Move Over Mickey Mouse - Turning the Tables on What You Know About CI Sound Quality

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- Hi, I'm Josh Stohl, I'm the director of MED-EL's North American Research Laboratory in Durham, North Carolina. Today I'd like to talk to you about how our longstanding key design principles come together to provide natural sound quality. And allow us to overcome this idea that cochlear implants sound up shifted or like a cartoon. We're learning a lot from these incredible images produced by investigators at Western University in London, Ontario. These are images produced using a synchrotron technology at the Canadian Light Source. And what we see here are really remarkable representations of the delicate structures of the cochlea. And these images are helping us understand more about the anatomical configuration of individual cochlea, but they're also reinforcing our longstanding key design principles, the first of which is the use of atraumatic electrode arrays to ensure the protection and preservation of these delicate structures.

We also want these electrode arrays deeply inserted into the cochlea so that we have complete coverage of the target spiral ganglion neurons, which we, again from these new images know extends to about two turns beyond the round window or about 720 degrees into the cochlea. Once we have an atraumatic electrode array placed deeply into the cochlea, we then wanna mimic the sound coding mechanisms of the natural system. And so today I'd like to talk about how these technologies come together to produce the most natural sound quality one can experience with a cochlear implant. In order to understand what these cochlear implants sound like, we're going to rely on some work from Dr. Michael Dorman at Arizona State University.

Dr. Dorman has worked with single-sided deaf cochlear implant users and asked them to listen to various acoustic simulations in their normal hearing ear and compare those acoustic simulations to the quality of their cochlear implant, so that we can better understand how these devices sound. The example I'd like to give comes from a 17 year old patient, who at the time of testing had two years of a device experience. This is a patient with an atraumatic FLEX28 electrode array, a deep electrode insertion of

580 degrees, and our fine structure FS4-p sound coding strategy. I'll refer to these angular insertion depths throughout the talk. So let me just remind you when we talk about angular insertion depth, we're speaking relative to the round window, which is at zero degrees in this coordinate system.

If we go into the cochlea one full turn, that's 360 degrees. A half turn, or one and a half turns will get us to 540 degrees. And then, two full turns to 720 degrees. So again, for this particular patient, we're talking about an insertion depth of 580 degrees for the most apical contact. And this is what the cochlear implant sounds like for that patient. First, I'll play the original sound.

- [CI] Do you like camping?

- And this is the sound quality of the speech match to the cochlear implant with a rating of a 10 out of 10 match.

- [CI] Do you like camping?

- And as you can hear, they're nearly identical, a little bit of distortion, but otherwise the pitch is nearly the same and the sound quality is very natural. I'll play that one more time.

- [CI] Do you like camping?

- Now with this same patient, Dr. Dorman deactivated electrode one. The idea here was to simulate a shallow insertion depth corresponding to approximately 460 degrees in this patient. And he repeated the quality match. They were able to again achieve a 10 out of 10 match, but let's hear what the implant sounds like with the first electrode deactivated.

- [CI] Do you like camping?

- So here we hear a clear upshift in pitch and degradation and the quality. Now, one might argue that this is a result of this patient having listened to a deeply inserted electrode array in their daily life and having acutely deactivated electrode one. In Michael Dorman's most recent publication, he tries to get at this idea that patients will adapt to their cochlear implant given enough time. Dr. Dorman evaluated five users of advanced bionics cochlear implants. Here we can see they have a relatively shallow insertion depth compared to the MED-EL device from the prior slide between 340 and approximately 420 degrees. So these arrays are inserted to about one turn into the cochlea. He asked these patients about the sound quality of their cochlear implants at two time points relatively close to activation.

And then after some extended device use, in some cases multiple years. And then he represented the changes in the sound quality relative to zero at these two time points. The first time point corresponds to the initial quality match for each of these subjects and the second time point to the second quality match. And the numbers, 1, 2, 3, 4, 5 correspond to the patients one through five here. Provide some examples of what these might sound like to the patient. So here's the original speech.

