Compensatory Contribution of Ca\textsubscript{v}2.3 Channels to Acetylcholine Release at the Neuromuscular Junction of Tottering Mice

Simon Kaja,\textsuperscript{1,2} Rob C.G. van de Ven,\textsuperscript{3} Michel D. Ferrari,\textsuperscript{1} Rune R. Frants,\textsuperscript{3} Arn M.J.M. van den Maagdenberg,\textsuperscript{1,3} and Jaap J. Plomp \textsuperscript{1,2}

Departments of \textsuperscript{1}Neurology, \textsuperscript{2}Molecular Cell Biology - Group Neurophysiology, \textsuperscript{3}Human Genetics, Leiden University Medical Centre, Leiden, The Netherlands.

Abstract

*Tottering* (*Tg*) mice carry the mutation P601L in their *Cacna1a* encoded Ca\(_{\text{v}}\)2.1 channels. Transmitter release at the wild-type neuromuscular junction (NMJ) is almost exclusively mediated by Ca\(_{\text{v}}\)2.1 channels, and we use this model synapse to study synaptic consequences of the *Tg* mutation. With electrophysiology, and using subtype-specific Ca\(_{\text{v}}\)2 channel-blocking toxins, we assessed a possible compensatory contribution of non-Ca\(_{\text{v}}\)2.1 channels to evoked acetylcholine (ACh) release at *Tg* NMJs. Release was reduced by \(~75\%\) by the Ca\(_{\text{v}}\)2.1 channel blocker \(\omega\)-agatoxin-IVA, which was less than the \(~95\%\) reduction observed in wild-type. Release at *Tg* NMJs, but not at wild-type synapses, was reduced by \(~15\%\) by SNX-482, a Ca\(_{\text{v}}\)2.3 channel blocker. No Ca\(_{\text{v}}\)2.2 channel involvement was found. Probably, there is a small reduction in functional presynaptic Ca\(_{\text{v}}\)2.1 channels at *Tg* NMJs, which is compensated for by Ca\(_{\text{v}}\)2.3 channels. The remaining Ca\(_{\text{v}}\)2.1 channels are likely to convey enlarged Ca\(^{2+}\) flux, because evoked ACh release at *Tg* NMJs, at low extracellular Ca\(^{2+}\) concentration, was \(~6\)-fold higher than at wild-type NMJs. This is the first report of compensatory expression of non-Ca\(_{\text{v}}\)2.1 channels at NMJs of mice with a single amino acid change in Ca\(_{\text{v}}\)2.1.

Acknowledgements

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Compensatory $\text{Ca}_{V}2.3$ Channels at Tottering NMJs

Introduction

Tottering ($Tg$) mice carry an amino acid change (P601L) in the pore-forming subunit of $\text{Cacna1a}$ encoded $\text{Ca}_{V}2.1$ (P/Q-type) $\text{Ca}^{2+}$ channels (Fletcher et al., 1996; Doyle et al., 1997), causing ataxia and epilepsy in homozygous animals. In humans, $\text{CACNA1A}$ mutations cause familial hemiplegic migraine and other autosomal dominant neurological disorders (Ophoff et al., 1996; Jouveneau et al., 2001; Imbrici et al., 2004).

High voltage-activated neuronal $\text{Ca}^{2+}$ channels consist of $\text{Ca}_{V}1$ (L-type), $\text{Ca}_{V}2.1$ (P/Q-type), $\text{Ca}_{V}2.2$ (N-type) and $\text{Ca}_{V}2.3$ (R-type) channels (Catterall, 2000). P- and Q-type channels are splice variants (Bourinet et al., 1999) with different sensitivities to $\omega$-agatoxin-IVA (Stea et al., 1994). $\text{Ca}_{V}2.2$ channels are blocked by $\omega$-conotoxin-GVIA, $\text{Ca}_{V}2.3$ channels by SNX-482, and $\text{Ca}_{V}1$ channels by dihydropyridines (Catterall, 2000).

$\text{Ca}_{V}2.1$ channels mediate neurotransmitter release at many central synapses and at the peripheral neuromuscular junction (NMJ), where they govern >90% of release (Uchitel et al., 1992). At mouse NMJs, synaptic effects of $\text{Cacna1a}$ mutations can be studied with relative ease (Plomp et al., 2000; Van Den Maagdenberg et al., 2004). Previously, we showed abnormal spontaneous ACh release (~2-fold increased miniature endplate potential [MEPP] frequency) at $Tg$ NMJs, as well as reduced high-rate (40 Hz) evoked release (increased endplate potential [EPP] amplitude rundown). However, low-rate (0.3 Hz) evoked release was unchanged (Plomp et al., 2000).

