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Review

The nicotinic receptor of cochlear hair cells: A possible pharmacotherapeutic target?

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ABSTRACT

Mechanosensory hair cells of the organ of Corti transmit information regarding sound to the central nervous system by way of peripheral afferent neurons. In return, the central nervous system provides feedback and modulates the afferent stream of information through efferent neurons. The medial olivocochlear efferent system makes direct synaptic contacts with outer hair cells and inhibits amplification brought about by the active mechanical process inherent to these cells. This feedback system offers the potential to improve the detection of signals in background noise, to selectively attend to particular signals, and to protect the periphery from damage caused by overly loud sounds. Acetylcholine released at the synapse between efferent terminals and outer hair cells activates a peculiar nicotinic cholinergic receptor subtype, the $\alpha9\alpha10$ receptor. At present no pharmacotherapeutic approaches have been designed that target this cholinergic receptor to treat pathologies of the auditory system. The potential use of $\alpha9\alpha10$ selective drugs in conditions such as noise-induced hearing loss, tinnitus and auditory processing disorders is discussed.

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Abbreviations: ACh, acetylcholine; *Chrna9*, gene that codes for the $\alpha9$ nAChR subunit; *Chrna10*, gene that codes for the $\alpha10$ nAChR subunit; IHCs, inner hair cells; MOC, medial olivocochlear; nAChRs, nicotinic acetylcholine receptors; NIHL, noise-induced hearing loss, OC olivocochlear; OHCs, outer hair cells.

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1. Introduction

Sensory systems perform a series of common functions. Each system responds with some specificity to a stimulus from the surrounding world and employs some specialized receptor cells at the periphery to translate those stimuli into electrical signals that all neurons can understand. That initial electrical event begins the process by which the central nervous system constructs an orderly representation of for example, sounds, odors, tastes and visual objects. Thus, basic sound detection begins when sound waves strike the eardrum, which transmits that physical stimulus to the organ of Corti within the cochlea, the sensory epithelium of the mammalian inner ear. Here the primary receptor cells transform mechanical input into electrical signals that are sent to the central nervous system by the auditory nerve [1]. However, unlike vision, touch and the chemical senses, sound transduction is modulated by efferent signals (olivocochlear, OC) that travel in reverse, from the brain back to the inner ear [2]. The present work reviews the data which demonstrates that synaptic transmission between medial OC (MOC) fibers and cochlear hair cells is mediated by a peculiar nicotinic cholinergic receptor (nAChR), the α9α10 receptor. In addition, we discuss possible pharmacological targeting of this receptor in inner ear pathologies, as well as in auditory processing disorders and reading disabilities.

2. Organization of the mammalian cochlea

There are approximately 16,000 sensory hair cells in the human cochlea. They are organized in a tonotopic fashion, with those sensitive to high frequency sound at the basal end and those sensitive to low frequency at the apical end of the cochlear coil [1]. Hair cells are neuroepithelial cells, with the apical pole specialized for mechanotransduction and the basal pole specialized for the release of neurotransmitter. The mammalian cochlea contains two classes of hair cells arranged in rows along the organ of Corti. Inner hair cells (IHCs), of which there are approximately 3500 in each human cochlea, are innervated by dendrites of the auditory nerve and are considered to be the primary sensory hair cells of the cochlea. Outer hair cells (OHCs) number approximately 11,000 in each human cochlea and lie in three rows. They have a much less pronounced afferent innervation, but are the target of an efferent neural pathway [2–5]. IHCs are also a target for a descending pathway, but in this case, the efferent axons form a synapse on the postsynaptic (afferent) terminal and will not be considered further here.

3. Amplification in the mammalian ear

The receptor cells of most sensory organs must amplify their signals in order to separate them from background noise. Photoreceptors, for example, use a biochemical cascade to enhance their responses several thousand-fold after transduction has been accomplished. Cochlear hair cells, instead use an active mechanical process to amplify their inputs [6,7]. When sound reaches the cochlea, it elicits mechanical vibrations that are sensed and transduced into an electrical response by motion of the hair bundles of hair cells which contain the mechanically-gated ion channels. At the same time, however, the hair cells perform work by increasing the magnitude of their mechanical input. This amplification of the stimulus constitutes a positive feedback that enhances the sensitivity of hearing by countering the loss of energy through the viscous dissipation that accompanies the motion of hair bundles and other structures through the fluids of the inner ear.

