrays: Speech and Auditory Perception for Adult Cochlear Implant Recipients

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- - [Melissa] Okay Rene, we can begin. Okay Rene, we can begin.

- [Rene] Okay, can you hear me okay? Can everyone hear me? Yes, excellent. Okay, so welcome, everyone. It's noon for probably many of you and a little bit earlier for some of you and myself included. I'm really excited today to talk about this topic about precurved electrode arrays, specifically with respect to speech and auditory perception that we've been measuring in the lab here at Vanderbilt. Now, before we get started, of course, we need to do a little bit of housekeeping. So learning outcomes, we do have three points that we're gonna be covering today. We're gonna be covering expected cochlear implant outcomes in a large clinical population, we're gonna be doing that with knowledge and without knowledge of electrode location and device wear time, and then we'll talk about those variables with respect to how they inform our patient outcomes. We're gonna talk about differences, what we've seen in the classic literature, which many of us have probably learned in our cochlear implant classes that we took way back when, as compared to what we're finding now with modern day recipients who are, have more modern atraumatic electrode arrays, better neural health, so forth.

And finally, we're gonna talk about how the effects of having this well-placed precurved electrode array would potentially benefit or impact how we might program our patients, such as what upper stimulation levels we might expect, how we might expect them to do for speech recognition and quiet and noise as compared to our other patients, such as lateral wall recipients. So now I'm going to share my screen with you, and let's just hope that this goes off without a hitch. And I'm gonna share. Looks good I believe. And I'm gonna go to my slideshow. Bam. Okay, so there's my title slides. Disclosures, of course, it is important for me to mention that most of the research we're presenting today is funded by the NIH, the National Institute of

Deafness and Communication Disorders. Our cochlear implant program here at Vanderbilt that I direct does receive industry sponsored studies, or industry sponsored funding for studies from all three of the cochlear implant manufacturers, and I am also a consultant for both Advanced Bionics and Cochlear. Okay, so acknowledgments, this work, it takes a huge amount of people to get good work done. And I really would be remiss if I didn't include all of them. The ones who are highlighted in green, particularly relevant to the studies that are gonna be presented and discussed today, and a number of NIH funding opportunities that have funded this work. You can see that at the top the behavioral studies, which are funded, and then we have a lot of different studies that are our funding opportunities that help us with our imaging studies. Alright, moving along. Well, what you're looking at here is, well, first of all, this quote that cochlear implants are considered really the most successful of all the neural prosthesis that have ever been developed. And this is the case I mean, there isn't a more effective, for example, bionic eye, or there hasn't been a prosthetic that has been able to restore touch or smell, nothing in the way in which that the cochlear implant has been successful.

But surprisingly, there's a lot of people out there that don't really even know about the cochlear implant. I'm sure that all of us have encountered you know, family members, people out in the street in our everyday life that just are like, "Oh, never heard of that." Well, one of the reasons that I wanna show you that, here you're looking at a valve chart. And so, I'm sure you remember from your speech science class, again, who knows when we all took that, but we talked about this categorical perception of valves, in that you can see that we have these clustering of valve recognition spaces. So we're looking at the second formant plotted against the first formant, and recall that really, if the formants occur anywhere within that particular cluster, which can span a couple thousand hertz in some cases, we're gonna perceive it as that same sound, like ee or eh or ah, and this particular fact, the fact that speech is so redundant and we are so malleable and able to adapt to the incoming stimuli is really one of the reasons that cochlear implants are so successful, particularly for speech perception, which of course, we know speech tends to be a little bit less spectrally temporary complex as compared to say music. And so, moving along. Another thing that's related here is that cochlear implants have been shown over time to not really need a ton of spectral information to get high levels of speech understanding. So here, what you're seeing is percent correct. It's a function of the number of channels. This is a study by Loizou and colleagues published over 20 years ago. And this is a group of nine listeners who are listening to the timet sentences. And so these are normal hearing listeners using cochlear implant simulations. And what you can see is that by five channels of spectral information, these patients, or these participants are maxing out. They're at the ceiling. And so again, we've got a lot of acoustic cue redundancy in speech. And thankfully, that's the case, because that allows this prosthetic to be so highly successful. And then, moving along.

Of course, here is the similar figure. This is percent correct function of a number of electrodes. But this is for a group of 11 Nucleus 22 Cochlear Implant recipients and this was published also over 20 years ago. And although the overall percent correct is very, it's pushed down a bit, because of course, cochlear implant patients are expectedly not performing as high as a group of young listeners with normal hearing. But the trend and the way that the data are presented is almost identical, such that by five channels, these patients are reaching their, essentially, their asymptote with CUNY sentences and quiet. And so, these data that were collected with first generation cochlear implant technology in patients that had, you know, much different electrode arrays, much more invasive cochlear implant surgical techniques, and who we know had much poor hearing going into surgery, you know, 'cause our patients that we were implanting 20, 30 years ago look very different than the auditory profile of patients that we're implanting today. Despite that, we're really, for the most part, using data, these data in particular, that have driven a lot of what we do clinically. And what I mean by that is a lot of the device selection and parametric selection for cochlear implants does, in least in some ways, use a sort of one size fits all. And so what I mean by that is we have this mindset that we can choose, for example, the same internal device for most patients, and that most cochlear implant patients are gonna do really well with using just the default parameters, such as stimulation rate You know, for example, with cochlear, most patients are programmed using a 900 hertz rate. Az using eight maxima 'cause those are the defaults, and using that standard electrode to frequency allocation, so that, you know, we go from 188 to 7938 hertz, and that's, that really does give high levels of performance for a lot of patients. But interestingly, that is particularly the max number of electrodes that we use, the eight does actually originate from those data collected 25 years ago, in that we really don't see increases in performance beyond about five to eight independent channels for these patients. And so, what I mean is that, you know, for most patients implanted worldwide, we're using this sort of one size fits all approach to audiologically managing our patients to device selection, and even cochlear implantation on the surgeon side, but realistically, we know that there are great differences in of course, the underlying cochlear anatomy, the resulting electrode placement. You know, for most patients, we really don't have any clue where that electrode lives. Is it in scala tympani?