$\text{Ca}_{V}2.1$, -2 and -3 channels act in a mutually compensatory fashion. Thus, transmitter release at $\text{Ca}_{V}2.1$ (null-)mutant NMJs and central synapses becomes to rely on $\text{Ca}_{V}2.2$ and -3 channels (Leenders et al., 2002; Urbano et al., 2002; Cao et al., 2004), whereas compensatory $\text{Ca}_{V}2.1$ expression occurs in $\text{Ca}_{V}2.2$ null-mutant neurons (Takahashi et al., 2004a; Takahashi et al., 2004b). At $Tg$ central synapses, compensatory $\text{Ca}_{V}2.2$ channels were shown (Qian and Noebels, 2000; Leenders et al., 2002). We tested the hypothesis that compensatory, non-$\text{Ca}_{V}2.1$ channels contribute to ACh release at the $Tg$ NMJ in electrophysiological experiments using $\text{Ca}_{V}2$ subtype-specific blocking toxins. We also measured low-rate (0.3 Hz) evoked ACh release at $Tg$ NMJs at low extracellular $\text{Ca}^{2+}$, in order to test whether effects of the $Tg$ mutation not visible at normal $\text{Ca}^{2+}$ concentration can be unmasked, similar to our recent finding in mice carrying the human familial hemiplegic migraine-associated mutations R192Q and S218L (Kaja et al., 2004; Van Den Maagdenberg et al., 2004; Kaja et al., 2005).

Materials and Methods

Mice

All animal experiments were in accordance with national legislation, Leiden University guidelines and the American Physiological Society’s Guiding Principles in the Care and Use of Animals. $Tg$ mice were raised from original breeder pairs obtained from Jackson Laboratories (Bar Harbor, ME, USA). Animals were genotyped as described previously (Plomp et al., 2000). Homozygous $Tg$ and wild-type mice were used at 6 weeks of age, with the investigator blinded for genotype.

Ex vivo NMJ electrophysiology

Mice were euthanized by carbon dioxide inhalation. Hemi-diaphragms with phrenic nerve were dissected and kept in Ringer’s medium (in mM: NaCl 116, KCl 4.5, CaCl₂ 2, MgSO₄ 1, NaH₂PO₄ 1, NaHCO₃ 23, glucose 11, pH 7.4) at room temperature. Intracellular recordings of MEPPs and EPPs were made at NMJs at 28 °C using standard micro-electrode equipment.
At least 30 MEPPs and EPPs were recorded at each NMJ, and 5-10 NMJs were sampled per experimental condition per muscle. Muscle action potentials were blocked by 3 µM µ-conotoxin-GIIIB (Scientific Marketing Associates, Barnet, UK). For EPP recording, the nerve was stimulated at 0.3 or 40 Hz. Procedures for analysis of MEPPs and EPPs and calculation of quantal contents, i.e. the number of ACh quanta released per nerve impulse, have been described before (Van Den Maagdenberg et al., 2004). EPPs and MEPPs were also measured in presence of the specific Ca^{2+} channel blockers ω-agatoxin-IVA (Ca_{v}2.1, 200 or 400 nM, as indicated), ω-conotoxin-GVIA (Ca_{v}2.2, 2.5 µM) and SNX-482 (Ca_{v}2.3, 1 or 2 µM, as indicated), following a 20 min pre-incubation period. Toxins were from Scientific Marketing Associates. We also probed for the presence of Ca_{v}2.2 channels more distant from the Ca^{2+} sensor at release sites by testing the effect of ω-conotoxin-GVIA on the quantal content in the presence of 50 µM of the K^{+} channel blocker 4-aminopyridine (4-AP, Sigma-Aldrich, Zwijndrecht, The Netherlands), in a 0.5 mM Ca^{2+}/5.5 mM Mg^{2+}-Ringer medium, according to the methods described by Urbano et al. (2003).

Statistical analysis
Paired or unpaired Student’s t-tests were used where appropriate, on grand mean values with n as the number of mice tested, and 5-10 NMJs tested per muscle, per condition. P<0.05 was considered to be statistically significant. Data is presented as mean ± S.E.M.

Results
Reduced ω-agatoxin-IVA sensitivity of evoked ACh release at Tg NMJs
Total 0.3 Hz stimulation-evoked ACh release at normal (2 mM) Ca^{2+} concentration was the same at Tg and wild-type NMJs, in line with earlier observations (Plomp et al., 2000). The quantal content was ~32 (Figure 1). ω-Agatoxin-IVA (200 nM) reduced quantal content at NMJs of wild-type muscles by 94%, from 32.5 ± 1.6 to 1.8 ± 0.8 (n=4 muscles, 7-10 NMJs per muscle, p<0.001; Figure 1A). However, at Tg NMJs it decreased only by 73% (from 33.9 ± 1.9 to 9.0 ± 2.0, n=4 muscles, 7-10 NMJs per muscle, p<0.001; Figure 1A). ω-Agatoxin-IVA decreased EPP amplitude by 93% (from 22.8 ± 1.1 mV to 1.6 ± 0.7 mV) in wild-type, but only by 69% (from 27.2 ± 0.8 to 8.5 ± 1.0 mV) at Tg NMJs (n=4 muscles, 7-10 NMJs per muscle, p<0.01; Figure 1B). In the presence of ω-agatoxin-IVA, EPP failure upon a stimulus was frequently observed at wild-type but almost never at Tg NMJs (29.8 ± 11.8 and 1.5 ± 1.5 % of the stimuli, respectively, n=4 muscles, 7-10 NMJs per muscle, p<0.05; Figures 1B, C). MEPP amplitudes and kinetics were unaffected by ω-agatoxin-IVA (data not shown). MEPP frequency was reduced by ~50% at both Tg and wild-type NMJs (Table 1), as shown previously (Plomp et al., 2000).

