Cholinergic efferent synaptic transmission regulates the maturation of auditory hair cell ribbon synapses

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1. Summary

Spontaneous electrical activity generated by developing sensory cells and neurons is crucial for the maturation of neural circuits. The full maturation of mammalian auditory inner hair cells (IHCs) depends on patterns of spontaneous action potentials during a ‘critical period’ of development. The intrinsic spiking activity of IHCs can be modulated by inhibitory input from cholinergic efferent fibres descending from the brainstem, which transiently innervate immature IHCs. However, it remains unknown whether this transient efferent input to developing IHCs is required for their functional maturation. We used a mouse model that lacks the α9-nicotinic acetylcholine receptor subunit (α9nAChR) in IHCs and another lacking synaptotagmin-2 in the efferent terminals to remove or reduce efferent input to IHCs, respectively. We found that the efferent system is required for the developmental linearization of the Ca2+-sensitivity of vesicle fusion at IHC ribbon synapses, without affecting their general cell development. This provides the first direct evidence that the efferent system, by modulating IHC electrical activity, is required for the maturation of the IHC synaptic machinery. The central control of sensory cell development is unique among sensory systems.

2. Introduction

Hearing in mammals depends on temporally precise neurotransmission via the ribbon synapses between inner hair cells (IHCs) and auditory afferent nerve terminals [1]. In order to become so highly specialized, immature spiking IHCs undergo a number of developmental transitions such that their properties change almost completely at around the onset of hearing [2], which is at postnatal day 12.
caused hyperpolarization and cessation of the firing activity only in the control IHC. Similar effects were seen in six control and seven KO IHCs (P8–P10).

Clamp recordings were obtained by injecting a depolarizing current from the IHC resting membrane potential. Note that the extracellular superfusion controls and four P10 KO IHCs.

Figure 1. Efferent activity in IHCs from control and α9nAChR KO mice. (a,b) Whole-cell voltage-clamp recordings from immature IHCs (P7–P9) in control (a) and α9nAChR KO (b) mice during the superfusion of ACh. Note that 1 mM ACh did not elicit an inward current from a holding potential of −90 mV in α9nAChR KO mice. Experiments were performed on three IHCs for each genotype. (c,d) IPSCs evoked with 30 mM extracellular KCl during long-lasting recordings from a P9 control (c) and a P10 α9nAChR KO (d) IHC (holding potential: −84 mV). Note that IPSCs were absent in the α9nAChR KO IHC. Similar effects were seen in all six P9–P10 controls and four P10 KO IHCs. (e,f) Action potential activity recorded from late postnatal (P8) IHCs in control and α9nAChR KO mice, respectively. Whole-cell current-clamp recordings were obtained by injecting a depolarizing current from the IHC resting membrane potential. Note that the extracellular superfusion of 30 μM ACh caused hyperpolarization and cessation of the firing activity only in the control IHC. Similar effects were seen in six control and seven KO IHCs (P8–P10).

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in most altricial rodents. One such change involves the maturation of IHC ribbon synapses [3–5]. Prehearing spiking IHCs release neurotransmitter with a high Ca2+ cooperativity [6,7], similar to conventional synapses [8,9]. However, in mature IHCs exocytosis from the ribbon synapses is linearly dependent on Ca2+ influx [4,10,11], the effect of which is likely to broaden the cell’s dynamic range in order to encode continuous and finely graded signals [12]. This linearization of the exocytotic dependence depends upon the presence of normal spontaneous spiking activity during the second postnatal week of development, which is just before the onset of hearing [13].

Calcium-dependent action potential activity occurs in IHCs throughout prehearing stages of development [14,15]. In IHCs, action potentials are generated by the interplay between a depolarizing Ca2+3.1. Action potential activity in immature inner hair cells from α9nAChR knockout mouse

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3. Results

Using near-physiological experimental conditions (35–37 °C and 1.3 mM extracellular Ca2+) [21] we performed electrophysiological recordings from IHCs of transgenic mice and investigated whether efferent modulation of IHC spiking activity is required for the maturation of IHC ribbon synapses.