- [CI] Do you like camping?

- For a frequency shift and the speech frequency region or the form frequencies corresponding to 300 hz like we saw for Patient 3. Sound quality is upshifted.

- [CI] Do you like camping?

- And similarly, for a fundamental frequency shift up to 50 hz like we see for Patient 4. We hear an upshift.

- [CI] Do you like camping?

- And so what we can see in these data is even after years of device use at least one of these pitch shifts was present at the second time point for all five of these users. Interestingly, when you look at the text of this paper these users described the cochlear implant as sounding normal. But what we can see from the objective quality matches is that these upshifts in pitch do not resolve over time. And so from Dr. Dorman's work as a whole over the last five or so years, we can see that for these shallow insertion angles in the prior slide between 340 and 420 degrees, we can see an upshift in either the formant frequencies or the fundamental frequency.

And these upshifts persist even after years of device use. For insertion angles shallower than 450 degrees, Dr. Dorman has also observed an upshift in pitch and an upshift in the speech frequency spectrum. And it's only for implants that are inserted beyond 450 degrees where this pitch shift goes away. So how do we get beyond 450 degrees? As you may know MED-EL provides a wide range of electrode arrays, so that we can accommodate the variations that we see in cochlear anatomy. Or in this case, I'll describe cochlear anatomy in terms of cochlear duct length, or CDL. So our default electrode array or recommended electrode array is the FLEX28. And you can see that for an average cochlear duct length, we're well beyond that 450 degrees.

But it's certainly possible that a patient receiving a cochlear implant has a longer than average cochlear duct length. And in that case, the FLEX28 is only gonna get us just beyond that 450 degrees. And we would really much rather see our longer electrode variant, the FLEXSoft, in the patient with this long CDL. Similarly, it's not necessary to put an extremely long electrode array in a patient with a very short cochlear duct length. And so in this way not only are we providing electrode options for each patient, but now we'd like to be able to enable you to choose the correct variant for that individual cochlea. In order to do that, we're providing information about individual cochlea based on preoperative CT or MRIs that can be shared with MED-EL through our OTOPLAN on demand service.

To visit this website, you can use the QR code shown on the screen here. This pre-operative CT or MRI is shared with MED-EL through our secure platform. We'll do an analysis with our trained experts internally here and provide estimates of insertion depths for various electrode array options for each individual cochlea. I highly encourage you to at least take a look at this service if you haven't already started using it for your patients. As again, this service can be used preoperatively with an MRI or a CT. So, we started at the end of the story, which is what happens when we put all of these technologies together? Atraumatic electrode arrays, deeply inserted electrodes, and our natural sound coding.

I'd like to focus a little bit more now on just the sound coding. When we design our sound coding strategies, our design goal is to mimic the natural auditory system and so far it's possible with our modern technologies. So if we look at the block diagrams, or the various signal processing stages, within one of our implant processors, audio processors, we can relate various stages in that system to aspects or functions in the normal hearing system. And that's what I'd like to do in the next part of the talk. We're going to start with the natural directionality technology from MED-EL. Here, we're mimicking the pinna, or the outer ear, and its ability to emphasize sounds from the front.

What we're looking at here is a so-called polar plot. This is like looking down on top of the head with the noise pointing here towards 0 degrees. Each color represents the spatial response to a different frequency. The 0 dB line here represents no gain or attenuation. And closer to the center of the figure represents attenuation. If we look first at the 500 hz response, we see that the system is more or less sensitive in all directions for this low frequency, just as it is the case at the natural system, as these low frequencies pass through the pinna. However, high frequencies bounce off the pinna, especially from the back. And we see that here for the 8,000 hz tone, for example.