The possibility exists that the Tg mutation renders the Ca_{v}2.1 channel less sensitive to ω-agatoxin-IVA, although such an effect is not very likely in view of the distant localizations of the Tg mutation (amino acid 601, P-loop of repeat II) and the ω-agatoxin-IVA binding site (amino acid 1658, C-terminal end of S3, repeat IV, Bourinet et al., 1999; Winterfield and Swartz, 2000). However, such an effect could explain the lesser reduction of quantal content by ω-agatoxin-IVA, compared with wild-type NMJs. We, therefore, experimentally tested this possibility by measuring ACh release at wild-type and Tg NMJs also in the presence of a higher ω-agatoxin-IVA concentration (400 nM), which is more than five times the IC_{50} for wild-type quantal content, as determined in our laboratory (~75 nM, unpublished data). No extra reduction was observed, compared to that in the presence of 200 nM toxin (n=3-4 muscles, 10 NMJs per muscle, p=0.85 in wild-type and p=0.34 in Tg, Figure 1A), excluding the possibility of a reduced toxin-sensitivity of Tg-mutated Ca_{v}2.1 channels.
Figure 1. Effect of selective Ca\textsubscript{v}2 channel blockers on 0.3 Hz evoked ACh release at the Tg diaphragm NMJ, as determined with electrophysiological recording of synaptic signals. (A) Ca\textsubscript{v}2.1 blocker ω-agatoxin-IVA (200 nM) reduced quantal content by ~95% at wild-type NMJs (n=4 muscles, 7-10 NMJs per muscle, p<0.001), but only by ~75% at Tg NMJs (n=4 muscles, 7-10 NMJs per muscle, p<0.001), which was a statistically significantly smaller reduction (p<0.05). The quantal content reductions induced by a higher ω-agatoxin-IVA concentration (400 nM) were similar. (B) Representative examples of nine superimposed 0.3 Hz evoked EPPs, before (top panel) and after (bottom panel) application of ω-agatoxin-IVA. Arrowheads indicate moment of nerve stimulation. (C) Quantification of EPP failures during 0.3 Hz stimulation in the presence of 200 nM ω-agatoxin-IVA, which were much more common at wild-type NMJs. (D) Ca\textsubscript{v}2.2 blocker ω-conotoxin-GVIA (2.5 µM) did neither affect quantal content at wild-type (n=4 muscles, p=0.73) nor Tg (n=4 muscles, 7-10 NMJs per muscle, p=0.71) NMJs. (E) Lack of sensitivity of quantal content to ω-conotoxin-GVIA (2.5 µM) in the presence of 0.5 mM Ca\textsuperscript{2+}/5.5 mM Mg\textsuperscript{2+}-Ringer and 50 µM 4-AP. (F) Ca\textsubscript{v}2.3 blocker SNX-482 (1 and 2 µM) reduced quantal content at Tg NMJs by ~15% (n=3-4 muscles, 7-10 NMJs per muscle, p<0.05). Subsequent addition of 400 nM ω-agatoxin-IVA almost completely blocked evoked ACh release (n=3 muscles, 10 NMJs per muscle, p<0.01). * p<0.05, † p<0.01, ‡ p<0.001.
**Ca\textsubscript{2,3} channels contribute to evoked ACh release at Tg NMJs**

