Selective modification of the squid axon Na currents by
Centruroides noxius toxin II-10*

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SUMMARY:

1° We have studied the effects of the purified toxin II-10, from the venom of the scorpion Centruroides noxius Hoffmann, on the Na and K currents of voltage clamped squid giant axons.

2° Extracellular applications of 10 μM of toxin II-10 produced a selective depression of peak Na currents, with no significant effects on the time course of K currents.

3° On pharmacologically separated Na currents, low concentrations of toxin II-10 (0.28-1 μM) caused a reversible decrease in inward and outward peak Is, with little effect on either the maintained level of the currents or their turning-off.

4° At high concentrations ( > 3 μM), toxin II-10 drastically reduced the peak conductance and increased both the level of the maintained conductance, and the time course of its turning-off.

5° It is suggested that, when applied extracellularly on squid axons, toxin II-10 primarily reduces the peak Na conductance by modifying the activation of fast-inactivating Na channels. At high concentrations (10 μM), the toxin also modifies the rate constants of the transition from the inactivated to the second open state of the channel (CHANDLER and MEVES, 1970) thus producing an increased level of the maintained Na conductance. It is also very likely, however, that peak conductance and maintained conductance reflect two separate populations of Na channels on which toxin II-10 has a differentiated action. Under these conditions, toxin II-10 would be the first reported toxin which can pharmacologically separate the two types of channels.


INTRODUCTION

Neurotoxins have become increasingly important tools with which to investigate the molecular components that control membrane excitability (NARAHASHI, 1974; CATTERALL, 1980). Among them, scorpion toxins have recently been shown to interact specifically with either the Na channel of various cell preparations (ROMET et al., 1975; BERNARD et al., 1977; MOZHAYEVA et al., 1980; MEVES et al., 1982; JAIMOVICH et al., 1982; WANG and STRICHARTZ, 1982; BARRANIN et al., 1983) or with the K channel of squid giant axons (CARBONE et al., 1982; CARBONE et al., 1983). Toxins acting on Na channels can be divided into two classes: those affecting Na activation and those affecting Na inactivation (HU et al., 1983; WHEELER et al., 1983). Very likely, different modes of action reflect different chemical structures of the various toxins. For instance, toxins acting on K channels appear to have rather similar molecular weight and amino acid sequence (POSSANI et al., 1982), which differ considerably from those of toxins acting on Na channels (BARIN et al., 1975; GARCIA, 1976).

In this paper we present additional data on the purification and physiological characterization of toxin II-10 from the venom of the Mexican scorpion Centruroides noxius Hoffmann. The major effect of the toxin is that it selectively reduces the peak Na conductance of squid axon membrane leaving the K-system almost unaltered. At concentrations greater than 3 μM the peak decrement is usually accompanied by an increase in the maintained conductance, which was not clearly observed in previous studies (CARBONE et al., 1982), where the concentrations used were lower than 1.4 μM.

From its mode of action and partial amino acid sequence II-10 appears to be very similar to other toxins known to act on the activation machinery of other Na channels (JAIMOVICH et al., 1982; MEVES et al., 1982).
METHODS

Axon preparation and voltage clamp. All experiments were performed on internally perfused giant axons of the squid Loligo vulgaris, available in Camogli (Italy). The perfusion technique, voltage clamp apparatus and pulse protocol for measuring Na currents were similar to those previously described (Wanke et al., 1979; CARBONE et al., 1981). Axons were bathed in artificial sea water (ASW) containing (mM): 435 NaCl, 10 KCl, 10 CaCl₂, 40 MgCl₂, 20 Tris, pH 8.0. The standard intracellular medium (50 Na-SIS) contained (mM): 267 CaF, 307 sucrose, 50 NaF, 45 K-phosphate, pH 7.2. When both Na and K currents were recorded, the intracellular medium was 400 K-SIS containing (mM): 371 KF, 307 sucrose, 45 K-phosphate buffer, pH 7.2. The fibres were held at a holding potential of −70 mV, and preconditioned to −90 mV for 80 ms before applying the depolarizing pulse. The temperature of the bath was maintained at 5 °C throughout all the experiments. Stock solutions of the purified toxin were added directly to the external bath by means of a Hamilton microsyringe to attain the desired final concentration.