Has it shown, has it moved from scala tympani to scala vestibuli? What about the electrode insertion depth? Are there any extra cochlear electrodes? Of course, sometimes we can get that information from our patient's behavior, where they don't have, you know, any perception, and so we can deactivate or you know, that coupled with lack of, say, electrically evoke compound action potentials that gives us information. But, you know, for some patients, we don't have behavioral responses, such as very young children. And so realistically, a lot of patients implanted worldwide, we are going in doing the very best that we can, but with very limited information. And so what's really interesting is imagine if we used a one size fits all approach in vision. And I'm using we, the world we, because I have nothing to do with vision or optometry, but I'm sure most people here today have had at least one vision screen or vision test, and so y'all know what it's like when you get there and they put this giant, you know, piece of equipment up to you. And imagine if instead of doing that, you go to see the optometrist, and the optometrist just gives you the average prescription. Okay, and so, you know, they're just like with, you know, we have default averages that work for cochlear implant patients, there are averages that fit sort of a bell curve, the majority of the patients at a particular age group, and so you get the prescription that gives you this visual perception. Now for some people believe it or not, that might actually be improvement from where they came in. And so you think, "Okay, well, they got some benefit." But then for some others, they might get this prescription right. So like their vision might not have started out as poorly and they're doing better. For some people just by chance that prescription might work really well for them. However, had we had individualized information about that patient's actual, you know, eye curvature, their perception, their eye health, underlying, you know, optic neural health, we could potentially get them to essentially 20/20. And so that's sort of, you know, the analog. Now, of course, we know that cochlear implants can't completely restore normal audition.

That's just not gonna happen. But we can pr-, you know, strive to provide a more precise precision medicine, I'm sorry, precision medicine approach to audiology than we're doing today. Because right now, we're making assumptions that really aren't going to be correct for everyone. So for example, we tend to program threshold levels and comfort levels across the electrode array, like I mentioned, using, you know, essentially very similar stimulation rates, Very similar pulse widths. For example, we know you know, a 632, the default pulse width is 25 microseconds, but if you get a 622, the default pulse width is gonna be 37 microseconds. That same frequency allocation, we're gonna use basically all of the active electrodes, irrespective of where they are, we're gonna use the same number of a maxima. And even though we might not understand that we're making these assumptions, we are making at least two primary assumptions with each of our patients. One, that the electrodes are in the right place. So they're in the cochlea, in the scala tympani. And we have a similar and basically similar insertion depth across ears. So for our bilateral patients, we just sort of assume things are across the ears, very similar. And we also make the assumption that there's a relatively uniform electrode to neural interface across the array. And what I mean by that is we sort of don't think that, well, maybe one electrode is further away from the modiolus than other electrodes, and maybe we might expect to see differences in terms of upper sin levels on that basis. But realistically, from the data I'm gonna show you today, these assumptions aren't accurate for most of the patients that we see. And in fact, if I were you guys and I was taking the quiz, I would be interested in this next piece of information. For adult cochlear implant recipients, we know that there's just considerable variability in outcomes. And one prominent influencing variable that we don't have information for most of our patients is scalar location of that electrode array. Where is that electrode?

And what's that electric to modiolus distance? What does it look like? And so, so the objective here, at least the research that I've been working on for close to 10 years with my colleagues here at Vanderbilt, which is Rob Labadie who's our surgeon and engineer, Jack Noble, Ben Won-de-wa, who are electrical computer engineers, is we're trying to move towards a more precision medicine approach or model for both audiology, otology, of course otology is outside the scope of the talk today, as well as cochlear implant programming. And so how we can do that is using pre and post operative CT scans for our patients. It actually having this information does allow us to use that imaging information to determine where those electrode arrays are in the cochlea. So does this patient have a complete scala tympani insertion? Do we see transcalar displacement? We can create more specialized patient-specific maps. And what's really cool to see this, from my perspective as someone who's not a surgeon, is to start to see our surgeons who are already fantastic, you know, top of the line surgeons improve their technique even further, 'cause we've actually plotted this over time where we've seen the amount of translocations significantly decrease, where we've seen the placement of the electrode array become, you know, from more of population average specifics to essentially ideal every single time by having this visual information and confirmation of placement following the surgery. So, how do we do this? Well, first of all, a little bit of background. Looking at electrode position in vivo or inside a human, it can be quite difficult because, you know, we can't really get good high quality, I'm sorry, high quality images of the electrodes, and all of those internal structures with a standard clinical CT scan. So we know that the, you know, electrode arrays, we've got this metallic artifact, so it provides some shading of the electrode arrays, and we can't see with the standard clinical CT resolution, we can't see basilar membrane, we can't use Reissner's membrane, and we certainly can't see spiral ganglion. You know, the spiral ganglion, those nerve bundles are, have diameter. You know, their diameter is a few microns.