Hence, in view of the reduced \(\omega\)-agatoxin-IVA-sensitivity of evoked ACh release at Tg NMJs, compensatory involvement of non-Ca\textsubscript{2,1} channels is likely. Both Ca\textsubscript{2,2} and Ca\textsubscript{2,3} channels are known to mediate neurotransmitter release (Reid et al., 2003), and both partially compensate for the loss of Ca\textsubscript{2,1} channels at NMJs of *Cacna1a* null-mutant mice (Urbano et al., 2003; chapter 7). In order to investigate compensatory involvement of Ca\textsubscript{2,2} channels, we recorded MEPPs and EPPs at NMJs of Tg and wild-type muscles before and after application of the selective blocker \(\omega\)-conotoxin-GVIA (2.5 \(\mu\)M). In either genotype, the toxin affected neither evoked nor spontaneous ACh release (Figure 1D, Table 1). Quantal contents were similar (31.8 \(\pm\) 1.2 and 32.9 \(\pm\) 2.5 at wild-type NMJs, \(n=4\) muscles, 7-10 NMJs per muscle, \(p=0.73\), and 31.4 \(\pm\) 1.2 and 30.0 \(\pm\) 3.2 at Tg NMJs, \(n=4\) muscles, 7-10 NMJs per muscle, \(p=0.71\), before and in presence of the toxin, respectively). The possibility exists that compensatory expressed Ca\textsubscript{2,2} channels are localized more distantly from the Ca\textsuperscript{2+} sensor at release sites, as proposed for *Cacna1a* null-mutant NMJs (Urbano et al., 2003). We tested this hypothesis using the protocol described in Urbano et al. (2003). The quantal content was first measured in Ringer medium containing 0.5 mM Ca\textsuperscript{2+}/5.5 mM Mg\textsuperscript{2+} and was similar at wild-type and Tg NMJs (0.58 \(\pm\) 0.09, and 0.51 \(\pm\) 0.09, respectively, \(n=5\)–6 muscles, 10 NMJs per muscle, \(p=0.64\)). Addition of 50 \(\mu\)M 4-AP increased quantal content equally (about 37-fold) in both genotypes (Figure 1E). Further addition of 2.5 \(\mu\)M \(\omega\)-conotoxin-GVIA did not affect quantal content (19.1 \(\pm\) 2.3 and 20.8 \(\pm\) 2.4 before and during toxin in wild-type, \(n=5\) muscles, 10 NMJs per muscle, \(p=0.64\)). These results further indicated absence of compensatory expression of Ca\textsubscript{2,2} channels at Tg NMJs, even at distant sites.

Next, we tested the Ca\textsubscript{2,3} channel blocker SNX-482 (1 \(\mu\)M). Quantal content of wild-type NMJs was unchanged (29.4 \(\pm\) 0.9 before and 30.0 \(\pm\) 1.4 in presence of SNX-482, \(n=4\) muscles, 7-10 NMJs per muscle, \(p=0.51\); Figure 1F). However, at Tg NMJs SNX-482 reduced quantal content by \(\sim\)15\% (from 30.5 \(\pm\) 1.6 to 25.8 \(\pm\) 1.7, \(n=4\) muscles, 7-10 NMJs per muscle, \(p<0.05\); Figure 1F). Together, Ca\textsubscript{2,1} and Ca\textsubscript{2,3} channels mediate \(\sim\)90\% (\(\sim\)75\% and \(\sim\)15\%, respectively) of the 0.3 Hz evoked ACh release. Thus, the apparent reduction of Ca\textsuperscript{2+} influx through \(\omega\)-agatoxin-IVA-sensitive channels at the Tg NMJ is almost fully compensated for by Ca\textsuperscript{2+} influx through SNX-482-sensitive channels, i.e. Ca\textsubscript{2,3}, since Ca\textsubscript{2,1} channels mediate 90-95\% of 0.3 Hz evoked release at wild-type channels. SNX-482 did not statistically significantly affect spontaneous release in either genotype, although there was a tendency for reduction at Tg NMJs (Table 1).

It might be speculated that the Tg mutation brings (some) SNX-482-sensitivity onto Ca\textsubscript{2,1} channels, by creating a (low-affinity) receptor site in the Ca\textsubscript{2,1} protein, instead of indirectly inducing the expression of compensatory Ca\textsubscript{2,3} channels. In that case, the 15\% reduction of quantal content by 1 \(\mu\)M SNX-482 at Tg NMJs could be regarded as a sub-optimal inhibition of SNX-482-sensitive Tg-mutated Ca\textsubscript{2,1} channels. Although this possibility is not very likely in view of the distant localizations of the Tg mutation in Ca\textsubscript{2,1} (in P-loop of repeat II) and the SNX-482 binding site in Ca\textsubscript{2,3} (on repeats III and IV, presumably in S3-4 regions, Bourinet et al., 2001), we nevertheless tested it by exposing Tg NMJs to a doubled SNX-482 concentration (2 \(\mu\)M). However, no extra reduction of quantal content at Tg NMJs occurred, compared to that observed upon incubation with 1 \(\mu\)M SNX-482 (\(n=3\)-4 muscles, 10 NMJs per muscle, \(p=0.85\), Figure 1F), indicating that it is very unlikely that the Tg mutation rendered the Ca\textsubscript{2,1} channel sensitive to SNX-482. We also added 400 nM \(\omega\)-agatoxin-IVA to the Tg preparations that were incubated in 2 \(\mu\)M SNX-482, and observed an almost
complete block of quantal content (to only 2.3% of the quantal content before the toxins, n=3 muscles, 10 NMJs per muscle, p<0.01, Figure 1F), again showing that ACh release at Tg NMJs is governed exclusively by Ca\textsubscript{v}2.1 and Ca\textsubscript{v}2.3 channels.