3.1. Action potential activity in immature inner hair cells from α9nAChR knockout mouse

In immature IHCs, the ACh-activated current is mediated by Ca2+ entering hair cells through α9α10nAChRs [27,28], which
activates SK2 channels [17,18,23]. While control IHCs showed a large ACh-mediated current (figure 1a), cells from α9nAChR knockout (KO) mice did not respond to ACh even in the presence of a high extracellular concentration of the neurotransmitter (1 mM ACh, figure 1b). Immature IHCs, which were held at −284 mV, respond with an inward current when superfused with 30 mM KCl owing to a positive shift in the $K^+$ reversal potential. The superfusion of KCl additionally depolarizes the efferent terminals and triggers the release of ACh-containing vesicles, which manifests in IHCs as inhibitory postsynaptic currents (IPSCs) superimposed on the KCl-induced inward current (figure 1c). Although both α9nAChR control and KO IHCs showed a similar sustained inward current response to extracellular KCl, only the former showed IPSCs, further confirming that in the absence of α9nAChRs IHCs were unable to respond to efferent input (figure 1c,d).

We then investigated the effect of the inhibitory cholinergic efferent system on IHC firing activity during prehearing stages of development. Spiking activity has been shown to influence ribbon synaptic maturation during the second week of postnatal development [13], a period when the ACh-activated current reaches its maximal size [18,23]. Action potentials in vivo are likely to be spontaneous throughout immature stages of development [15]. However, under in vitro recording conditions, spiking activity during the second postnatal week can only be elicited by injecting depolarizing currents owing to the reduced or negligible contribution from the depolarizing resting mechanoelectrical transducer current [15]. In order to

Table 1. Properties of mature IHCs from α9nAChR and Syt-2 KO mice. Values are means ± s.e.m.; number of hair cells is in parentheses. $I_K$, total outward $K^+$ current; $I_K,f$, $Ca^{2+}$-activated $K^+$ current; $I_K,n$, negatively activating delayed rectifier $K^+$ current. Values are not significantly different between genotypes.

<table>
<thead>
<tr>
<th></th>
<th>control (P18–P26)</th>
<th>KO (P18–P26)</th>
<th>control (P16)</th>
<th>KO (P16)</th>
</tr>
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<tr>
<td>resting potential (mV)</td>
<td>−67.8 ± 2.5 (4)</td>
<td>−71.8 ± 3.6 (3)</td>
<td>−76.9 ± 1.0 (6)</td>
<td>−76.0 ± 1.3 (6)</td>
</tr>
<tr>
<td>$I_K$ at 0 mV (nA)</td>
<td>14.5 ± 1.4 (4)</td>
<td>13.8 ± 1.3 (8)</td>
<td>10.2 ± 0.3 (6)</td>
<td>10.7 ± 0.6 (6)</td>
</tr>
<tr>
<td>$I_K,f$ at −124 mV (pA)</td>
<td>288 ± 17 (4)</td>
<td>281 ± 54 (7)</td>
<td>430 ± 33 (6)</td>
<td>396 ± 54 (6)</td>
</tr>
<tr>
<td>$I_K,n$ at −25 mV (nA)</td>
<td>2.8 ± 0.2 (4)</td>
<td>3.2 ± 0.4 (8)</td>
<td>4.0 ± 0.1 (6)</td>
<td>4.1 ± 0.3 (6)</td>
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mimic the evoked release of ACh from the efferent fibres [22], we superfused IHCs with 30 μM ACh during depolarizing current injections. ACh caused a large hyperpolarization in control IHCs (−13.7 ± 0.5 mV, n = 5, P8; figure 1e) that resulted in the inhibition of action potential activity. All four P8–P9 9nAChR KO cells tested failed to respond to ACh (figure 1f). Despite IHCs from 9nAChR KO mice being non-responsive to efferent input, they showed similar K⁺ currents (see the electronic supplementary material, figure S1) and resting membrane potentials (control: −55.7 ± 0.7 mV, P4, n = 7; KO: −56.1 ± 0.4 mV, n = 10) to those of control animals.