There is little debate that in mammals OHCs are the principal players providing the feedback that drives cochlear amplification. Two alternative mechanisms for amplification have been described. One in which amplification results from a nonlinearity in the transduction mechanism itself [8–10] and another in which the hair cell receptor potential drives a novel motile process within the lateral membrane of the OHC soma [11]. In this scenario, hyperpolarization causes the cell to expand along its longitudinal axis and depolarization causes it to contract. Somatic electromotility of OHCs, as the basis for cochlear amplification, is a mammalian novelty and is mediated by the motor-protein prestin [12], a member of the solute carrier anion-transport family 26 (*SLC26*) that has undergone Darwinian selection only in the mammalian lineage [13,14]. The contribution of transduction nonlinearity to amplification in the mammalian cochlea is still a matter of debate.

4. Amplification is under the control of the medial olivocochlear system

The MOC efferents (Fig. 1A) originate in the medial portion of the superior olivary complex and project to the organ of Corti, where they form large synaptic contacts with OHCs (Fig. 1A and B) [2]. Activation of the MOC pathway reduces cochlear sensitivity and tuning in a frequency selective manner, by inhibiting the mechanical amplification of low-level sounds that occurs before the sound stimulates the IHCs and the auditory nerve fibers [2,15]. Olivocochlear efferent neurons permit the central nervous system to control the way that sounds are processed in the auditory periphery, offering the potential to improve the detection of signals in background noise [16–18], to selectively attend to particular signals [19,20], and to protect the periphery from damage caused by overly loud sounds [21–25].

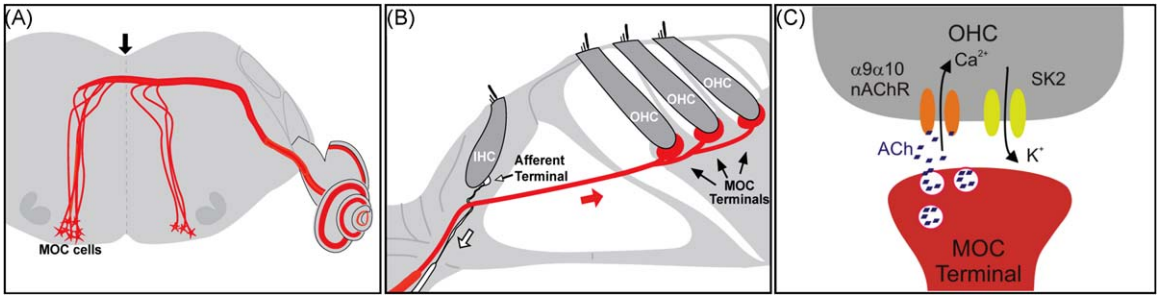

Fig. 1. Schematics showing the central origin (A) and peripheral projections (B) of the MOC fibers and the cholinergic synapse onto OHCs in the mature organ of Corti (C). MOC efferent neurons are located in the superior olivary complex of the brainstem and project to the cochlea, where they make direct synaptic contacts at the base of the OHCs. At this synapse ACh is released. It binds to α9α10 receptors present at the OHCs, leading to Ca^{2+} influx and the subsequent activation of Ca^{2+}-dependent SK2 K^+ channels and hair cell hyperpolarization. The arrow in (A) indicates the place of electrical stimulation to activate the MOC fibers. The white arrow in (B), indicates the afferent fibers which bring information from the IHCs to the central nervous system and the red arrow the MOC fibers. For approximately 10 days after birth (before the onset of hearing), cholinergic efferents temporarily synapse directly with IHCs and the cholinergic receptors at that synapse are also of the α9α10 subtype (not shown). Reproduced from Taranda et al. [25].