Increased 0.3 Hz evoked ACh release at Tg NMJs in low Ca\textsuperscript{2+}

We investigated 0.3 Hz evoked ACh release at Tg NMJs in low (0.2 mM) extracellular Ca\textsuperscript{2+}. At wild-type NMJs, quantal content was 1.7 ± 0.4 (n=4 muscles, 7-10 NMJs per muscle). However, at Tg NMJs it was ~6-fold higher (10.7 ± 0.9, n=4 muscles, 7-10 NMJs per muscle, p<0.01; Figure 2A). EPP amplitudes were 1.8 ± 0.6 and 9.1 ± 0.8 mV at wild-type and Tg NMJs, respectively (n=4 muscles, 7-10 NMJs per muscle, p<0.01; Figures 2B, D). In 0.2 mM Ca\textsuperscript{2+}, EPP failure upon a stimulus was regularly observed at wild-type but not Tg NMJs (48.7 ± 5.7 and 1.3 ± 1.3% of the stimuli, respectively, n=4 muscles, 7-10 NMJs per muscle, p<0.001; Figures 2B, C). MEPP amplitudes did not differ between genotypes (1.00 ± 0.10 and 0.96 ± 0.05 mV at wild-type and Tg NMJs, respectively, n=4 muscles, 7-10 NMJs per muscle, p=0.73).

In a separate experimental series, the quantal content at Tg NMJs at low Ca\textsuperscript{2+} was unaffected by SNX-482 (7.6 ± 1.7 before and 7.2 ± 1.5 in presence of the toxin, n=4 muscles, 10 NMJs per muscle, p=0.41), but was reduced by 98%, to 0.2 ± 0.1 (n=2 muscles, 5 NMJs per muscle) by \(\omega\)-agatoxin-IVA (Figure 2E).

**Ca\textsubscript{v}2.3 channels do not contribute disproportionally to rundown of EPP amplitude during 40 Hz nerve stimulation**

Previously, at normal extracellular Ca\textsuperscript{2+} concentration, we have shown that rundown of EPP amplitude during tetanic (40 Hz) nerve stimulation is somewhat more pronounced at Tg NMJs (the rundown plateau level, expressed as percentage of the first EPP, was ~8% lower, Plomp et al., 2000). Specific Ca\textsubscript{v}2.3 channel behaviour, for instance a relatively large use-dependent inhibition, might underlie such increased rundown. In order to test this hypothesis we recorded and quantified 40 Hz EPP rundown at Tg NMJs in the presence of either no channel blockers, \(\omega\)-agatoxin-IVA (200 or 400 nM), SNX-482 (1 or 2 \(\mu\)M) or both toxins in combination, at normal Ca\textsuperscript{2+} level (Figures 3, B). Normalized EPP rundown in the presence of \(\omega\)-agatoxin-IVA and in the presence of SNX-482 was similar (to about 77% of the first EPP in the train, n=3-6 muscles, 7-10 NMJs per muscle, p=0.65, Figure 3C), which does not differ from the control condition without toxins. This indicates that Ca\textsubscript{v}2.3 channels do not contribute disproportionally to EPP rundown at Tg NMJs.

### Table 1. Effect of specific Ca\textsubscript{v}2 channel blocking toxins on MEPP frequency.

<table>
<thead>
<tr>
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<th>Wild-type</th>
<th>Tg</th>
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<tbody>
<tr>
<td>Control</td>
<td>0.96 ± 0.12 s(^{-1})</td>
<td>2.04 ± 0.32 s(^{-1})</td>
</tr>
<tr>
<td>+ (\omega)-agatoxin-IVA (200 nM)</td>
<td>0.49 ± 0.05 s(^{-1})*</td>
<td>1.04 ± 0.17 s(^{-1})*</td>
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<tr>
<td>Control</td>
<td>0.90 ± 0.11 s(^{-1})</td>
<td>2.01 ± 0.20 s(^{-1})</td>
</tr>
<tr>
<td>+ (\omega)-conotoxin-GVIA (2.5 (\mu)M)</td>
<td>0.89 ± 0.13 s(^{-1})</td>
<td>1.98 ± 0.26 s(^{-1})</td>
</tr>
<tr>
<td>Control</td>
<td>0.96 ± 0.16 s(^{-1})</td>
<td>1.88 ± 0.20 s(^{-1})</td>
</tr>
<tr>
<td>+ SNX-482 (1 (\mu)M)</td>
<td>0.93 ± 0.15 s(^{-1})</td>
<td>1.57 ± 0.24 s(^{-1})</td>
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Values are means ± SEM. Effect of specific Ca\textsubscript{v}2 blocking toxins on spontaneous ACh release (measured as MEPP frequency) at both wild-type and Tg NMJs. Neither the selective Ca\textsubscript{v}2.2 channel blocker \(\omega\)-conotoxin-GVIA (2.5 \(\mu\)M), nor the Ca\textsubscript{v}2.3 blocker SNX-482 (1 \(\mu\)M) significantly affected spontaneous ACh release. N=4 muscles, 7-10 NMJs per muscle.

