New trends with cochlear implant electrodes

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Depending on the etiology of sensory neural hearing loss and patient age, it is postulated that a significant number of cochlear implant candidates today have a rich neural substrate consisting of nondegenerated dendrites and a large number of spiral ganglion cells with associated axons. In addition, many patients have some residual hearing especially in the low frequencies, demonstrating neural survival in the apical regions. With long electrodes covering the scala tympani from base to apex, it has become feasible to improve tonotopic stimulation. Key to the long-term success of implantation is preservation of intracochlear structures during electrode insertion. Round window membrane insertion combined with free-fitting lateral wall electrode placement tends to preserve residual hearing. New coding strategies providing fine structure information in the apex can enhance patient performance. Delicate intracochlear tissues must also be preserved during the multiple explanations and reimplantations that young patients face during their 80+ year life span, otherwise some benefits will be lost over time.

Key words: cochlear implant, hearing preservation, atraumatic, round window, electrodes

Background
A cochlear implant (CI) electrode is a neural interface to the excitable tissue of the inner ear. Small currents, driven through electrodes distributed within scala tympani, are able to synchronously depolarize small to large groups of afferent neurons depending on current intensity. Originally, CI electrodes were designed for profoundly deaf patients assuming that a mostly depleted neural population was present in the form of spiral ganglion cells and associated axons. No measurable residual hearing was present in the patient group, and it was often assumed that the dendrites were absent because of the duration of deafness and associated slow retrograde degeneration of unstimulated neurites. Retrograde degeneration of neurons begins at the first synapse in the organ of Corti and progresses toward the habenula perforata and the soma of the primary auditory afferent neurons located in the superior portion of the modiolus and in the Rosenthal’s canal of the basal turn. The unmyelinated spiral ganglion cell soma was widely believed to be the site of spike initiation under electrical stimulation. Because no dendrite survival was assumed and no residual hearing was present, the issue of electrode trauma was reduced to protecting the soma of sensory cells within the modiolus.

In recent years, however, two new important trends in cochlear implantation have emerged worldwide.

1. Indications have widened from profoundly deaf to
severely deaf, and even to patients with considerable low frequency residual hearing up to 1 kHz or more. 2. Age of implantation has rapidly decreased from elderly and middle aged patients to young and very young aged children.

Today the neural substrate of many recipients of CI technology can be assumed to have a substantial dendrite population. The evolution of the CI population and indications calls for a reevaluation of the neural substrate targeted though electrical stimulation and a reconsideration of requirements for the neural interface. Neural substrate complexities are now included in the theoretical modeling of nerve fibers and responsiveness to electrical stimulation.

**Neural substrate targeted for electrical stimulation in the CI population**

A single afferent auditory nerve fiber in the inner ear consists of a dendrite (peripheral or distal process), a spiral ganglion cell body, and an axon (also called proximal or central process). Electrical stimulation causes depolarization at one or more nodes of Ranvier in the dendrite or axon when a minimum potential difference is reached, thereby initiating orthodromic and antidromic action potentials at the site of depolarization. Because the spiral ganglion cell soma is unmyelinated, nerve fiber modeling indicates that spikes are difficult to initiate at the cell body but can be initiated at the first node of Ranvier closest to the soma.

Many etiologies of sensory neural deafness affect young and very young children, and it can be assumed that a comparatively intact neural substrate is in place including the dendrite portion of the nerve fiber. Often deafness in that population is caused by a loss or absence of hair cell function, not by a degradation of neurites or spiral ganglion cells. The majority of sensory neural hearing losses includes gene mutation (especially the GJB2), auditory neuropathy, ototoxic injury (amino glycoside and cisplatin induced deafness), as well as viral and bacterial infection induced deafness. Duration of deafness in young and very young CI candidates is short by definition and little neural degeneration takes place. In these cases, a free-fitting electrode array inserted along the lateral wall of scala tympani, covering the cochlea from base to apex, provides the best solution for electrical stimulation of afferent neurites as well as axons. Greater selectivity and less channel interaction is achieved by distributing a finite number of electrode contacts over two and a half cochlear turns rather than concentrating the same number of contacts in a single turn (Fig. 1). In adults a similar trend of peripheral neural survival can be expected in many cases. Sudden hearing loss, mitochondrial, autoimmune and noise induced hearing loss result in a loss of hair cell function, while neurite

![Fig. 1](image_url)

A finite number of channels can be grouped in one basal cochlear location (left) or distributed along the whole cochlear length (right). Distinguishable pitch percepts between adjacent electrodes can be improved and channel interaction decreased by increasing contact separation and increasing cochlear coverage (photo of decalcified human cochlea with nerve bundles osmium stained, preparation by G. Wright and P. Roland, USWT, Dallas, USA).
preservation is maintained for some time when the implantation occurs shortly after injury.