5. The nicotinic cholinergic receptor of cochlear hair cells

Acetylcholine (ACh) is the principal neurotransmitter released by MOC terminals. While both muscarinic and nicotinic receptors have been proposed to mediate the effects of ACh in the cochlea, pharmacological and electrophysiological data suggest a central role for an atypical, nAChR located at the synapse between efferent fibers and OHCs [15,26–34]. Current data indicates that activation of the hair cell nAChR leads to an increase in intracellular Ca^{2+} and the subsequent opening of small conductance Ca^{2+}-activated K^+ (SK2) channels, thus leading to hyperpolarization of hair cells (Fig. 2) and reduction of electromotility [33–36].

The cloning of the α9 nicotinic cholinergic receptor subunit deciphered the ionotropic molecular nature of the hair cell cholinergic receptor and established its inclusion within the nicotinic family of cholinergic receptor subunits [37]. The generation of mice carrying a null mutation for the gene encoding the α9 subunit (*Chrna9*) has unequivocally demonstrated that this subunit is a main component of the native OHC cholinergic receptor [38]. Characterization of the rat α9 nAChR subunit revealed that it formed homomeric, calcium-permeable, ACh-gated channels when expressed in *Xenopus laevis* oocytes with pharmacological properties largely indistinguishable from those reported for the native hair cell cholinergic receptor [37,39–41]. Moreover, a combination of *in situ* hybridization and reverse transcription-polymerase chain reaction (RT-PCR) experiments have shown α9 transcripts in cochlear and vestibular hair cells of several vertebrate species [37,42,43].

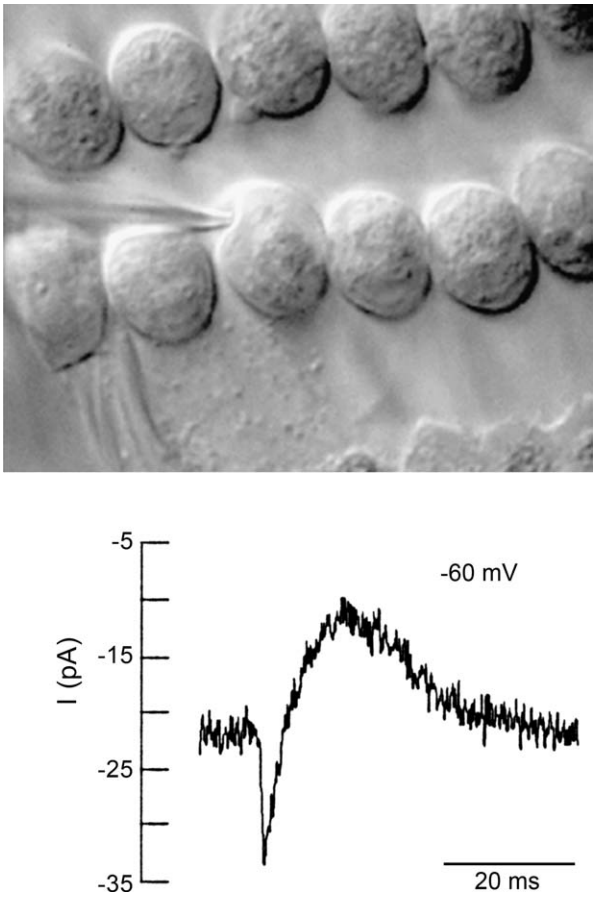

Fig. 2. Whole cell patch clamp used to record efferent synaptic currents from OHCs in the organ of Corti *ex vivo*. Upper panel shows a patch pipette attached to a first row OHC in the apical turn of a postnatal day 16 rat cochlea. Lower panel shows the typical biphasic synaptic current (−60 mV holding potential) produced by spontaneous ACh release from the presynaptic efferent terminal. It has been demonstrated that this biphasic current flow results from the sequential activation of α9α10-containing nAChRs, followed by calcium-gated (SK) potassium channels. Micrograph and recording courtesy of M. Lioudyno.