And so there's just no way we're gonna be able to see that with current CT resolution. So we really can't do that without doing a little bit of background or sort of pre human or pre clinical work. And so what we've done and what others have done, we're certainly not the first to have looked at this is you register your preoperative CT to the post operative CT. And so others have done it really more historically is that they've done this in a more of a manual way. So for example, they would take a post operative CT, and then manually register it to the pre-op. And what I mean by that is looking at a slice by slice. So you know, from CTs, you're actually looking at a sort of a whole profile or portfolio of images, which is slice by slice by slice. And so for example, an engineer or a tech would go in and actually register and move the patient's post-op CT to completely match that pre-op CT on the areas that you can see. So on a clinical CT, what you can see very well is the out-, you know, the bony capsule of the cochlea, so you can see the outer wall of the cochlea very well. And so you could do that. The problem with that, it can be precise, but it's extremely time intensive and labor intensive. In it's such that some of these can take up to eight hours for a single patient, so that you can ultimately get a three dimensional reconstruction of that patient's cochlea, with the electrode array in place. But there is another way to do it. And so you can do it with a little bit of preclinical work, which is what we've done here by first doing micro CT in a number of temporal bone specimens. And then that actually allows us to use a statistical shape model, which is more of an automatic way of registering or taking that post offers CT and registering it to that patient's own preoperative CT. And I'll take it even a step further, the pre-op CT, because you're not getting all of that precise information, such as basilar membrane, Reissner's membrane, you know, you can't see all that info, but you can see it on a micro CT. So you can take that patients pre-op CT and use inferences that we've learned from, you know, these many, many temporal bone specimens and build this model that will build out the individual scale up. And so the way we have this is I'm gonna give you actually some examples in a moment, but it's automatic. It's completely based on statistical shape modeling.

And our degrees of error today are approximately 0.1 to 0.15 millimeters, which is completely reasonable if you think about the size of the cochlea. So what you can see here is, this is actually a micro CT. So this is in a cadaver head. and it's moving in a lateral to medial plane. And so what's happening as it's moving and you're looking through all of those slices, the scala tympani is being built out in read, the scala vestibuli is being built out in blue, and then modiolus is in green. And so this is based on looking at 16 cadaver micro CTs, which were used to construct the statistical shape model of the individual scala as well as the modiolus. Now this is at this stage of the science, this is manual. So this is done manually. And then the statistical inference, it comes at a later point, which comes here. And so now what you're looking at here, this is an actual cochlear implant patient, this is a pre-op CT. And so the first thing you can see is that the degree of resolution is certainly not as, as precise as it was in the micro CT. But we can't subject patients in humans to micro CT, because the radiation dosage would be, would be fatal. So this is just the standard, you know, temporal bone CT, but we can then build these, this 3d reconstruction using information that we had from all of those cadaver micro CTs. Then the patient of course, gets a cochlear implant, and it's best to have the pre-op CT, because then you have an artifact free image, because as you can see here in this particular patient, this is actually the same patient, as you saw in the previous slide, it's not as precise because we have that sort of shading or the shadowing that's coming from those individual electrical contacts. And then what can happen as we've built this is that what you're looking at here is a 3D reconstruction of the cochlea. So the scala tympani was in red, and now it kind of fades away at the end. You can see the modiol-er surface and green. And what we can do from this is we can determine first of all, which scala each electrode is residing in and determine are there any extra cochlear electrodes that we might wanna deactivate? We can also look at the individual electrode to modiolus distance for each one of those electrical contacts. And in this particular case, you can see that it's certainly not uniform.

In this particular case, this is a Freedom Contour Advance electrode, but that's an older electrode. So let's look at some more modern day electrode arrays. But first, you might be thinking, "Okay, this seems like a lot of work, "and why in the world would this even matter?" Well, it matters because we know that electrode to modiolus distance does influence charge. So meaning the further the electrode is from the neural stimulation targets, which are the spiral ganglion, which is located within the modiolus, the higher the charge that's needed for auditory perception. And this is just a well known fact that people who have lateral wall rays require higher charge for comfort levels. And so, what that also then means is that higher charge results in greater channel interaction or greater spread of inter-cochlear electrical activity. And we all know that channel interaction is one of the primary limiting factors with cochlear implants today, because that provides a much poorer spectral resolution than we would have if we had less channel interaction. So that's one reason why electrode position matters, because it has the potential to impact outcomes. And so the other reason it matters is that not all electrode insertions are created equal. And so what you're looking at here is actually two CI532s. So this is before the the profile plus was available, but this is from two patients from our clinic here that were implanted for, with the 532. Now, for both of these patients, they have complete scala tympani insertion. So you know, you would think, "Okay, same electrode, no transcoder location." But the patient, as you see here on the left, has what I would characterize as a near perfect insertion, such that the average electrode to modiolus distance, if you averaged across all 22 of those inter cochlear contacts is 0.13 millimeter. So that is a very perimodiolar electrode placement, whereas the patient here on the right, they have the same electrode, but it's a little over inserted. So you can see that that most basal contact is pushed much further than the patient here on the left. And so what happens is that you have a perimodiolar placement in the apex and the base for electrodes one and two. But the really all of the other electrodes are much closer to the lateral wall than they are to the modiolus. So this patient has essentially a hybrid of a perimodiolar and lateral wall electrode array. So we're going to expect greater charge needed in the middle, which is gonna be greater channel interaction, poor spectral resolution.