3.2. The efferent activity promotes inner hair cell development

Neurotransmitter release at IHC ribbon synapses becomes more sensitive to Ca²⁺ entry from around the onset of hearing in mice and gerbils [4,6]. This developmental change does not occur when the frequency of IHC action potentials is artificially raised in vivo during a period spanning the second postnatal week [13]. As an absence of inhibitory cholineric input to IHCs in vivo would likely increase the overall frequency of action potential activity over the same time window [22], we investigated presynaptic activity in IHCs from mature 9nAChR KO mice by measuring the change in cell membrane capacitance (ΔC_m) with cell depolarization. This allows us to estimate the magnitude of synaptic vesicle fusion with the basolateral membrane [7,11]. Similar to conventional synapses, synaptic vesicle fusion in immature spiking IHCs shows a nonlinear (high-order) Ca²⁺ dependence, which changes into a near-linear relation upon functional maturation [4,6,11]. In 9nAChR KO adult IHCs, the maximal size of the Ca²⁺ current (I_Ca) and corresponding ΔC_m was similar to that of control littermates (figure 2a,b). However, the exocytotic Ca²⁺ dependence was significantly (p < 0.0001) less linear in the 9nAChR KO (power of 2.56 ± 0.26, n = 11) than in control cells (1.07 ± 0.10, n = 11, figure 2c: values are from fits to individual IHCs). The steeper dependence on Ca²⁺ influx found in 9nAChR KO IHCs (figure 2c) resembled that observed in immature IHCs (see the electronic supplementary material, figure S2), indicating a failure in the normal maturation of the synaptic machinery. The abnormal exocytotic Ca²⁺ sensitivity was the only biophysical change that we detected in adult IHCs from 9nAChR KO mice, which were otherwise normal regarding other key biophysical properties (table 1; see the electronic supplementary material, figure S3a,c; see also [14]).

3.3. Synaptotagmin 2 is important for efferent activity and normal action potential activity in immature inner hair cells

The above findings suggest that a failure to respond to the cholinergic efferent input in vivo is likely to favour a sustained spiking activity in immature IHCs. In order to better understand the mechanism underlying efferent system control over IHC functional development, we recorded from IHCs while attempting to manipulate the release of ACh from the efferent terminals.

Synaptotagmin 2 (Syt-2), a Ca²⁺ sensor at most conventional synapses [29,30], is expressed in the efferent terminals throughout immature cochlear development [7,31,32]. The only study that used a specific Syt-2 antibody tested in Syt-2 KO mice demonstrated some protein expression also in the cytoplasm of immature IHCs during the first postnatal week [31]. However, the presence of Syt-2 in IHCs is still controversial.