The cloning of the α9 subunit added a peculiar member to the nicotinic family of receptor subunits. When expressed in *X. laevis* oocytes, α9 forms a homomeric receptor–channel complex that is activated by ACh, but displays a very distinct pharmacological profile. This matches neither the nicotinic nor the muscarinic subdivision of the pharmacological scheme of cholinergic receptors, and in addition has sensitivities in common with $GABA_A$, glycine and $5HT_3$ receptors [40]. Moreover, α9 is a distant member of the nAChR family with an amino acid sequence identity compared to all known nicotinic subunits (other than α10) of less than 39%. This, taken together with the fact that the structure of the gene that encodes the α9 nAChR (*Chrna9*) subunit differs from that of all known genes coding for nAChR subunits [26,29,37,44], indicates that α9 represents an early divergent branch closer to the ancestor that gave rise to the nicotinic gene family [45,46].

With the cloning of α9, the working hypothesis was that the α9 nicotinic subunit, functioning as a homopentameric acetylcholine-gated channel, was the native hair cell cholinergic receptor. However, three properties of homomeric α9 receptors did not match those seen in isolated hair cells: the current–voltage relationship, the Ca^{2+} sensitivity and the desensitization kinetics [26,29,44]. The cloning of the α10 nAChR from cochlear libraries and the expression of both α9 and α10 in *X. laevis* oocytes demonstrated that the α9α10 receptor thoroughly recapitulates the pharmacological and biophysical properties of hair cell nAChR [47–49]. Moreover, the generation of *Chrna10* null mutant mice has indicated that, while functional homomeric α9 channels are present in OHCs of these genetically modified mice, they are insufficient to drive normal MOC efferent inhibition to the cochlea, demonstrating that the α10 subunit is also an essential component of the hair cell nAChR [50]. Thus, it is now believed that the hair cell cholinergic receptor that mediates synaptic transmission between efferent OC fibers and hair cells of the cochlea, is formed by both α9 and α10 subunits, in a pentameric structure with a most likely $(\alpha9)_2(\alpha10)_3$ stoichiometry [37,47,51].

An interesting feature of the α9 and α10 nAChR subunits is their evolutionary history [14]. The introduction of a descending fiber pathway to the inner ear occurred early in evolution, predating the emergence of terrestrial life and is a common feature among all vertebrates [2]. Therefore, one would expect similar evolutionary histories of the genes coding for the α9 and the α10 subunits across all vertebrate lineages. Intriguingly, while *Chrna9* has been under strong purifying pressure throughout vertebrates, *Chrna10* shows signs of positive Darwinian selection only along the lineage leading to mammals [14]. This suggests that mammalian α9α10 nicotinic receptors probably acquired a novel function that evolved in conjunction with properties specific to mammalian hearing. Co-varying with the evolutionary history of *Chrna10* is prestin, the protein responsible for somatic electromotility of mammalian OHCs, which has also been under positive selection pressure only in mammals [14]. Thus, it is tempting to speculate that *Chrna10* has evolved to give the mammalian auditory system feedback control of prestin-driven somatic electromotility, a capacity that is not required in non-mammalian species.

6. The α9α10 nAChR and pathologies related to the auditory pathway. A target for pharmacological intervention?

6.1. Hearing loss

Millions of people the world round have hearing loss or associated conditions, such as tinnitus, otitis media and Ménières disease. According to the World Health Organization 250 million

people worldwide have a moderate-to-severe or greater hearing loss (www.who.int/pbd/deafness/facts/en/index.html). This figures more than doubles if people with mild hearing loss are included. Hearing impairment is one of the most common sensory disabilities, and may drastically limit the quality of life, with an incidence of 1:1000 in newborns. It becomes increasingly prevalent with age. Hearing loss affects approximately 17 in every 1000 children under the age 18, approximately 314 in 1000 adults over age 65, and 40–50% of people 75 and older. The Royal National Institute for Deaf People, UK (www.rnid.org.uk), estimates that there are over 300 million people in the world with age-related hearing loss and this is expected to increase to 900 million by 2050 [52]. It is the third most common chronic condition in the older population (after arthritis and high blood pressure) [52].