So, if I were taking a quiz for this particular course, you can say that without image based confirmation of electrode insertion and scalar location, we know that some precurved electrode arrays are not actually going to be in a truly precurved or perimodiolar fashion. In contrast, they're actually gonna be closer to the lateral wall, at least for the middle portion of the electrode array. And we would have no idea that this were the case if we didn't have imaging confirmation. So with that information, we published a study last year Chakravarthi and colleagues here come from Vanderbilt. And we looked at our current imaging database to get sort of an idea of, "What are the variables "that are really influencing outcomes?" Okay, so what we have here is that we had two at the time that we initially started this study, we had 220, cochlear implant patients that had been implanted that were in our database, who had all had postoperative CT, and who had all been assessed on measures of CNC word recognition postoperatively as well as BKB-SIN. And so what you can see is we had from the table shown here below, we had representation of all three manufacturers. We had almost essentially all of the electrode arrays in play with the exception of we didn't have any 532s or 632s because this was a little bit older, even though it was, just reached publication last year. And so what we did was, I wanna show you this next table first, is you can see all of the variables that were available to us from the database. So we had, you know, speech perception scores. How many of these patients had full scale activity insertion? What was the average electrode to modiolus distance across the array for these individual patients? How deep was the base insertion? So meaning was this electrode array potentially over inserted? What was the angular insertion depth of the most atypical electrode? Was the age of implantation, the patient's gender, were they prelingually defeaned or not? This is just a binary variable, "yes or no". And then the length of CI use. And so, you know, I'm not gonna spend much time here other than to point out a couple of things. One, I wanna point out that precurved arrays historically have shown greater rates of translocation. So what you can see is here for the precurved arrays on the left side of the, this figure. We saw about, you know, 50, only about half of them actually were completely inserted within scala tympani, meaning half had transcalar location.

Now this is, this for the most part, these were older electrode arrays. So this is not necessarily the case today, but historically speaking, this has been reported in literature and it's something that I might be interested in if I were taking a quiz for this course. So if you see on the right hand side for the straight arrays, really, you know, 80 to 85% of these electrode arrays were completely within scala tympani. And this does tend to still be the case today. You know, straight electrode arrays tend to be more flexible, less traumatic, and because they don't have rigidity to them, you know, they just sort of follow the outside wall of the cochlea and don't really evulse through the browser membrane through scala tympani into scala vestibuli. Okay, so with that, I'm gonna jump to the punch line. Here the variables we found that were significant using our multiple regression. And we found slightly different sets of variables for the different electrode types. So for precurved electrode recipients, we found that there were four variables that were primary importance. What was the mean electrode into modiolus distance? So was it truly perimodiolar? Or was there a portion of the array that was closer to the lateral wall? What was the age of implantation? And we did find that younger tended to do better. Whether or not the patient had a full scala tympani insertion. And there are others that have also shown this to be the case, primarily the Washington University group, Laura Holden, Margo Skinner, Charlie Finley, Jill Firszt and colleagues, they have published on this. And pre lingual onset of deafness, of course, we know that post lingual onset of deafness is more likely to be associated with higher auditory only speech perception. That's sort of a, we've known that for some time now. With the straight electrode recipients, we saw influence of basal insertion depth. So how deep was it inserted? Was it over inserted, was it under inserted? Such that we had extra cochlear electrodes, and of course, pre lingual onset of deafness. Now I'm gonna take all of these data that we found from our statistical modeling, and I'm gonna give you some hypothetical examples that will help you understand what this means in general because I like to look at things sort of more in a case study or you know, more of the individual level. So taking all of the data that resulted from this statistical modeling.

If we take a male, this is just a hypothetical patient, who has a cochlear implant at a relatively young age, this is very young to me, 35 years old, post lingually deafened, and you know, has good amount of experience with their implant at least five years. Here we're, I'm gonna show you the estimated CNC word recognition scores from this model, that we would get from a good cochlear implant position with the precurved, a population average, what we saw for most of them. And then if the patient had a very poor position. Okay so, here we have, if the patient was you know, relatively young, post lingually deafened, experienced user, and had good position, we would expect this patient to perform on average 82% for CNC word rec. So this is what we would call, you know, like the above average performer. This is a very good performer. If the patient had just sort of the population average position. So this is what just the majority of the patients we saw in our database, if they had this particular population average, we would expect about 56% correct CNC words. And if you recall in the literature, the average performance for CNC word rec across a number of studies is really in the range of 50 to 60% correct. So this sort of kind of makes some sense and is a little bit of foreshadowing for later. And then finally, we saw that if the patient had a slightly, you know, had a poor position of the electrode array, so like, not in scala tympani, over inserted such that, you know, the middle portion of the array was actually closer to the lateral wall, that we would expect this patient to score on average about 30% correct. So, this starts to inform us that really, you know some of the variability, that we've been seeing historically in outcomes really can be explained at least in part, by electrode position. Now in contrast, let's look at the same example. Male 35, post lingual, five years CI experience, but assuming that he had a straight cochlear implant electrode array, was taking a drink quickly. So if this patient had a good insertion depth, we would expect on average the CNC word recognition score to be about 68%. If he was the, had a population average insertion depth, we would expect 52% correct. So again, very similar to what we'd seen in the average scores in the published literature. And if this patient had a, just a poor position, so meaning there were some extra cochlear electrodes, or on the other hand, had a very over inserted electrode array, but in this particular case we assumed a, having extra curricular electrodes, the patient would perform on average based on this model, the statistical model, 36% correct.

So it starts to put things into perspective a little bit. And what you can see here is that a little bit of a summary is, it really does, electrode position does matter. And it's something that unfortunately, we don't have information for, you know, the majority of the patients that we see in clinic, which, you know, I'm spoiled, because I've been here now for almost 10 years and every patient I go into activate or that I see post operatively who's potentially having issues, thankfully, I have this imaging information. And I'm telling you, I don't think I could do my job anywhere if I didn't have this information, because it has completely changed the way that I practice audiology. We know that, at least from this data set, that precurved electrode arrays can outperform straight arrays, but the caveat there is the precurved array has to be optimally positioned. So it does take into account, you know, surgical placement of that electrode array. So looking here on the right, you can see CNC word rec for straight arrays, which is the unfilled bars, as well as precurved arrays, which are the filled bars. And I took the data just straight from that general linear model, our modeling from this study. And so you can see that in an optimal placement, a precurved electrode recipient is going to significantly outperform a straight electrode recipient. However, for the typical placement, so for, think about our population averages, our clinical population, our global population, on average, we're going to expect these patients to do about the same, because we're not gonna expect to have every single patient out there, whether they have a precurved array or a straight array to have a completely optimal placement of that array.