Initially, we tested whether the absence of this synaptic protein from the efferent terminals in Syt-2 KO mice affected IHC responses. We found no evidence for a change in spontaneous ACh release from efferent terminals based on the normal action potential frequency in immature IHCs (control: 2.6 ± 0.4 Hz, n = 12; Syt-2 KO: 3.2 ± 0.5 Hz, n = 7, figure 3a) and size of spontaneous inhibitory postsynaptic potentials (IPSPs; control: 6.6 ± 0.2 pA, 66 events from six IHCs; Syt-2 KO: 6.4 ± 0.2 pA, 69 events from seven IHCs, arrows in figure 3a). We also investigated the evoked release of ACh by depolarizing the efferent terminals with an elevation of extracellular K⁺ concentration from 5.8 mM to either 15 or 30 mM and measuring the amplitude and frequency of IPSCs [17]. At −84 mV, IPSCs could be recorded from both control and Syt-2 KO IHCs (figure 3b–d). We found that the amplitude of evoked IPSCs was significantly larger in control P5–P10 IHCs (15 mM K⁺: 44.1 ± 0.4 pA, 2405 events from 24 IHCs, p < 0.0001; 30 mM K⁺: 131 ± 11 pA, 1090 events from four cells, p < 0.015), than in Syt-2 KO IHCs.
The frequency of evoked IPSCs was not significantly different between the two genotypes (control: $5.0 \pm 2$ Hz, $n = 4$; Syt-2 KO: $2.7 \pm 0.7$ Hz, $n = 6$, P8–P9, 30 mM K$^+$). These findings show that in the absence of Syt-2, the evoked inhibitory exocytotic Ca$^{2+}$ dependence is abnormal in mature Syt-2 KO IHCs. Data are from apical coil control (black) and Syt-2 KO (red) mature mouse IHCs (P16–P18). (a) $I_{\text{Ca}}$ and corresponding $\Delta C_m$ recordings as described in figure 2. (b) Average $I_{\text{Ca}}$–voltage (bottom) and $\Delta C_m$–voltage (top) curves in Syt-2 control ($n = 8$) and KO ($n = 14$) IHCs. (c) Synaptic transfer curves obtained as described in figure 2. Fits in (c) are according to $\Delta C_m = c_{\text{IN}} I_{\text{Ca}}$.
4. Discussion

In this study, we found that the cholinergic efferent system descending from the brainstem directly controls the developmental increase in Ca\(^{2+}\) sensitivity of neurotransmitter release (i.e. linearization of the exocytotic Ca\(^{2+}\) dependence [7]) at IHC ribbon synapses (see the electronic supplementary material, figure S4). This control is achieved by tightly regulating IHC action potential activity. This work demonstrates a mechanism by which the central nervous system regulates action potential activity in immature IHCs and controls ribbon synapse maturation.

4.1. The efferent system regulates the maturation of the inner hair cell synaptic machinery

The important question raised from our findings is how a complete absence (ε9nAChR KO mouse) or reduction (Syt-2 KO mice) of efferent activity in immature IHCs impacts on the biophysical properties of the presynaptic machinery in mature IHCs. The opening of ε9n10nAChRs in IHCs leads to a Ca\(^{2+}\) influx that activates closely coupled SK2 channels, which mediates IHC hyperpolarization and reduces cell excitability [17,18,22,26]. Therefore, the efferent system acts as a negative feedback mechanism that directly influences the frequency of spontaneous action potentials that are characteristic of prehearing IHCs [15,21]. Because the IHC resting membrane potential is tightly regulated by the efferent system [17,21], even a reduction in evoked efferent input to IHCs in vivo (e.g. in Syt-2 KO mice) is likely to produce an abnormal action potential activity in developing cells [22]. Moreover, as the contribution from Syt-2-dependent release from the efferent fibres becomes larger with depolarization, trains of efferent action potentials in vivo would make this component more pronounced. In altricial rodents, the maximal ACh responses are seen during the second week of postnatal development [18,23]. Therefore, the largest efferent-mediated inhibitory effect on IHCs occurs over the recently identified ‘critical period’ of spiking activity (second postnatal week), which has been shown to be crucial for the normal developmental linearization of the exocytotic Ca\(^{2+}\) dependence in adult cells [13]. The activity patterns that drive ACh release from efferent terminals to the auditory brainstem are still not understood [22], and their specific influence over IHC function and development will only become evident by performing extremely challenging in vivo recordings.