Hearing loss is a social and economic burden. It can cause considerable difficulties in communication with the outside world in general and lead to sadness, depression, anxiety, social isolation, and insecurity [53]. To function in a hearing society, hearing-impaired persons require specialized education, social services, and other resources. Children who are born profoundly deaf face severe difficulty acquiring spoken language and are often taught in special schools. Severe to profound hearing loss is expected to cost society $297,000 over the lifetime of an individual. Most of these costs (67%) are due to reduced work productivity, although the use of special education resources among children contributes an additional 21%. Lifetime costs for those with prelingual onset of deafness exceed $1 million [54].

Hearing loss is caused by several environmental and genetic factors and the proportion attributed to inherited causes is thought to be at least 50% [55,56]. Progress in identifying genes involved in deafness has been remarkable over the past few years. At the end of 1996, no non-syndromic deafness genes had been cloned. In the 12 years since then, almost 50 new genes involved in non-syndromic deafness have been identified, together with an even larger number of genes implicated in syndromic deafness [55]. Whereas single-gene defects probably account for over half of the cases of childhood deafness, the nature of the genetic contribution to progressive and age-related hearing loss has not yet been clearly defined. So far, over 100 loci involved in non-syndromic deafness have been reported (The Hereditary Hearing loss Homepage, http://webh01.ua.ac.be/hhh/) and over 400 distinct syndromes including hearing impairment are listed in Online Mendelian Inheritance in Man (http://www.ncbi.nlm.nih.gov/sites/entrez?db=omim). Thus, there are many more genes awaiting identification.

Mutations in *Chrna9* and *Chrna10* associated with hearing impairment have not been identified so far. Human *Chrna9* and *Chrna10* are localized to chromosomes 4p14 and 11p15.5, respectively (Ensembl, www.ensembl.org). In addition, no non-syndromic loci have been linked near the *Chrna9* locus (The Hereditary Hearing loss Homepage, http://webh01.ua.ac.be/hhh/). As reported in the The Hereditary Hearing loss Homepage (http://webh01.ua.ac.be/hhh/). A genetic linkage study conducted on a large multigenerational US family with non-syndromic autosomal dominant progressive hearing loss resulted in the localization of a deafness locus, DFNA32. The deafness gene segregating in this family was mapped to the telomere region of chromosome 11p15 with a maximum lod score of 4.1 with marker D11S1984 (The Hereditary Hearing loss Homepage, http://webh01.ua.ac.be/hhh/). No further studies have been performed which narrow down the locus or identify a candidate gene. This genetic marker is 2 cM away from the *Chrna10* locus, pinpointing *Chrna10* as a candidate gene. However, the fact that in *Chrna9* and *Chrna10* knockout mice the basal auditory function is normal [38,50], might indicate that no major hearing impairment is expected from mutations which lead to loss of function of the α9α10 nAChR. Gene knockout experiments have the drawback that compensatory expression of other genes might obscure a clear interpretation. Alternative experiments in which the efferent system has been sectioned have indicated alterations in cochlear functioning. In an anatomical study, Pujol and Carlier [57] sectioned the OC bundle in neonatal cats and reported that the afferent innervation of OHCs failed to develop normally. They suggested that the normal arrival of MOC terminals at the OHCs during postnatal development is necessary to effect the pruning of exuberant afferent contacts in the OHC area. In a physiological study, Walsh and McGee [58] showed that transection of the OC bundle in neonatal cats eliminates the rhythmic responses normally seen in the spike trains of immature auditory neurons and suggested that the OC bundle may play a role in culling exuberant contacts between IHCs and their afferents. Both results are consistent with the idea that the OC bundle plays a role during cochlear development. Moreover, cats de-efferented shortly after birth show increased characteristic frequency-threshold, broadened tuning, and compressed spontaneous rates in adulthood [59], indicating that the OC system provides developmental influences necessary for the acquisition of normal adult cochlear function. It should be noted that during early developmental stages cholinergic OC fibers project to the IHC region where they make direct contacts with these cells [60]. The fact that the efferent synaptic activity during this developmental period is mediated through α9α10 nAChRs [60–62], indicates that the developmental effects of the OC system are due to the activation of these receptors. It still remains to be established in humans whether alterations in the efferent system during early developmental periods lead to similar cochlear developmental abnormalities and if mutations in either *Chrna9* and/or *Chrna10* lead to hearing impairment.