So it really is telling because again, as I mentioned earlier, that typical placement results in, you know, performance in the range of 52 to 56% correct for CNC word rec, which has been approximately the average score presented for very large clinical populations in the peer-reviewed literature for at least the last 20 years, maybe longer. So, at least in some ways, we know that electrode placement does influence cochlear implant outcomes for at least our adults. So in summary, for this particular study, electrode position does matter, and the precurved recipients can significantly outperform straight electrode recipients, but that precurved electrode array has to be well positioned. Having imaging and more of a, you know, individualized information for your patient can potentially improve hearing outcomes. It can change what we do audiologically, it can maybe help our patient counseling. So for example, you have a patient who has, you know, a sub optimal placement, and they're performing 60% correct on average for CNC. I'm pretty pleased with that, because that person's actually exceeding what I would probably expect them to do. In contrast, if I have a patient who has a perfect placement, say of a 632, and they're performing 40% correct on CNC, I'm concerned because this person should be doing much better. Are they programmed appropriately? Are they wearing their device full time? Is there some sort of neurocognitive issue? So it does really help with counseling in our audiologic approach. It could also really help with surgical outcomes. I mean, I've seen it here. It can even help with the training of future surgeons and refinement of those surgical techniques and future electrode design. And this is very important because we published a paper a couple years ago now that we showed that over 13% of patients who had been implanted, you know, really at number of different centers, but we had at the time, a few hundred patients, I wanna say like over 300 patients in our imaging database, but we found that 13% of them had extracochlear electrodes that hadn't been specified in the operative report. So what that means is that 13% of patients, for those patients, they had extracochlear electrodes, and the surgeon had reported in the report, it was a full complete insertion. So, thankfully, we found that audiologists are really good at identifying extracochlear electrodes. They were able to identify in 60% of the cases, that an electrode was extracochlear and have actually already deactivated that electrode in the patient's map. But there were 40% of those patients that still had active electrodes that were located in the middle ear space. So I think we can do better, and we're working on that now.

So we have future work to really significantly beef up our database to have, right now we have over 1,000 patients images in there, we've got much greater demographic factors, you know, we're including information like etiology and cognitive status, and what type of stimulation strategy they use. And also things like data logging, which I'm gonna talk about again in a few minutes. So let's take a break here before we move to the next one. And let's talk about the quiz. So, recall, we know there's considerable variability in adult outcomes. We know that scala location can account for at least some of those in that if you have a well-placed perimodiolar precurved electrode array, we would expect higher auditory outcomes than a straight array. And we also know that without image-based confirmation of electrode insertion and scalar location, some precurved electrode arrays are gonna be over-inserted. So it's just, that's just gonna happen. There's going to be extracochlear electrodes for which we may not be aware. And we are not gonna be able to offer really a precision-based approach to audiology in cochlear implant patient management without having more information about that individual seated across from us. So, moving on. So that's just one study, but let's talk about this next study. So this is a much more recent study that came out late last year. And I definitely wanna give props to Jordan Holder, who is an audiologist and PhD student here at Vanderbilt. She wanted to really look at a, you know, 'cause we had started, we were seeing this in our clinic, that we were seeing, you know, just felt like our precurved patients were doing better. We had the information from our, you know, statistical model from that previous paper that, that I just discussed. And so Jordan was like, "Well, I wanna look at things more "from a clinical perspective "and really get more of a matched cohort."

So she painstakingly went through our electronic medical record and was able to, at the time that she did this, we had only implanted 29 532s. We have like eons more than that now, but she then, for each of them who had imaging and had, who had been, you know, implanted, she found a 422 and/or 522 patient that matched that patient with respect to age at implantation and preoperative audiometric thresholds, just so we could kinda get, and now, this isn't of course the, you know, this isn't the gold standard clinical study design, but it's one method of study design. And so important is that there was no significant difference between these groups with respect to preoperative CNC word rec, so they all were about at the same, you know, playing field starting, and postoperatively, they all were using their cochlear implant approximately the same number of hours per day. So that just kind of happened. That was more serendipity, because we just looked at this, we wanted to find, we want it to age match, and we want it to, you know, auditory sensitivity match preoperatively. So, the outcome measures for most of the patients, they had six months of CI experience. And so, what you're looking at here is, for this group of individuals, we're looking at percent correct for CNC words, AzBio sentences in quiet, and AzBio sentences at plus five. The unfilled circles are those with the 442 and 522, and the filled circles are those with 532. Of course, this all was prior to the profile plus so, but it's the same electrode array. And so, what we found is first of all, if you look at just the means, which are the bars, you know, so the bars that encapsulate those individual data plots, our precurved patients are performing higher on average than our straight electrode patients. But statistically speaking, we did not see statistical significance for AzBio sentences in quiet or noise, but we did see a statistically significant difference between precurved and straight up electrode recipients for CNC word rec. And so this was pretty telling on, I mean, it was over 10 percentage points on average. And so, but it didn't end there. And so interestingly, and I gotta say we looked at this and we double checked and triple checked and quadruple checked, because these patients went into the study with almost exactly the same preoperative thresholds. And so looking here, what you see is audiometric threshold at three different frequencies, 125, 250, and 500. And these are averages preoperatively, which are here at the top and the dashed lines and then postoperatively. For the precurved patients, which are the circles, the dark circles, and the straight electrode patients which are the gray triangles.