Biochemical characterization of toxin II-10. The venom from the Mexican scorpion Centruroides noxius Hoffmann was previously fractionated by Sephadex G-50 gel filtration followed by ion exchange chromatography on carboxymethylcellulose column in 20 mM ammonium acetate buffer pH 4.7 (Possani et al., 1981). Another chromatographic step in CM-cellulose column equilibrated with 50 mM sodium phosphate buffer, pH 6.0, was introduced (see Results). The homogeneity of the toxin was verified by polyacrylamide gel electrophoresis in the acetic-urea-b-alanine system of Rausch et al., (1962) and by amino acid sequencing. The pure toxin was reduced and carboxymethylated according to the procedure described (Possani et al., 1981), and its N-terminal amino acid sequence was determined by Edman degradation in a Beckman 890 C sequencer following the method of Edman and Beggi (1967). The identification of the phenylthiohydantoin amino acids (PTH) was performed by high liquid pressure chromatography and by amino acid analysis (Durrum D-500) of the PTH amino acids back hydrolyzed, as already published (Possani et al., 1981).

RESULTS

A - Purification and partial sequence determination of toxin II-10

The toxin component II-10 from the venom of the scorpion Centruroides noxius (lethal to mice) was completely purified by a second ion exchange chromatographic step (Fig. 1). From the three toxic fractions (b, c and d) the second one was shown by amino acid analysis and by voltage clamp experiments to correspond to our previous toxin II-10, which affects the peak Na conductance of squid giant axons (Carbone et al., 1982).

The N-terminal amino acid sequence of the reduced and carboxymethylated toxin II-10 (c) (≈ 50 nmole) was shown to be: Lys-Glu-Gly-Tyr-Leu-Val Asn-Leu-Tyr-Thr-Gly-Cys-Lys-Tyr-Glu-Cys-Phe-Lys-Leu-Gly-Asp Asn Asp-Tyr-Cys-Leu.... Only one amino acid was identified at each step of the sequence with an over-all yield of 95%. These results corroborate the purity of the toxin II-10 (c) (same as II-10 from CARBONE et al., 1982). Toxin from this preparation was used for the present study.

B - Effects of the purified toxin II-10 on Na and K currents.

The effects of 10 μM of toxin II-10 on the time course of Na and K currents are shown in Fig. 2. Toxin II-10 produces a rapid decrease of peak I Na at 0 mV without altering either the steady-state level of I K or the time course of the tail currents recorded on repolarization to −70 mV. Closer inspection shows that the depression of peak currents is accompanied by a slight prolongation of the time to peak, and by a sizeable slow down of the outward current component (Fig. 2 trace T). The latter effect, observed in two other axons, can be due either to a prolongation of the time course of the outward K currents or to a slowing down of the Na inactivation process. As shown below the
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Fig. 2. — Selective modification of Na currents after external application of 10 μM toxin II-10. The records were obtained on step depolarization to 0 mV from an axon maintained near physiological conditions. Trace (c) was taken before application of the toxin. Successive records (showing progressively smaller peak inward currents) were recorded at 1 min intervals. Trace (T) was the last before the recovery started. Note the constancy of the steady-state level of I_K at the end of the pulse, and the little effect of the toxin on the time course of tail currents on repolarization to −70 mV. Bars: 2 mA/cm², 2 ms. In : 400 K-SIS. Out : ASW. Axon C12FB82. Temperature : 5 °C.

The second possibility can account for most of these effects, suggesting only a weak interaction, if any, of II-10 with the K channel kinetics. This point, however, was not further investigated.

C - Effects of II-10 on pharmacologically separated Na currents.