* Different from control, p<0.01; † different from control, p<0.05; ‡ as described previously (Plomp et al., 2000), Ca\textsubscript{v}2.1 blocker \(\omega\)-agatoxin-IVA reduced MEPP frequency ~50% in both genotypes.

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Plomp et al., 2000. Ca\textsubscript{v}2.3 channel behaviour, for instance a relatively large use-dependent inhibition, might underlie such increased rundown. In order to test this hypothesis we recorded and quantified 40 Hz EPP rundown at Tg NMJs in the presence of no channel blockers, \(\omega\)-agatoxin-IVA (200 or 400 nM), SNX-482 (1 or 2 \(\mu\)M) or both toxins in combination, at normal Ca\textsuperscript{2+} level (Figures 3, B). Normalized EPP rundown in the presence of \(\omega\)-agatoxin-IVA and in the presence of SNX-482 was similar (to about 77% of the first EPP in the train, n=3-6 muscles, 7-10 NMJs per muscle, p=0.65, Figure 3C), which does not differ from the control condition without toxins. This indicates that Ca\textsubscript{v}2.3 channels do not contribute disproportionally to EPP rundown at Tg NMJs.
Figure 2. Evoked (0.3 Hz) ACh release at \( Tg \) NMJs at low (0.2 mM) extracellular \( \text{Ca}^{2+} \) concentration. (A) At \( Tg \) NMJs, quantal content was ~6-fold higher than at wild-types (\( n=4 \) muscles, 7-10 NMJs per muscle, \( p<0.01 \)). (B) Representative examples of ten superimposed 0.3 Hz evoked EPPs from wild-type and \( Tg \) NMJs. Arrowheads indicate moment of nerve stimulation. (C) Quantification of EPP failures during 0.3 Hz stimulation, which were much more common at wild-type NMJs. (D) Mean EPP amplitude was ~5-fold higher at \( Tg \) NMJs (\( n=4 \) muscles, 7-10 NMJs per muscle, \( p<0.001 \)). (E) \( \text{Ca}_{2.3} \) blocker SNX-482 (1 \( \mu \)M) did not affect quantal content at \( Tg \) NMJs at low \( \text{Ca}^{2+} \) (\( n=4 \) muscles, 10 NMJs per muscle, \( p=0.41 \)), while \( \text{Ca}_{2.1} \) blocker \( \omega \)-agatoxin-IIVA (200 nM) almost completely inhibited it (\( n=2 \) muscles, 5 NMJs per muscle). \( \dagger \) \( p<0.001 \).

**Discussion**

We investigated compensatory contribution of non-\( \text{Ca}_{2.1} \) channels to evoked ACh release at \( Tg \) NMJs. At wild-type mouse NMJs, \( \omega \)-agatoxin-IIVA reduces quantal content by >90%, indicating that ACh release is almost exclusively mediated by \( \text{Ca}_{2.1} \) channels (Uchitel et al., 1992; Giovannini et al., 2002; Kaja et al., 2005). The lesser inhibition found at \( Tg \) NMJs (only ~75%) suggests compensatory involvement of non-\( \text{Ca}_{2.1} \) channels. The experiments with SNX-482, a selective blocker of \( \text{Ca}_{2.3} \) channels, show that ~15% of the total release at \( Tg \) NMJs is mediated by \( \text{Ca}_{2.3} \) channels. ACh release at NMJs of \( \text{Cacna1a} \) null-mutant mice, which lack \( \text{Ca}_{2.1} \) channels and die at ~3 weeks of age, becomes dependent on \( \text{Ca}_{2.3} \) as well as \( \text{Ca}_{2.2} \) channels (Urbano et al., 2003). However, we could exclude compensatory involvement of \( \text{Ca}_{2.2} \) channels at \( Tg \) NMJs by showing insensitivity of quantal content to \( \omega \)-conotoxin-GVIA, even in a protocol testing for \( \text{Ca}_{2.2} \) channels localized more distantly from the \( \text{Ca}^{2+} \) sensor at release sites. Thus, we show that \( \text{Ca}_{2.3} \) channels are recruited first as compensatory channels at \( Tg \) NMJs. This is the first report of compensatory expression...
Figure 3. Ca\textsubscript{v}2.3 channels do not contribute disproportionately to rundown of EPP amplitude during 40 Hz nerve stimulation at Tg NMJs. (A) Averaged EPP rundown profiles at normal (2 mM) extracellular Ca\textsuperscript{2+} concentration at Tg NMJs in the presence of either no Ca\textsubscript{v}2 blocker, the Ca\textsubscript{v}2.3 blocker SNX-482, the Ca\textsubscript{v}2.1 blocker \(\omega\)-agatoxin IV A, or the combination of both toxins. N=3-6 muscles, 7-10 NMJs per muscle. (B) Typical examples of EPP rundown profiles. (C) Normalized EPP rundown levels (mean amplitude of EPP number 21-35, expressed as percentage of the first EPP in the train) do not differ in the presence of either SNX-482, \(\omega\)-agatoxin-IVA or the control condition without added toxins (p=0.65).