So our straight electrode recipients, the 422 and 522 patients actually had slightly greater hearing loss postoperatively as compared to the 532. And this is interesting 'cause we were just kind of assuming that they would both get about the same, or maybe even the precurved would be worse. Because, you know, historically speaking, we've thought about lateral wall electrode arrays as being atraumatic and being the electrode array you want for hearing preservation. But we actually found that precurved electrode arrays have the potential to preserve hearing, and in this particular cohort actually had better hearing preservation than the straight electrode recipients. And that's an important point for the quiz as well. So in summary, again, we've seen examples that electrode type matters. Precurved electrode arrays in this particular study were shown to have significantly higher CNC word rec, significantly better hearing preservation, and what I didn't discuss, significantly lower electrode impedances. Now, they also have showed a lower charge at sea level, but that did not reach statistical significance at the group level. And as I mentioned, they also showed higher sentence recognition in quiet and noise but also didn't reach statistical significance. Now of course, time is not gonna allow me to discuss but I do also recommend you investigate a study by the UNC Cochlear Implant Research program. Lisa Park is the first author, it's from 2017. This is a group of 14 children that had a precurved electrode array in one ear, and a straight electrode array in the other ear. And they also show that the ear with the precurved array outperformed the array with the lateral wall. Now there are some issues with sequential placement and so forth. But here's another piece of evidence in support of precurved arrays Okay, so we're getting close to being finished. And if I can anytime in, put something that has a reference to Monty Python in my talk, I'm gonna do it. So now let's move on to something a little bit different. How many electrodes do we need?

So, you know, I grew up in this field at a time where it was like five to eight electrodes is really the maximum our patients can use. Anything else is just an insurance policy, you know, just in case electrodes might become an open circuit or, you know, let's say an electrode array migrates and you can't use some electrodes. I was, I completely believed this until just a couple of years ago. And many people still believe it today. In fact, we know that from a number of very well controlled, very rigorous studies from the late '90s and even early 2000s, sorry, taking a quick drink. You know, there was really no additional gains in speech perception performance on a number of variables, consonants, vowels, monosyllabic words, sentences in quiet, sentences in noise, as well as consonants and vowels in noise. We just didn't see it. And so, like I mentioned earlier, you know, the eight channel maximum, that was sort of pulled from the scientific literature. That is, that was evidence base. We don't need more than that. And so, but again, this was, all these studies were completed with 20 plus year old technology. They had all had straight electrode arrays. They were very different populations of patients, you know, patients with very long durations of deafness, just very, very different. And, realistically, we also know that in a group of normal hearing listeners, using CI simulations, at least in the Friesen, et al. paper that patients did actually show, or these normal hearing listeners showed improvements in performance in noise, for say vowels and consonants with up to at least 16, maybe even 20 channels. So this did appear to be a limitation of, you know, the inter cochlear electrical stimulation, this channel interaction, and so we just sort of reserved ourselves to, "Eh, patients only need eight channels, that's all we need." Okay so, that brings us to this particular paper we published last year in JASA. And this is something I've actually been wanting to do for gosh, I mean, at least a decade. And I, Katie Burke, who was an audiologist, and now a PhD student, she jumped all in on this particular project and just took the ball and ran with it. And so we recruited 11 precurved electrode recipients for this particular study. And we basically wanted to replicate some of the stuff that had been done by Bob Shannon and his colleagues. So particularly that that Freisen, et al. 2001 paper, but we wanted to replicate it in modern day cochlear implant recipients who had precurved electrode arrays, who for whom that we could verify that they were all implanted with a electrode array that's completely in scala tympani, so we verified that using imaging and 3D reconstruction in the manner that I showed you earlier through the videos. You can see that this is a broad range of, you know, ages 24 to 87. And we had some contour advanced patients.

So these were, you know, slightly older technology, and we had four 532s. So what we did, as I mentioned, we did replicate the Friesan, et al. methods. And so we looked at four channels, eight channels, 10, 16, and 22. Now, I do mention that for four, eight, 10, and 16, so those four electrode conditions, so going from the bottom up to, you know, one, two, three, four from the bottom up, those were using a CIS-based strategy. So we would use four of four, eight of eight, 10 of 10, and 16 of 16. For our 22 channel condition, or what we called all-on, because some patients might have had, for example, electrodes one and two deactivated, so we would only have had 20 for example. Our, you know, limitations in the clinical software only allowed us to go up to 16 maxima. So for that 22 or all-on channel condition, that was really an Az condition which was 16 of n, or 16 of m, which in this case ranged anywhere from like 19 to 22. Okay, so what we looked at, we looked, we did try to replicate almost everything Friesen did. These four patients were here in the lab for something like 10 hours, usually over, you know, two to three days, because we wouldn't wanna put someone in the booth for 10 hours straight in one day. That really wouldn't be useful. And we looked at you know, words, sentences, sentences in noise, vowels, consonants. We quantified sound quality measurements. We looked at not only consonants but features, so place, manner, voicing. We looked at spectral resolution, we looked at everything. And I'm gonna only of course for time, I'm only gonna focus on a few things. But the main thing I'm focusing on here is what you're looking at is first of all here, we transformed the percent correct scores to rationalize arcsine units or RAU. And we did this to help control for floor and ceiling effects.