In axons internally perfused with 217 mM CsF to block K outward currents, addition of 280 nM of toxin II-10 (Fig. 3, left) reduces by 60% the size of peak I_{Na} at 0 mV with no significant effects on: (1) the time course of Na activation and inactivation, (2) the maintained level of currents at + 100 mV, and (3) the time course of tail currents on step repolarization. At this concentration the action is fully reversible (Fig. 3, right), and requires approximately 10 min to be complete. Larger doses of toxin (up to 1 μM) speed up the reduction of peak currents and increase the extent of the depression (see also Fig. 2d in CARBONE et al., 1982).

At large concentrations (> 3 μM) the action of toxin II-10 becomes somewhat more complex. At 10 μM (Fig. 4) the depression of peak I_{Na} is more pronounced (87% at 0 mV) while the level of the maintained currents increases by 60% at + 100 mV. Comparing the records at 0 mV taken before (C) and after 8 min addition of the toxin (T), it is evident that II-10 prolongs the time to peak of I_{Na}, as well as the time constant of Na inactivation. The effects of the toxin are even more striking on the kinetics of Na channel closing. Tail currents recorded on repolarization to −70 mV become larger and markedly slower in the presence of the toxin. Usually, at these toxin concentrations leakage currents show a slight and progressive increase which, in any case, never contribute more than 15% to the level of peak outward current at + 100 mV. Under these conditions, recovery was usually largely incomplete.

Fig. 4. — Effects of high concentrations of toxin II-10 on Na currents. Lower records were taken at 0 mV; upper records at + 100 mV. Traces (C) were recorded before the addition of 10 μM of toxin II-10. Successive traces, showing progressively smaller peak amplitudes, were taken after toxin application at intervals of 1 min. Traces T were the last records before recovery (not shown). Note the increase of maintained currents at the end of the + 100 mV pulse and the pronounced increase in tail current amplitude during successive repolarization to −70 mV. Bars : 1 mA/cm², 2 ms. In : 50 Na-SIS. Out : ASW. Axon B12FB82. Temperature : 5 °C.

Fig. 3. — Reversible action of toxin II-10 on Na currents. The records on the left were obtained during application of 280 nM of toxin II-10, those on the right during washout. Lower traces were recorded on depolarization to 0 mV; upper traces to +100 mV. Pulses to 0 mV and +100 mV were separated by 3 s, and repeated each minute. Arrows indicate the sequential order in which the voltage clamp currents were recorded. Repolarizations were to −70 mV. Bars : 1 mA/cm², 2 ms. In : 50 Na-SIS. Out : ASW. Axon 26JN82. Temperature : 5 °C.
DISCUSSION

Our results show that II-10 acts on the squid axon membrane by selectively decreasing the peak Na currents. The action of the toxin is fast, develops at low concentrations (at 280 nM Na currents are nearly halved at +100 mV) and is fully reversible (Fig. 3). Thus, the present data confirm our previous findings obtained with a similar toxin, which has been shown to affect the peak Na-conductance in a dose-dependent manner (CARBONE et al., 1982). From these observations it was concluded that toxin II-10 might interact specifically with the transiently open Na channel by fully blocking it in a one to one ratio. Such interpretation, however, is now in contrast to the present results. At large depolarizations, the block of the peak conductance is largely incomplete and the level of the maintained Na-conductance increases in the presence of 10 μM toxin (Fig. 4).

From the above arguments it is tempting to suggest that toxin II-10 acts on the Na-conductance mechanism by increasing the number of channels which go from the peak conductance state into the maintained conductance state (CHANDLER and MEVES, 1970; GILLESPIE and MEVES, 1980). But it is also possible that peak conductance and maintained conductance reflect two separate populations of Na channels (one with fast activation and inactivation, and one with slow activation and no inactivation) and that II-10 transforms one type of channel into the other (MATTESON and ARMSTRONG, 1982). In the second case, however, we can not exclude the possibility that toxin II-10 has a differentiated action on the two channels: partially blocking those fast-inactivating and decreasing the rate of closing of those slowly activating. The latter effect would account for most of the increased level of the maintained conductance as well as for the drastic slow down of tail currents during membrane repolarizations. A better discrimination between the various mechanisms of action presently requires further experimental work.