We see a large attenuation of that sound from behind the listener. So again, these emphasis of sounds from the front by attenuation of high frequency sounds from the back is mimicking the pinnas job of emphasizing sounds that are in front of the listener. Once that sound goes through the pinna, and the ear canal moves the tympanic membrane and goes through the middle ear, then we're into the cochlea and the acoustic system. And that's where the first stage of compression is applied. We often talk about the narrow electric dynamic range saying that it's 10 to 20 dB, but indeed that's the neurodynamic range. And so just like we have to apply compression in a cochlear implant system, there is compression happening in the acoustic system bringing down the very wide acoustic dynamic range down to the neurodynamic range.

So we're just trying to do the same thing here by mimicking the various aspects of compression in the acoustic system. The first of which is basilar membrane compression. This compression is the result of the stiffness of the basilar membrane, shown in gray here, which is a product of the membrane itself, as well as the stiffness of these outer hair cell bundles shown in green. And an experiment in 2000, Plack and Oxenham looked at the basilar membrane compression in normal hearing listeners as a function of frequency. And these are the compression ratios that they derived from that normal hearing acoustic experiment. The MED-EL automatic gain control system just has one channel. It operates on the full microphone signal, and so we need one compression ratio, and that compression ratio is 3:1 to closely match the natural compression ratio that we see on average across the cochlea.

I'll spend a little more talking about our automatic gain control stage in our system now. This is the sys part of the system that's responsible for being able to process a wide range of input intensities from about 25 dB sound pressure level or SPL, up to just over 100 dB SPL. If we're to freeze the system at any given time, the instantaneous input range dynamic range is 55 dB. This is plenty of room to cover the typical 40 dB variation that we see in speech. The way that this 55 dB window is used to capture the full 75 dB input dynamic range is through our automatic adjustment of the gain. When the processor, or the user, is in a quiet environment, like a classroom, for example, the gain is increased to provide amplification and access to these softest sounds.

If the user moves into a loud environment, they're attending a sporting event or a rock concert, both of which are so important for a good quality of life, or if there's an emergency situation, and there's an alarm sounding that needs to sound much louder than conversational speech, then the system will turn down the gain to ensure proper representation of those loud sounds without clipping. Again, our compression ratio, which I'll describe in just a moment, with respect to this knee point is 3:1. And that knee point, where we transition from the linear region of the system to the compressive region, is determined by the sensitivity. This is a parameter that the user can adjust in their daily life to increase access to soft sounds, but as by default set the 75%, which corresponds to about 53 dB SPL.

I'll come back to our knee point in just a moment. I'd like to use this figure for the next couple of slides to be able to compare cochlear implant systems. This figure and the comparisons and details I'll share in the next few slides all come from this 2014 paper by Vaerenberg and colleagues. Here we still see the MED-EL automatic gain control input output function. Input sound pressure level is shown on the horizontal axis here. And at the output of the AGC, we see dB full scale, FS corresponds to full scale. These are digital units, where 0 is clipping. And when we go through the AGC, we get to our second stage of compression, which I'll describe later, our MAP Law compression, and our mapping onto the individual electric dynamic range of each electrode between the threshold and the maximum comfortable loudness or the MCL level.

And in this way we can map input levels to output levels. So I mentioned that the system is linear up to the knee point. That is to say for a 1 dB change at the input, you'll get a 1 dB change at the output. Above the knee point, which again is set by the sensitivity in the MED-EL system, can be set by the user, and is by default 53 dB SPL. Above that knee point, we see a transition to our 3:1 compression ratio where we need a 3 dB change at the input to produce a 1 dB change at the output. The main thing I'd like you to take away from these next few slides is mapping of intensities above the knee point.

So in the MED-EL system, as we continue to increase the input intensity, what we can see is that we also continue to increase the stimulation level within the electric dynamic range, providing a nice representation of loudness growth all the way from about 25 dB SPL up to about 100 dB SPL. If we compare that input output function to the system from cochlear, we see that their knee point is at this C-SPL parameter, so they're also linear up to the knee point. But then by default, the C-SPL parameter, which is set to 65 dB SPL, or with the auto sensitivity set to 12 dB, then this value is maximally 77 dB SPL. This is the sound pressure level SPL that maps onto their C level, which is the maximum stimulation level in the cochlear system.