For the population with some residual hearing in the low frequencies, it is clear that neurite survival has taken place in the apical region with a possible partial depletion in the basal turn. The histopathology of temporal bones of patients with presbyacusis shows partial depletion in the high frequency region of the cochlea. The poorest neural survival is found in cases of meningitis. Rapid ossification of the otic capsule causes a serious depletion of neurites and spiral ganglion cells as well as obliteration of the cochlea. In malformations, such as common cavities and incomplete partitions, the neural substrate organization may also be compromised. The distribution of auditory nerve fibers in malformations can be difficult to evaluate although many of these patients benefit from the implant.

**Neural interface requirements**

The high probability of good neurites survival in all turns of the cochlear is both an opportunity and a challenge for electrical stimulation. The opportunity dwells in the density of electrically excitable neural tissue in the inner ear from base to apex. The challenge resides in focusing electrical stimulation to the dendrite portion of the neural fibers to achieve better selectivity and, perhaps, lower thresholds. The neurites in the spiral lamina are distributed in a single plane as they reach the habenula, while they coalesce in fascicles as they enter the modiolus (Fig. 2). As described earlier, in the ideal situation neurite survival is essentially intact from base to apex. The neural interface should, therefore, be positioned on the lateral wall of the scala tympani with channels distributed from base to apex of the cochlea. An advantage of having electrodes in the most apical region is the possibility of reaching low and very low frequency fibers more directly and without current having to penetrate and stimulate higher frequency regions. Low frequency nerve fibers in the basal turn of the modiolus are the axons that reside in the center of the modiolus (Fig. 3). They are surrounded by high frequency soma located in Rosenthal’s canal. With an electrode spanning one cochlear turn, either lateral or medial, the low frequency and some mid frequency fibers can never be specifically addressed, not at any current intensity. Low frequency pitch perception of electrical stimulation is probably the result of recruitment of low frequency fibers in addition to high- or mid-frequency ones. For an electrode in the apex, the challenge is to preserve frequency specificity as current increases by confining the potential field to the apical region.

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**Fig. 2**

A. View of the decalcified spiral lamina with dendrite nerve fibers fanning out to the basilar membrane. The nerve fibers have been osmium stained for better visualization. The 3D bundling of spiral ganglion cells in the modiolus gives rise to multiples fascicles in the spiral lamina. The termination of nerve fibers in the organ of Corti is 2D planar, an ideal arrangement for tonotopicity.