6.2. Noise-induced hearing loss

Noise is the greatest causative factor among the defined etiologies of hearing loss. Since the industrial revolution, an increasing number of people are being exposed to extreme levels of noise. Noise at levels 85 dBA and higher can lead both to mechanical and metabolic damage of the cochlea [63,64]. Single, repeated or continuous exposure to high levels of noise can cause noise-induced hearing loss (NIHL, Table 1). Since millions of people are daily exposed to harmful levels of noise, NIHL is one of the most important workplace hazards. Occupations such as the military [65–67], construction [68–70], mining [71], forestry [72], farming [73], aviation [74–76], rail [77,78] and trucking [79,80] report the urgent need to develop hearing conservation programs. In addition, recreational noise, like attending rock concerts or discos or the use of MP3 players, reach sound pressure levels in the dangerous zone [81,82]. The efficacy of hearing-protection devices (e.g. earplugs) and hearing-protection measures (i.e. reduced noise exposure time) could be augmented by pharmacological agents that might reduce NIHL more effectively, reducing the compensation costs associated with NIHL across all industries [83].

Table 1
Maximal sound pressure levels (SPLs), durations and sources that can irreversibly damage hearing (The National Institute for Occupational Safety and Health, http://www.cdc.gov/NIOSH/).

SPL	Duration	Source
140 dB	<1 min	Firearms, jet planes
130 dB	>1 min	Jackhammers
120 dB	>5 min	Amplified car stereo
110 db	>15 min	Rock concerts, planes
100 dB	>1 h	Woodshops, chainsaws
90 dB	>4 h	Motorcycles, lawnmowers
85 dB	>8 h	Interior plane cabins

At present, there is no FDA-approved drug product that can reduce or prevent NIHL. However, animal work has demonstrated that different compounds acting on several biochemical pathways are effective in preventing NIHL [83]. This include agents that reduce the concentration of reactive oxygen species, reactive nitrogen species and free radicals [84], glutathione precursors [85], agents that prevent hair cell apoptosis by disrupting mitogen-activated protein kinase (MAPK) cell death signaling through peptide inhibition of c-Jun N-terminal Kinase [86], drugs like ebselen that mimic the effect of glutathione peroxidase [87] and NMDA receptor antagonists [88,89]. A few compounds are in the pharmaceutical pipeline, like ebselen (Phase II, Sound Pharmaceuticals) and the JNK MAPK-mediated apoptosis blocker AM-111 (Phase II, Auris Medical).

Compounds that augment the effect of the MOC system to the OHCs appear as an alternative strategy to prevent NIHL. Many studies have implicated OC feedback in protecting the cochlea from acoustic injury: electrical stimulation of the OC bundle reduces temporary threshold shifts from acoustic overexposure [90] and chronic section of the OC bundle renders the ear more vulnerable to permanent acoustic injury [91,92]. In mice, an assay that measures the strength of this sound-evoked OC feedback pathway to the inner ear, has shown that it is inversely correlated with the degree of hearing loss after subsequent noise [22]. That the medial branch of the OC system is involved in protection has been demonstrated in a transgenic mice that overexpress the α9 nAChR subunit [23]. Moreover, a knockin mouse engineered to accommodate a leucine for threonine substitution at position 9′ of the second transmembrane region of the α9 subunit, has a pronounced prolongation of efferent synaptic currents, a dramatic increase in the MOC effect as assessed by electrical stimulation of efferent axons in the floor of the IVth ventricle, and increased auditory thresholds [25]. In addition, this sole mutation renders mice more resistant to permanent NIHL. These results confirm that protection by MOC feedback depends explicitly on activation of the hair cell's α9α10 nAChR and indicates that the nAChR itself could be modulated to provide therapeutic protection. In addition, it gives some hints concerning the properties of a possible otoprotectant drug, since in the mutant mice nAChRs have decreased desensitization kinetics plus increased agonist apparent affinity [25].