Because of course, we did see some floor effects for you know, the four channel conditions and for speech in noise, and then we were flirting with ceiling effects in the all-on condition, because a lot of these patients were just doing really, really well. So this is, we're looking at RAU scores for the different number of channels, so four, eight, 10, 16, and all-on. And in this particular figure, you've got CNC in gray, AzBio in quiet in black, and AzBio at plus five in the unfilled. And so you can see that these data certainly do not follow the same trend as the more classic literature, such that we actually did see a statistically significant improvement all the way through 16 to 22, or the all-on condition. And if you look at some people might say, "Well, you know, they're used to using Az, "and so maybe that's a familiarity effect." To that, I would say, "Yes, that certainly does have some merit." Although keep in mind that these patients all had come in with eight maxima. So switching them to 16 maxima was not something with which they were familiar. But also secondly, let's just look at the

CIS-based channels, which is four, eight, 10, and 16. We still saw a statistically significant improvement in CNC word rec and AzBio sentences when you look at 16 channels as compared to just eight channels. And this is something that's never before been shown in the previous literature. And what's important is that these were precurved electrode recipients for whom we did have confirmation that the electrode array was completely in scala tympani. Now, over the course of the study, we actually and I'm gonna just go to black for just a moment, we started to notice that in the all-on condition, so with 16 maxima as compared to eight, that our patients were kind of outperforming what was reported in the electronic medical record with their eight maxima. And we started worrying, "Do we have an issue with calibration or what's going on?" And so we, we actually did a control condition, we started looking at in that exact same testing environment, we would then retest them with eight maxima and 16 maxima. Okay so, what we found, what you're looking at here is I'm plotting percent correct for 16 maxima as a function of eight maxima score. And so you got CNC words on the left, AzBio sentences at plus five on the right. This was a sample of 30 participants. So this was the original 11 that participated in the previous study that you saw, but more, you know, additionally more patients, and not all of them had had a CT scanning. So the ones that had had CT scanning that were completely in scala tympani represented by unfilled circles, those that had CT scanning and had transcalar location, so went from scala tympani to scala vestibuli have the circles with a cross, so the cross meaning it crossed scala.

And then we have those for whom were unknown, maybe they, you know, either didn't wanna have CT scanning, they didn't wanna have additional radiation or they just time didn't allow, or you know, sometimes our scanner is down and it just kind of happens and that's, we can't get it. But what we then did was, if these data points fall within that dashed kind of banana looking line in the middle of the graph, there's no difference at the individual level. So that represents the 95% confidence interval. And, you know, no, statistically not different. If the data points fall above that upper dash line, the patient actually did significantly better with 16 maxima as compared to eight. If the data points fall below that lower dash line, they did statistically better with eight maxima. Now at the group level, we ran statistics and we found that at the group level, we did see statistically significantly higher outcomes with 16 maxima as compared to eight maxima for this group of 30 individuals. You can see by the P values that it was in much higher effect size for speech and noise as compared to the words in quiet. Something else I wanna point out is that we also then looked at these differences. So how did they do with 16 maxima as compared to eight maxima? And tried to relate it to the individual electrode placement. So, that's what the next slide is. And what you see here is we're showing the difference in score with 16 over eight maxima. So a higher score means they did better with 16 as compared to eight, and negative score means I did better with eight as compared to 16. We plotted that different score, that Delta, as a function of what that patient's average electrode to modiolus distance was in millimeters. And what you can see here is this, this is a statistically significant correlation, meaning that those that had a much tighter, closer, more perimodiolar placement showed greater benefit with increasing those maxima as compared to those that had more of what I would call lateral wall placement, like those that had a 0.8 millimeter electrode to modias distance, that's closer to, those are more of like the over inserted electrodes.

So now, you know, we can't always know, because we're, this technology is not available to everyone yet. But we do have to keep in mind that, you know, there are gonna be patients who have our you know, 522s, 422s, 622s. And what about them? Do they you know, even though this is a lateral wall and it's not completely precurved and close to the modiolus, might they also benefit from more channels? So this is not yet in publication yet, but we have submitted it for publication, and I'm gonna give you a little, kind of a foreshadowing of things to come. So we have recruited 11, 522, I'm sorry, 522 recipients. We verified all electrodes are in scala tympani, and this is their data. And so what you can see is that, statistically speaking, we don't see any difference between scores of eight, as compared to 10, 16 or all-on. So what this means is that these patients who have electrodes that are further away that we know require higher charge for upper stim levels, which we know is associated with greater channel interaction for spectral resolution, in theory, that they are actually achieving close to maximum performance with eight channels and not seeing individual improvements as you increase the number of available channels. So let's look at this as compared to our data that we reported for the precurved arrays. So this, what you're looking at here is, the straights are the unfilled, the precurved are the filled. And this is the transform data, the RAU with just eight channels. So what you can see here is with just eight channels our straight electrode recipients do outperform our precurveds. So they're getting better performance earlier. However, when we go to 16 channels, you can see that they're essentially equivalent. And statistically, there's no difference between those groups. And then when we go to 22 channels, you can see that for particularly for the two most difficult measures we use, CNC words and AzBio plus five our precurved electrode recipients significantly outperformed our straight electrode recipients. And so what this means is that we're seeing that our current cochlear implant users who have precurved arrays, those patients are different than what's reported in the classic literature. They have greater channel independence.