of non-Ca\textsubscript{v}2.1 channels at NMJs of mice with a single amino acid change in Ca\textsubscript{v}2.1. On the basis of the results of the present extensive study we have to revise our earlier, preliminary view of similar \(\omega\)-agatoxin-IVA-sensitivity of evoked ACh release at wild-type and Tg NMJs, which was based on only a single experiment per genotype (Plomp et al., 2000).

The studies on Cacna1a\textsubscript{null}-mutant NMJs have led to the hypothesis that ACh release sites have ‘slots’ that are preferentially filled with Ca\textsubscript{v}2.1 channels, but in their absence become occupied by Ca\textsubscript{v}2.3 channels (Urbano et al., 2003). This would suggest a small reduction in the presynaptic membrane expression of Ca\textsubscript{v}2.1 channels at Tg NMJs, leaving ‘slots’ available for Ca\textsubscript{v}2.3 channels. However, although reduced Tg-mutated Ca\textsubscript{v}2.1 channel expression at nerve terminals has indeed been proposed (Leenders et al., 2002), such a reduction was not supported by our previous finding of a 2-fold increased spontaneous ACh release at Tg NMJs that remains sensitive to \(\omega\)-agatoxin-IVA (Plomp et al., 2000). The explanation may be that the effect of a small reduction in Tg Ca\textsubscript{v}2.1 channel expression is masked by increased Ca\textsuperscript{2+}-flux through the remaining channels, due to a mutation-induced shift of their activation voltage towards more negative values, as proposed by us earlier (Plomp et al., 2000). Extra Ca\textsuperscript{2+} influx through Tg-mutated Ca\textsubscript{v}2.1 channels was further substantiated here, by the finding that ACh release in low extracellular Ca\textsuperscript{2+} was ~6-fold increased at Tg NMJs. This increase was solely due to the Tg-mutated Ca\textsubscript{v}2.1 channels and not to compensatory Ca\textsubscript{v}2.3 channels, since it was unaffected by SNX-482 and almost completely inhibited by
ω-agatoxin-IVA. There is an interesting parallel between the electrophysiology of Tg NMJs and those of R192Q and S218L Cacna1a-mutated mice (knock-in models for human familial hemiplegic migraine), in that we have recently observed similar increases in MEPP frequency and low-Ca \( \text{Ca}^{2+} \) quantal content at those NMJs (Kaja et al., 2004; Van Den Maagdenberg et al., 2004; Kaja et al., 2005). Voltage-clamp measurements in (transfected) primary cultured neurons and heterologous expression systems showed a clear negative shift of activation voltage for both R192Q- and S218L-mutated channels (Tottene et al., 2005; Van Den Maagdenberg et al., 2004). These parallels with Tg synapses further suggest that Tg-mutated Ca\(_{\alpha,2.1}\) channels at NMJs may have a negatively shifted activation voltage. However, enigmatically, Wakamori and colleagues showed normal activation voltage for Tg channels in Purkinje cell bodies and transfected baby hamster kidney cells (Wakamori et al., 1998). It may, however, be that extrapolation of data obtained at cell body channels to behaviour of presynaptic channels is not justifiable because of the specific interactions of presynaptic channels with their native environment at transmitter release sites.

Besides a shift in activation voltage, Tg channels may have altered modulatory properties following a mutation-induced change of interaction with factors such as calmodulin or G-proteins (Lee et al., 1999; Catterall, 2000), leading to increased Ca\(^{2+}\) influx. However, such an explanation is not very likely in view of the very different localizations of the Tg mutation and known binding and effector sites of modulatory factors (Zhong et al., 2001).

As yet, it is unclear how compensatory presynaptic Ca\(_{\alpha,2.3}\) channels are recruited. At wild-type NMJs, they do not contribute to ACh release, and are undetectable with immunohistochemistry (Westenbroek et al., 1998). It may be that protein expression must first be triggered, e.g. by the changed Ca\(^{2+}\) influx due to Tg Ca\(_{\alpha,2.1}\) mutation. Alternatively, membrane insertion may normally fail due to absence of available ‘slots’ at ACh release sites, but become successful when Tg Ca\(_{\alpha,2.1}\) mutation results in some free ‘slots’.