6.3. Tinnitus

Tinnitus (commonly referred to as ringing in the ears or head) is often one of the first signs of potential damage to hearing, especially after exposure to loud noise. One in 10 adults have clinically significant tinnitus (regular prolonged spontaneous tinnitus lasting 5 min or more), and for 1 in 100 tinnitus severely affects their ability to lead a normal life [93–95]. Estimates indicate that 13 million people in western Europe and the USA currently seek medical advice for their tinnitus [52]. Over 4 million prescriptions are written each year for tinnitus relief, but these are all for off-label drugs from a wide variety of therapeutic classes and most are associated with considerable side effects. Despite the significant unmet clinical need for a safe and effective drug targeting tinnitus relief, there is currently no FDA-approved drug on the market. The Royal National Institute for Deaf People, UK, estimates that a novel tinnitus drug could have a product value of US$689 million in its first year of launch [52].

There are very few drugs in clinical trials for tinnitus. One that has reached Phase III is neramexane, from Merz Pharmaceuticals Gmbh (www.clinicaltrials.gov). Neramexane was developed as a follow up to memantine used for Alzheimer disease. Like memantine, neramexane was studied in individuals with moderate-to-severe Alzheimer disease, but it did not meet its primary endpoint efficacy measurements of SIB (Severe Impairment Battery) and ADCS-ADLsev (ADCS-ADL severe subset) when tested in Phase III trials in combination with cholinesterase inhibitors. A second Phase III trial as monotherapy showed statistical significance for neramexane in individuals with moderate-to-severe disease; the primary endpoint of this trial was efficacy measurement of ADCS-ADL, and further Phase III studies are under way [96]. As memantine's patent is expected to expire in 2010, neramexane may be an early follow-on product and must show a level of differentiation over memantine if it is to succeed. Nonetheless, with a number of other indications also in development for neramexane (including neuropathic pain, tinnitus and alcohol dependence), it is clear there is commitment from Merz behind it [96].

According to the information provided in the clinical trial web site (www.clinicaltrials.gov), it is proposed that neramexane may alleviate tinnitus symptoms due to its NMDA [97] and α9α10 [98] nAChR blocking activities. Although early on tinnitus was considered an inner ear disorder, it is now clear that chronic tinnitus is due to neuronal abnormalities in the central nervous system [99]. Thus, it is difficult to envision how targeting a receptor expressed in the inner ear might be beneficial for chronic tinnitus. One possible explanation might result from the fact that in those patients where tinnitus is associated with hearing loss, tinnitus is alleviated when hearing impairment is reduced. This is the case for patients with hearing loss and tinnitus that have been cochlear implanted [100]. Thus, blockage of α9α10 receptors could increase cochlear amplification by decreasing the activity of the MOC feedback effector system and therefore α9α10 antagonists might be beneficial for the treatment of tinnitus, most likely in conjunction with some central nervous system acting drug. Possible side effects as the result of the blockade of α9α10 nAChRs, such as increased sensitivity to NIHL, should be taken into account.

6.4. Auditory processing disorders

Failure to acquire adequate reading skills (reading being slower or less accurate than expected for age) is one of the most common neurobehavioral problems affecting children. Dyslexic children have an impairment of the development of the phonetic skills necessary to identify and properly use the constituent sounds of written words, due to a temporal processing deficit that affects the sensory input needed for the proper phonological coding critically required for reading [101,102]. These deficits are aggravated in the presence of background noise, suggesting that a noisy environment, such as often prevails in the classroom, is particularly deleterious for such children [103,104].