B. View of the modiolus with nerve fibers in discreet bundles (bottom of the picture) and spiral lamina (upper portion) with nerve fibers fanning out.
With cochlear implant recipients implanted earlier in life and the overall patient population displaying a much better neural substrate, as shown by measurable residual hearing, the issue of an atraumatic electrode and insertion has become more central. At one point, it was assumed that the cochlea was dead and that there was nothing to preserve except the modiolus. This led to the forceful insertion of traumatic electrodes with dramatic consequences. The number of meningitis cases of patients implanted with a traumatic electrode positioner was disproportionately high. Today electrodes tend toward being more atraumatic in design and in the surgical approaches to minimize potential damage to the cochlea by insertion through the round window membrane. Insertion of an electrode through the round window membrane reduces drilling of the promontory to partial removal of the round window niche, and ensures that the electrode is in scala tympani thereby avoiding injury to the spiral ligament and venous system at the entry point (Fig. 4). A good measure of atraumaticity and surgical quality in CI is an immediate postoperative evaluation of hearing preservation in patients. Preservation of some residual hearing means that the basilar membrane has not been perforated and that the endocochlear potential is intact. In addition preservation of residual hearing to within 10 dB of preoperative levels demonstrates an excellent electrode design and remarkable surgical quality. Immediate loss of residual hearing after implantation could mean that a violation of scala media occurred, or that the electrode deviated from one scala to another with associated destruction of Reissner’s membrane. Delayed loss of residual hearing on the other hand could be related to some inflammatory process responsible for the toxic release of cytokines, with possibly extended fibrosis taking place within the scala tympani. One unexpected new development in CI and hearing science is the recent demonstration of hearing preservation even in the presence of a long electrode covering the residual hearing region (Fig. 5). Basilar membrane vibrations and mechanoreceptors can be unaffected by the pres-
ence of the electrode in scala tympani. More studies, prospective as well as retrospective, are needed to evaluate this unanticipated phenomena. Another critical aspect of CI implantation in young and very young population is the preservation of cochlear structures during not only electrode insertion but also during explantation and re-implantation of an electrode multiple times. Because the very young implanted child will wear a CI for 80 years (unless functional sensory epithelium regeneration becomes possible), preservation of the maximum neural reserve during the 4 to 6 re-implantations expected in their lifetime is necessary. An electrode that causes additional tissue damage during explantation is not an acceptable choice. Preshaped electrodes designed to hug the modiolus require extra forces to uncoil the memory shaped silicone during explantation (Fig. 6), and rub against the fragile medial wall (Fig. 7). The protective fibrous encapsulation around the electrode is probably destroyed during the explantation process. Therefore, reimplantation in the original fibrous sheath is not possible. Free-fitting lateral wall electrodes may be a better choice in electrode design for long-term preservation of cochlear structures because they do not exert additional force during explantation, and can be reimplanted in the same fibrous sheath encapsulation that surrounded the previous electrode. Given the pace of developments in molecular biology, it is likely that within the next 50 years some form of gene therapy will be available for the very young patients of today. Therefore, atraumatic electrode and surgical techniques, including reimplantation, are of great importance.

**Conclusion**

Early cochlear implantation in the 1970s was directed at profoundly deaf adult patients. This population had no residual hearing and had often been afflicted with hearing loss for decades. Extensive neural degeneration was suspected in this group. As the indications for cochlear implant have evolved in age at implantation and in the amount of quantifiable residual hearing, a new respect for atraumaticity during CI electrode insertion has emerged. Cochlear degenera-
Patient’s right ear X-ray of complete cochlear coverage electrode (MED-EL standard) and patient audiogram pre- (A) and postop (B) at 8 months. The patient uses a Duet system (combined electric and acoustic stimulation) and benefits from simultaneous electric stimulation and acoustic input. Atraumatic surgery and electrode insertion through the round window membrane performed at Shinshu university, Matsumoto, Japan, by Prof. Usami.

Fig. 5

Preservation of at least some residual hearing with medium and deep electrode insertion is a measure of the electrode quality and surgical expertise and is much more accurate than temporal bone studies. The trend in electrode design is toward placement of a lateral wall free-fitting electrode, which is soft and flexible and able to reach a greater cochlear length while also being highly atraumatic. As more and more young and very young children are implanted, we must do our utmost to preserve cochlear structures for a lifetime use of CIs. This includes the design of electrodes that can be easily explanted and reimplemented without aggravation of trauma. Today, more and more centres systematically monitor and report hearing preservation in electric-acoustic stimulation and other patients to demonstrate electrode and surgical quality, a very healthy trend indeed.
Comparison of extraction (explantation) forces between 2 devices in a scala tympani model: preshaped perimodiolar electrode versus lateral wall electrode. Peak explantation forces for a perimodiolar electrode are seven times greater than a lateral wall electrode. After several years of implantation, the presence of a fibrous tissue envelope around the electrode may increase explantation forces further, as well as destroying the protective sheath.

Fig. 6

Fig. 7

Squeletized medial wall of the human cochlea. The clear portion of the image looks at scala tympani and osseous spiral lamina. Scala vestibuli in the shadowy upper portion. The otic capsule lateral wall has been removed. Bony channels harboring nerve bundles and fenestration are visible on the rugged modiolus surface. Photo by Dr. Ichiki and Anneliese Schrott-Fischer, University of Innsbruck, Austria.

References


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