The lack of compensatory involvement of Ca\(_{\alpha,2.2}\) channels at Tg NMJs, as opposed to Cacna1a null-mutant NMJs, may be explained by the presence of remaining Ca\(_{\alpha,2.1}\) channels. For instance, expression of syntaxin-1A is dependent on selective Ca\(_{\alpha,2.1}\)-mediated Ca\(^{2+}\) influx (Sutton et al., 1999). This presynaptic protein can inhibit the function of Ca\(_{\alpha,2.1}\) and Ca\(_{\alpha,2.2}\) channels (Bezprozvanny et al., 1995), but not that of Ca\(_{\alpha,2.3}\) channels. Thus, if altogether present at the NMJ, Ca\(_{\alpha,2.2}\) channels in the Tg presynaptic membrane may be silenced. The situation at central synapses seems different. Compensatory Ca\(_{\alpha,2.2}\) channels have been shown at Tg hippocampal synapses (Qian and Noebels, 2000) and forebrain synaptosomes (Leenders et al., 2002).

The changes at Tg NMJs partly resemble those found at NMJs of the R192Q knock-in mouse model for familial hemiplegic migraine (Van Den Maagdenberg et al., 2004; Kaja et al., 2005): increased spontaneous ACh release and evoked release that is normal at physiological extracellular Ca\(^{2+}\) but strongly increased, compared to wild-type, at low Ca\(^{2+}\). However, clear differences exist. There is no compensatory involvement of Ca\(_{\alpha,2.3}\) channels at R192Q NMJs, because ω-agatoxin-IVA reduces quantal content by the same extent (>90%) as in wild-types. Furthermore, the reduction in high-rate evoked ACh release at Tg NMJs (Plomp et al., 2000), is more pronounced than that at R192Q NMJs (Kaja et al., 2005).

The Tg NMJ displays some extra rundown of high-rate evoked ACh release, compared to wild-type (Plomp et al., 2000). It may be that Ca\(_{\alpha,2.3}\) channel behaviour contributes to this phenomenon. Normal rundown at wild-type NMJs is likely due to a combination of Ca\(_{\alpha,2.1}\) channel inactivation, its recovery, and the replenishment of releasable ACh vesicles. A relatively large degree of use-dependent inhibition of Ca\(_{\alpha,2.3}\), compared to that of (Tg-)Ca\(_{\alpha,2.1}\)
channels, e.g., induced by faster inactivation (Williams et al., 1994), might add disproportionately to the EPP rundown at Tg NMJs. However, normalized EPP rundown at Tg NMJs in the presence of either SNX-482 or ω-agatoxin-IVA did not differ. This indicates that the contribution of use-dependent inhibition of Ca_{v}2.3 channels to EPP rundown is either similar to that of (Tg-)Ca_{v}2.1 channels, or that use-dependent inhibition of Ca_{v}2 channels is not at all a factor contributing to rundown at normal Ca^{2+} level. It may be that the replenishment rate of ACh vesicles at release sites is the major determinant of EPP rundown under these conditions.

The mechanism of increased ACh release becoming unmasked at low extracellular Ca^{2+} concentration at Tg as well as R192Q NMJs is unclear. The Ca^{2+} influx through mutant channels at physiological extracellular Ca^{2+} may be of such magnitude that presynaptic sensors saturate. Alternatively, Ca^{2+}/calmodulin-dependent Ca_{v}2.1 inactivation (Lee et al., 1999) may be increased at mutant synapses, due to increased Ca^{2+} influx or, although not very likely (as discussed above), a direct change in Ca_{v}2.1 modulatory characteristics. Alternatively, the localization of the different types of Ca_{v}2 channels relative to the Ca^{2+} sensor of the neuro-exocytotic mechanism may play a role (Urbano et al., 2003; Wu et al., 1999). Tg-mutated Ca_{v}2.1 channels might be more closely localized than wild-type channels and therefore contribute more efficiently to ACh release. This may also (partly) explain the higher MEPP frequency at Tg NMJs, compared to wild-type, at normal extracellular Ca^{2+} concentration. Similarly, a closer localization of Tg-Ca_{v}2.1 channels to release sites than Ca_{v}2.3 channels may explain the lack of contribution of Ca_{v}2.3 channels to evoked ACh release under the condition of low extracellular Ca^{2+}.

It is unclear whether compensatory Ca_{v}2.3 channel-mediated transmitter release at Tg CNS synapses, as present at the NMJ, influences the symptoms of ataxia and epilepsy. Central neurons can upregulate Ca_{v}2.3 channels after partial downregulation of Ca_{v}2.1 channels, as shown in cerebellar Purkinje cells (Pinto et al., 1998). However, total genetic Ca_{v}2.1 ablation results in unaltered or reduced Ca_{v}2.3 current density in cerebellar neurons (Fletcher et al., 2001; Jun et al., 1999). The unidentified residual Ca^{2+} current shown at Tg hippocampal presynapses after blocking Ca_{v}2.1 and Ca_{v}2.2 channels (Qian and Noebels, 2000) may be due to Ca_{v}2.3 channel expression. It would be interesting to cross-breed Tg with Cacna1e mice (Wilson et al., 2000) in order to test Ca_{v}2.3 channel involvement.