The neural mechanisms underlying speech intelligibility-in-noise have not yet been well identified, but the MOC system probably plays a role. Animal studies have shown that efferent bundle activation can improve hearing-in-noise by exerting an antimasking effect [17,105]. In humans, weak MOC functioning is correlated with poor tone detection in background noise [106–109] and reduced speech intelligibility-in-noise in both adults [110] and children [111]. Moreover, impaired MOC system functionality in learning-impaired children, in a context of multiple phonemic confusion between voiced/voiceless phonemes, has been described [112]. In addition, the MOC system has been shown to function more strongly in professional musicians [108,113], suggesting the possibility that sound conditioning could strengthen these auditory descending pathways. Indeed, intensive auditory training has been shown to increase MOC activity, and to improve speech perception [114]. MOC activity measured on the first training day strongly predicts the subsequent amount of improvement, such that weaker initial

MOC activity is associated with greater improvement [115]. Thus enhancing MOC strength in addition to auditory training might emerge as a strategy to treat dyslexic children. In this context, drugs that enhance α9α10 nAChR activity might be of therapeutic benefit.

7. Targeting α9α10 nAChRs

The evidence that nAChRs play a role in a number of different neural functions and disorders has given impetus to the search for drugs that selectively affect different receptor subtypes. However, the recent findings indicating that native receptors are much more heterogeneous than previously thought [116], has hampered the development of receptor-specific compounds [117]. This difficulty is most likely overcome in the case of α9 and α10-containing nAChRs, since these subunits appear only to assemble with each other and not with any of the other nAChR subunits [37,47].

Nicotinic receptor ligands can be classified into three main classes: (a) *agonists*; (b) *antagonists*; and (3) *allosteric modulators*, which may stimulate or inhibit nAChR function by binding to regulatory sites other than ACh binding sites [117,118]. As discussed above, the design of α9α10 selective agonists would be beneficial in the case of NIHL and as an adjuvant in auditory training of dyslexic children. However, very few compounds have been reported as agonists of α9α10 receptors. Most classical nAChR agonists, such as nicotine, cytisine and epibatidine are antagonists of this receptor subtype [41]. Thus, positive allosteric modulators emerge as good candidates to enhance receptor activity. Moreover, although nicotinic agonists have shown some beneficial effects in treatment of central nervous system disorders, chronic treatment of humans with such compounds has not been thoroughly characterized and may provide suboptimal benefit because of sustained activation and/or desensitization of the target receptor [119,120]. A different approach would be to administer a nicotinic receptor positive allosteric modulator that can reinforce the endogenous cholinergic neurotransmission without directly stimulating the target receptors [121]. Several positive allosteric modulators have been described in the case of α7 nAChR [122]. In particular, PNU-120596 not only increases maximal amplitude and potency of ACh-evoked α7 nAChR current by several fold, but also almost suppresses desensitization [123]. These characteristics are ideal for a compound targeting α9α10 nAChRs with the aim of preventing cochlear damage produced by intense noise, since they mimic the effects rendered by the leucine for threonine mutation used to generate the α9 knockin mouse with enhanced resistance to NIHL [25]. The fact that the store active compound ryanodine potentiates α9α10-mediated ACh-responses [124], opens a possible avenue for the design of positive allosteric modulators of this receptor subtype.

Finally, if blockade of α9α10 nAChRs would eventually result in a valid strategy to alleviate tinnitus, a wide variety of compounds could be designed. α9α10 nAChRs are not only blocked by nicotinic and muscarinic receptor antagonists [37,41,47], but also by compounds that block other members of the family of Cys-loop receptors [40,125]. Thus, compounds like tropisetron and ondansetron that are already used in clinical settings for other conditions and which have high potency on α9α10 receptors [125], would be likely first candidates.

8. Conclusions

Much has been learned over the last 60 years concerning the properties and function of the efferent system to the cochlea, beginning with its first description [4], the characterization of the effects of ACh on isolated hair cells [32,34], to the cloning of the atypical cholinergic receptor of hair cells [37,47]. The following years will probably witness the design of hair cell nAChR-based therapies. This most likely will include drugs to prevent NIHL, to alleviate tinnitus and to treat auditory processing disorders.

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