And so what we can see in this system is that once you get above the knee point further increases in input intensity produce no change in the stimulation level at the output of the cochlear implant. That's not to say that the system is clipping these sounds for a 10 dB increase at the input sound level the system will apply a -10 dB of gain to keep the output at the C level. And so what this means is that once you get above that C-SPL level, the patient is very unlikely to experience any increases in loudness. So we might have loudness growth up to this parameter, but typically not beyond. And if we look at the advanced bionic system, again, we see linearity up to the knee point, and a 12:1 compression ratio above, which produces a behavior that's somewhere in between the MED-EL and cochlear systems, where we see all of these increases in intensity mapping on to values that are changing, but are very close to the M level.

So we see a much smaller separation here for the upper part of the electric dynamic range compared to the MED-EL system. And these input output functions of our competitor systems really reveal the focus on transmitting speech information. What we see here is that they're trying to push the energy around the level of conversational speech around their knee points, 60-65 dB SPL, up against the upper end of the electric dynamic range. And we know that this provides limited loudness growth for high intensities, but it also may create asymmetric loudness growth when you're pairing that cochlear implant with some acoustic system on the contralateral side, whether that's a hearing aid, or in the case of single-sided deafness, a normal, or near normal hearing ear.

In order to ensure that we don't have this asymmetry and loudness growth, we first need to mimic loudness growth throughout the acoustic dynamic range. And here, by design, we're really trying to mimic the natural system. And this is especially important for our users of cochlear implants who are single-sided deaf, but for our bimodal population, they might be using a hearing aid on the contralateral side that has a compression ratio that's similar but not identical to the MED-EL system. Hearing aids are also trying to address the loss of outer hair cells and restore basilar membrane compression. And so that's why we see similar compression ratios here. And the MED-EL system can be adjusted, such that the compression ratio can be matched to the compression ratio of the contralateral hearing aid.

And this really allows the hearing aid audiologist to provide the preferred and best amplification solution for either the contralateral ear or even the implanted ear if for some reason an EAS system is not the best solution. And again really what we've tried to do is design the system so that it when it's paired with a normal hearing ear on the contralateral side, as is in the case of single-sided deafness and cochlear implantation, that we're matching the natural compression of their normal hearing ear. Another property of the basilar membrane is that it decomposes sounds into various frequencies, again, based on its stiffness. To mimic the decomposition properties, the frequency decomposition properties of the basilar membrane, we use bell-shaped filters.

What you see in the MED-EL clinical system software, our MAESTRO software, corresponds to these red bars here. We just see the top parts of the filters up to the point where they overlap. But indeed, these filters continue to overlap and roll off beyond the crossover frequency. And it's this continuous overlap and these bell shaped designs that really produce intermediate pitches for our cochlear implant users that allow us to provide a continuous representation of the frequency spectrum. Some other features of these time domain filters are that they produce a very short processing delay. As soon as the sound hits the microphone, we begin processing that sound. And so this allows for a processing delay of about 1.5 milliseconds from the time that the sound arrives at the microphone to the time that the sound is being presented electrically.

In our competitor systems, they use a different method for frequency analysis. And that method requires that the processor fill up a time window of sound 8-12 milliseconds. And then that full-time window of sound is transformed to the frequency domain for spectral analysis. But that initial time window that needs to be filled up, again, 8-12 milliseconds introduces a processing delay or a delay between the time that the sounds arrive at the microphone and that the sounds are presented to the auditory nerve. And having a short processing delay in our system, again, allows us to match our system with a hearing aid on the contralateral side by delaying the start of our processors, so that those two devices can be time aligned.

Another feature of our filter design is that it mimics the traveling wave delay. That is when you put an acoustic click into a natural system, that click will take time to travel up the basilar membrane from the base where the sound enters the cochlea up to the apex. And what we see here is the response to a click. This is the filter bank output in response to an input click. And we see that again about 1.5 milliseconds after the start of the stimulus, We have an output on the most basal, or highest frequency channel. And the outputs of the lower channels are progressively delayed in time, mimicking that time that it would take to spiral up to the apex and the cochlea.