The distinct effects of toxin II-10 on the peak and maintained Na-conductance (Fig. 3, 4) are typical of other toxins known to act on Na channels. For instance, the action on the peak conductance observed at 280 nM (Fig. 3) is similar to that of toxin II of the venom Centruroides sculpturatus, C.s.s.II (JAIMOVICH et al., 1982) and of toxin-γ from the venom Tityus serrulatus, TTXγ (VJIVERBERG and LAZDUNSKI, 1983). In the case of C.s.s.II, 20 nM of toxin are sufficient to fully block the peak Na currents of frog skeletal muscles, while 100 nM of TTXγ block only 50% of the inward Na currents in neuroblastoma cells. As for II-10, the action of the two toxins is shown to be selective for the Na channel, but there is no proof of their reversibility of action. In contrast to that, the effects on the maintained conductance observed above 3 μM (Fig. 4) resemble more the actions of the venoms Centruroides sculpturatus Ewing and Leirus quinquestriatus on the Na channels of squid giant axons (GILLESPIE and MEVES, 1980) and of mammal toxin I, MTI, from the venom Androctonus australis Hector on the same preparation (PICCHION, 1983). In both cases, applications of 0.1 to 0.5 mg/ml of the venom C.s.E (or micromolar aliquots of MTI) produce a sizeable increase in the maintained Na-conductance and a slow down of its turning-off kinetics. Fig. 5 shows that similar effects can also be seen when 1 mg/ml of the venoms Centruroides sculpturatus C.s.s. and Centruroides noxius Hoffmann are applied on perfused axons, confirming the possible isolating properties of these venoms for the Na channel.

![Fig. 5. Effects on Na currents of — a: Venoms from the scorpions Centruroides noxius Hoffmann. — b: Centruroides sculpturatus C.s.s. Lower traces were recorded with pulses to 0 mV and upper traces to +100 mV. (C) traces were taken before the addition of 1 mg/ml of the venoms. (T) were the last records before recovery (not shown). In a the voltage clamp currents were recorded every 3 min; in b every min. Repolarizations to 70 mV. Bars: 1 mA/cm², 2 ms. In: 50 Na-SLS. Out: ASW. Axons: A26MR82 and BO3FB62. Temperature: 5 °C.](image-url)
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<td>CARBONE et al. (see text)</td>
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axes, indicating that the increase in the maintained conductance and related phenomena are a general property of most scorpion venoms when applied to the giant axon of the squid. It is noteworthy that the venoms C.s.E and L.q. applied to myelinated fibres produce rather different effects (CAHALAN, 1975; MEVES et al., 1982). The reason for this has still to be clarified.

Finally we would like to comment on the above physiological data with respect to the information available on the primary structure of the toxins from the venom of the scorpion Centruroides. In Table I we have reported the partial N-terminal amino acid sequence of 14 toxins from the scorpions of the genus Centruroides. As shown, toxins acting on Na channels appear to have very similar structure, which differs remarkably from that of K-toxins: NTX and C.n.II-II.10.2 (POSANI et al., 1982). Among Na-toxins the similarity between II-10, C.s.s.II and C.n.II-14 is remarkable. The latter, at high concentrations was observed to have a slight effect on the peak Na-conductance, while toxins C.n. II-9.2.2 and C.n.II-13 were found to be insensitive to both Na and K currents of the squid giant axon (CARBONE, PRESTIPINO, WANKE, POSANI and MAELICKE, unpublished observations).

A more detailed discussion of the effects of toxin II-10 compared to other Na-toxins requires of course more work and the full knowledge of its amino acid sequence. Since it is very likely that minor changes or deletions condition the fine mechanism of action of each toxin, it is conceivable that their identification will allow for a better understanding of the mode of action of the toxins and of the structure of their receptors at the channel site. In this respect, toxin II-10 seems to have all the prerequisites for such an approach: selectivity of action and high affinity for the channel.

REFERENCES