4.2. Role of synaptotagmin 2 and synaptotagmin 4 in the developing cochlea

Mature IHCs are functionally specialized for rapid and graded neurotransmission in order to encode sound over a wide dynamic range. IHC ribbon synapses differ from conventional synapses because they seem to lack conventional SNARE proteins [34] and express otoferlin as the main synapical Ca\(^{2+}\) sensor for exocytosis [35] and vesicle replenishment [7,36]. Moreover, the possible direct involvement of the classical Ca\(^{2+}\)-sensing proteins synaptogamins 1 and 2 [33] in IHCs remains largely unknown [37,38]. Otoferlin is a multi-C\(_2\) domain Ca\(^{2+}\)-binding protein that shows Syt-1-like properties [39] but is not functionally equivalent [32]. Moreover, otoferlin alone cannot account for the high-order to linear change in Ca\(^{2+}\) sensitivity of exocytosis upon functional maturation [7], nor for exocytosis that occurs in early postnatal IHCs [31]. Instead, Syt-4, a unique but ubiquitous isoform of synaptotagmin that does not bind calcium in the C\(_2\)A Ca\(^{2+}\)-sensing domain [33], is an essential element for the linear exocytotic Ca\(^{2+}\) dependence in IHCs [7,38] and exocytosis in hair cells from lower vertebrates [40]. The direct involvement of Syt-4 in hair cell exocytosis is further supported by the fact that, unlike Syt-2 (see below), it does not act as a modulator of IHC development through either the activity of the efferent system (see Results above) or the afferent afferents (as a retrograde regulator released by the afferent auditory fibres [7].
Similar to Syt-4 KO mice [7], we found that the absence of Syt-2 prevented the linearization of the exocytotic Ca²⁺ dependence in adult IHCs. However, the role of Syt-2 at IHC ribbon synapses seems indirect because it has no role in exocytosis at immature synapses (figure 4, see also [31]). Moreover, Syt-2 is not directly associated with developmental cues and is only transiently expressed in IHCs during the first postnatal week [31]. As such, Syt-2 is unlikely to be able to directly influence the maturation of the ribbon synapses, which is regulated by the IHC action potential activity during the second postnatal week [13]. Instead, we found that the absence of Syt-2 caused a significant reduction in the amplitude of IPSCs, which suggests a decrease in efferent strength onto IHCs. This result is consistent with previous findings showing reduced neurotransmitter release at Syt-2-deficient neuromuscular junctions [30].

4.3. Functional implications of the cholinergic efferent system in the developing mammalian cochlea

The development of neural circuits relies on the combination of intrinsic genetic programmes and the experience-independent or spontaneous action potential activity that occurs during immature development [41]. There is likely to be at least two roles for the efferent input to IHCs (see the electronic supplementary material, figure S4). During the first postnatal week, ACh has been shown to be a major player in generating tonotopic differences in pattern and rate of firing activity in IHCs along the cochlea [21]. In the α9nAChR KO mice, the altered action potential activity in IHCs would most likely affect the afferent discharge pattern [42], which in turn could disrupt the sharpening of tonotopic maps in the auditory brainstem nuclei known to mainly occur during the first postnatal week [43]. During the second postnatal week, IHC action potential activity has been shown to be required for regulating the maturation of the Ca²⁺ dependence of neurotransmitter release at their ribbon synapses [13]. Unlike other sensory systems, this immature electrical activity is centrally modulated via ACh released by the cholinergic efferent system descending from the brainstem. This represents the first evidence for a developmental role of the cholinergic efferent input to IHCs and highlights the need for exquisite control over the pattern of IHC activity [13,44].

5. Material and methods

5.1. Mouse lines

α9nAChR [45], Syt-2 [30] and Syt-4 [46] KO mice and their control littersmates were used in this study. In the UK, animal studies were licensed by the Home Office under the Animals (Scientific Procedures) Act 1986 and were approved by the University of Sheffield Ethical Review Committee. In Argentina, animal studies were approved by the Institutional Animal Care and Use Committees of INCEBI and all experimental protocols were performed in accordance with American Veterinary Medical Association’s AVMA Guidelines on Euthanasia (June 2007).