The idea here is that we want to get information to the brainstem in a time aligned way. The displacement of the basilar membrane causes deflection of the stereocilia of the inner hair cell, and this is how we send electrical pulses to the brain and the acoustic system. If we look at some inner hair cell receptor potentials from Guinea pigs, so these are voltages measured from Guinea pig inner hair cells, we see the responses to different tone pips or different frequencies. Here we have 100 hz, the lowest frequency, up to 1000 hz. And in this left group we see two properties of the stimulus. We see the envelope, the onset, the stimulus, and the offset, and we also see the fine structure or the phase lock, phase locked responses of the hair cell to the input stimulus frequency.

When we get above 1000 hz, the neurons can no longer keep up with the changes in pressure, the rapid changes in pressure that correspond to the fine structure, and we're left with just the envelope. So we can still see the onset, stimulus, and opposite, but we no longer see the rapid oscillations that correspond to the instantaneous frequency. That fine structure is only present for low frequencies. I'll come back to that in just a moment. But these inner hair cells also apply the second stage of compression in the acoustic system. Here on the horizontal axis we have normalized pressure and linear units of pascals. And on the vertical axis we have the peak receptor potential and millivolts. What I wanna point out here is the logarithmic shape of that response that maps pressure to voltage in the acoustic system, which is just like our map law stage, which maps pressure to charge in our cochlear implant system.

And so here our map law stage is mimicking inner hair cell compression. I mentioned before fine structure stimulation and envelope only stimulation. If we take a look at an electrogram, this is the word bean processed by our FS4-p strategy. In the low frequency region, we see the slow variations in pressure represented in the envelope. And we also see changes in the pulse timings that represent changes in the fine structure of this stimulus. In the high frequency channels, we see continuous stimulation, so that we can faithfully represent the envelope in each channel and just the envelope. The last technology that I'd like to talk to you about is our anatomy based fitting. This is a new frequency allocation option that relies on information taken from OTOPLAN and a post-operative CT scan.

So I mentioned earlier that our OTOPLAN, and our OTOPLAN on demand service can be used to analyze pre-operative CT or MRI images, so that an electrode array can be selected for the individual cochlea and cochlear duct length. And putting the longest array possible as deeply inserted into the cochlea as possible is the best way to produce this natural sound quality. But we also can make some postoperative corrections through frequency fitting or through this new anatomy based fitting technology. If we have a post-operative CT scan, our OTOPLAN on demand service can also be used to analyze a post-operative CT scan to locate the position of the electrodes within the cochlea. And what we want to do with anatomy based fitting is align the filters of the filter bank in the cochlear implant with the place of the electrodes to which those frequencies are assigned.

So again, the idea here is that we wanna align the place of stimulation and the frequencies delivered to that place of stimulation. For more information about this technology, I encourage you to check out this other AudiologyOnline talk presented by myself and some of my colleagues. This QR coach should take you directly to that talk. So again, our goal here is to provide an atraumatic electrode array that's deeply inserted and codes sound according to the natural system to provide good outcomes and a sound quality that's as close to the natural percept that someone would receive with acoustic hearing as possible. And so we're really relying on our longstanding key design principles. These have not changed over many years, and we still think that atraumatic electrodes, a complete coverage of the cochlea, and delivery of natural acoustic information, all are necessary components of providing best benefits with MED-EL's cochlear implants.

And now we're going a step further and allowing further individualization of our cochlear implant system, both in the pre-planning phase with our OTOPLAN technology, and also postoperatively with the anatomy based fitting technology. And it's really the combination of all of these technologies together that allow us to provide the closest to natural hearing to our patients and users. And so it's again, the combination of these technologies and the importance of getting the electrode array deeply inserted to the cochlea, and coding acoustic information in the natural way that has allowed us to say, "Move over Mickey Mouse. We're now talking about natural hearing through cochlear implants." Thank you very much.