They can benefit from more than eight channels. Now for our straight electrode recipients, at least, I mean, these data are still preliminary. We only have a couple, you know, 11 participants in each group. But we're still not seeing any gains behind, beyond a electrode. So, this is very similar to what, you know, Bob Shannon and colleagues showed, Michael Dorman and colleagues showed that, you know, beyond eight electrodes you get, you have some channel interaction, the further you are away. We're not seeing that channel specificity with more electrodes. But it does make me wanna rethink kind of these assumptions we've had about, "How many electrodes do our patients need?" Do we wanna potentially choose different maxima for different patients, different electrode per-, you know, recipients. And so a clinical tip that I would recommend is that, particularly for precurved, 'cause keep in mind we didn't see greater channel independence for our straight electrode patients, but for our precurved patients, so for our 532s, 632s, maybe even some of our old, you know, freedom contra-advanced, you can do this, you can check this in the clinic acutely, and it takes you maybe three to four minutes. So you can give your patient a 16 maxima map, you can give them their standard eight maxima map, just go to the clinic and test them for sentences and noise, you know, at a plus five. If they show an acute improvement, then great. They have a program that they could potentially try in noise. If they don't, you haven't lost anything other than the three to four minutes it took you to do the speech and noise assessment. So that's just a little clinical tip I would provide for you, but with the five minutes we have left this morning, I wanna talk a little bit more about some of the other variables that can be impacting cochlear implant performance. So again, we know there's considerable variance in the outcomes, and electrode placement is really, it's not accounting for everything, but it's accounting for some, but what else could be? So thankfully, more, you know, in just the last few years, we've had great opportunity to have data logging in our cochlear implant patients. And so we know that first of all, we've learned that our patients tend to not always tell us the truth, which is a big bummer.

But you know, you'll have a patient go, "Oh, yeah, I wear it all day long." And you see they're wearing it on average three hours a day. And so I, sometimes I don't think they're necessarily, you know, being dishonest. I think sometimes people think, "Yeah, I'm wearing it all day." And then when you break it down and use it as a counseling tool, they go, "Well, yeah, I guess I get up, "maybe I eat breakfast, "I might go to the gym, "and I'm not wearing it, and I go for a run. "Then I take a shower, and then I put it on. "I go into meetings. "And then if I'm in my office working, I'll take it off." It's like, "Okay, well, no, "we need to be wearing it all day." And so this Busch et al. paper is really fascinating. They looked at data logs for over 1500 patients, ranging in age from under one to nearly 100, and they found that the daily CI use was dramatically variable, ranging anywhere from like about two hours a day, in some cases, up to over 15 hours a day. But on average, they saw a mean of 10 and a half hours a day. And then this paper by VG Easwar and colleagues, published two years ago was 65 pediatric CI recipients. They not only looked at data logging information, but they also reported a significant relationship between how much the child wore the implant and speech recognition, such that greater CI wear time equaled greater speech recognition. But of course, that's just a correlation, and so we know that correlation does not equal causation. So that's an important point as we go through this. And this Guerzoni and Cuda, the same year, they looked at 10 children with cochlear implants. And they also found a significant correlation between daily CI use and outcomes, but in this case, it was vocabulary outcomes after one year of CI use. So finally, and I'm sorry, this is actually a miss, this, I, of course, I see the error now that I'm here in live mode. This is Schvartz-Leyzac et al. 2019, my apologies. And last year, this group from University of Michigan, they looked at patient, nearly 200 patient's data logs, these are all adults. And they found mean daily CI use was 12.1 hours. But they also saw a significant correlation between daily use and speech recognition. And interestingly, they did find that the strongest correlations were in the older groups, interestingly. However, they do also recognize that the youngest age groups that they had, there were only 23 participants in that sample. And so it's possible it might have just been a sampling issue.

But at the group level, there was a significant correlation. So of course, we wanted to look at this as well. And so, Jordan Holder and Nicole Dwyer and I pooled our data from our database, and this just came out in November of last year, and so I'm jumping right to the punch line. So we were able to obtain data logs from 300 patients in our database. So this is completely retrospective ranging in age from 18 to 96 years. Mean daily use was 10.2 hours, so very similar to what the Bush et al. paper, slightly less than the short Schvartz-Leyzac paper. And what you can see is that there is a statistically significant correlation between CNC word rec and daily CI use. And it's, you know, again, we can't say that this is causality, but we certainly can see that those that wear the device more tend to perform better. So we have a lot of work ahead of us to determine like, is it possible that if we take these people who are wearing their device five hours a day, and we can convince them through, you know, whether it be counseling or motivational techniques to go up to 15 hours a day, would we see their performance improve? Or is there may be something else that's, you know, contributing to their poor performance? So this is something that's gonna be exciting that we're gonna be seeing in the coming years. So in summary, our current cochlear implant electrode arrays and surgical techniques, we know that things are dramatically different here in 2020, as they were in 2000, in even as compared from 2000 to 1990. So we're seeing improvements, which is just phenomenal and so exciting. We know that we're seeing better, you know, better neural survival, because we have people with better hearing getting implants, shorter durations of deafness. We're getting better device placement because we have better electrodes. We have more trained surgeons. We're using imaging and imaging confirmation to, you know, determine where these electrodes are. And so there were a number of variables that influence outcomes. I do also wanna point out that I did not have time to cover electrocochleography and it is on the quiz.

So I did put a little asterisk at the bottom. We know that there is a correlation between underlying neural health and postoperative outcomes. But that's gonna be for another lecture. So, in conclusion, you know really, we know that a one size fits all approach is not a very good approach. It's really not a good approach for anything, but it's certainly not a good approach for audiology and cochlear implant patient management. And so as we move more towards a precision medicine or precision audiology approach to our patients, I really wanna look forward to us, you know, approaching each individual patient as an individual in our cochlear implant clinic, thinking about, "What electrode do they have? "Is there something I could do with this patient "as opposed to you know, the same patient "or a patient in similar age, gender, "etiology, might have a different electrode." So very excited, I have more things to come in the future. I really thank you for your attention. This is a picture of our cochlear implant team. And now Melissa is gonna pull me back to the classroom. I realize many of you probably have to go back. You have patients waiting, but I am going to answer some of the questions that are posted. Okay. Are you there, Melissa?

- [Melissa] Okay, if anyone has any questions, please go ahead and write those in. Otherwise you are welcome to log out. Renee, that was wonderful. Thank you very much for being with us today.

- [Rene] Thank you, it was a lot of fun.

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