5.2. Electrophysiology

Apical IHCs from α9nAChR, Syt-2 and Syt-4 KO mice and their control littermates were studied in acutely dissected organs of Corti from postnatal day 4 (P4) to P32. The day of birth (P0) corresponds to E19.5. Syt-2 KO mice usually died during the third postnatal week [30]. The cochleae were dissected and kept in the following solution (in mM): 135 NaCl, 5.8 KCl, 1.3 CaCl₂, 0.9 MgCl₂, 0.7 NaH₂PO₄, 5.6 d-glucose, 10 Hepes-NaOH. Sodium pyruvate (2 mM), MEM amino acids solution (50×, without t-glutamine) and MEM vitamins solution (100×) were added from concentrates (Fisher Scientific, UK). The pH was adjusted to 7.5. In some experiments, the extracellular solution used was (mM): 155 NaCl, 5.8 KCl, 1.3 CaCl₂, 0.9 MgCl₂, 0.7 NaH₂PO₄, 5.6 d-glucose and 10 Hepes buffer; pH 7.4. The dissected cochleae were transferred to a microscope chamber and immobilized under a nylon mesh attached to a stainless steel ring. The organs of Corti were viewed with an upright microscope (Leica DM-LFS, UK; Zeiss Axioskop microscope, Germany) with Nomarski optics. Unless specified, electrophysiological recordings were performed at near body temperature (34–37°C) and were made using an Optrapatch (Cairn Research Ltd, UK) or an Axopatch 200A (Molecular Devices, USA) amplifier. Command voltage- and current-clamp protocols were applied and data were acquired using pCLAMP software and a Digidata 1440A or a Digidata 1322A (Molecular Devices) board. Data analysis was performed with pCLAMP software, Origin (Origin Lab, USA) or the Mini Analysis Program (Synaptosoft Inc., USA). Statistical comparisons of means were made by Student’s two-tailed t-test. Means are quoted ± s.e.m. and p < 0.05 was used as the criterion for statistical significance.

For whole-cell recordings of current and voltage responses, soda and borosilicate glass pipettes were filled with (in mM): 131 KCl, 3 MgCl₂, 1 EGTA-KOH, 5 Na₂ATP, 5 Heps-KOH, 10 Na₂-phosphocreatine; pH 7.3. In some experiments, the following intracellular solution was used (in mM): 150 KCl, 3.5 MgCl₂, 0.1 CaCl₂, 5 EGTA-KOH, 5 Heps-KOH, 2.5 Na₂ATP; pH 7.2. Unless otherwise stated, the membrane potentials were corrected for the voltage drop across the series resistance Rₛ and a liquid junction potential (LJP) of −4 mV. Current and voltage traces were filtered at 2–10 kHz 8-pole Bessel and sampled at 5–20 kHz. Data were stored in computer for offline analysis. The pipette-filling solution used for exocytosis measurements contained (in mM): 106 Cs-glutamate, 20 CsCl, 3 MgCl₂, 1 EGTA-CsOH, 5 Na₂ATP, 0.3 Na₂GTP, 5 Heps-CsOH, 10 Na₂-phosphocreatine, pH 7.3. The different superfused extracellular solutions containing ACh or elevated K⁺ were applied by a gravity-fed multi-channel pipette positionned close to the patched hair cell.

Real-time changes in membrane capacitance (ΔCₘ) were measured as previously described [7,11]. Briefly, a 4 kHz sine wave command voltage (13 mV RMS) used for capacitance tracking was superimposed on the holding potential of −81 mV and was interrupted for the duration of the voltage step. The capacitance signal from the Optrapatch was amplified (50×), filtered at 250 Hz 8-pole Bessel and sampled at 5 kHz. ΔCₘ was measured by averaging the Cₘ trace following a voltage step (around 200 ms) and subtracting the prepulse baseline. The Ca²⁺ current and ΔCₘ were recorded in the extracellular presence of K⁺ channel blockers TEA (30 mM), 4-AP (15 mM) and, for immature IHCs, linopirdine (80–100 μM) or, for immature IHCs, apamin (300 nM).
Membrane potentials were corrected for the voltage drop across the series resistance $R_s$ and an LJP of $-11$ mV.

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