Mechanoafferent Neuron With An Inexcitable Somatic Region: Consequences for the Regulation of Spike Propagation and Afferent Transmission

Colin G. Evans,1,2 Bjoern Ch. Ludwar,1 and Elizabeth C. Cropper1
1Department of Neuroscience, Mt. Sinai School of Medicine; and 2Phase Five Communications, New York, New York

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INTRODUCTION

Commonly, peripherally and centrally generated activity is integrated so that motor output accommodates changes in the peripheral environment. Mechanisms that underlie these integrative processes are only partially understood. In this report, we study the regulation of afferent transmission in an experimentally advantageous Aplysia neuron, a mechanoafferent designated as B21 (Rosen et al. 2000b). B21 is of interest becauseafferent transmission is in part regulated via the control of active spike propagation. When B21 is peripherally activated at its resting membrane potential, spikes fail to propagate to an output process, and afferent transmission does not occur. In this report, we show that the propagation failure is in part a result of the fact that the somatic region of B21 is relatively inexcitable. We isolate this region and demonstrate that net currents evoked by depolarizing pulses are outward. Furthermore, we show that all-or-none spikes are not triggered when current is injected. Previous reports have, however, shown that spiking is triggered when current is somatically injected and cells are intact. We demonstrate that spikes evoked under these circumstances do not originate in the soma. Instead they originate in an adjacent part of the neuron that is excitable (the medial process). In summary, we show that the mechanoafferent B21 consists of excitable input and output processes separated by a relatively inexcitable somatic region. A potential advantage of this arrangement is that somatic depolarization can be used to modify spike propagation from the input to the output processes without altering the encoding of peripherally generated activity.

METHODS

Experiments were conducted in 200–300 g Aplysia californica (Marinus, CA) maintained in 14–16°C holding tanks. Animals were anesthetized by injection of isotonic MgCl2. Experiments were conducted at ~16°C in artificial seawater [ASW, containing (in mM) 460 NaCl, 10 KCl, 11 CaCl2, 55 MgCl2, and 10 HEPES, pH 7.6].

Equipment used in current-clamp experiments included: Getting Model 5A amplifiers modified for 100-nA current injection (Getting Instruments, Iowa City, IA), Tektronix AM 502 amplifiers (Tektronix, Wilsonville, OR), and a Tektronix storage oscilloscope (model 5111). Data were digitized [using a Digidata (Axon Instruments, Union City, CA)] and were acquired and analyzed using pClamp version 9 software (Axon Instruments), and a Sony Vaio PCG-GRT Notebook.

Equipment used in single-electrode voltage-clamp (SEVC) experiments included an NPI SEC-05LX amplifier (NPI Electronics GmbH, Tamm, Germany), a Model 410 filter amplifier (Brownlee Precision, San Jose, CA), and a CED Power 1401 AD/DA converter (Cambridge Electronic Design, Cambridge, UK). Scripts, written in Spike II (version 5.15; Cambridge Electronic Design), were used to control the amplifier, acquire the data, and subtract leak current. Voltage steps had durations of 200 ms and were given every 10 s. Between steps, the membrane potential was held at ~70 mV.

To record from the somata of neurons we used single-barrel electrodes filled with 3 M potassium acetate and 30 mM potassium chloride. Electrodes were beveled so that their impedances were generally <10 MΩ. In voltage-clamp experiments, electrodes were coated with silicone elastomer (Sylgard, Dow Corning, Midland, MI).

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Address for reprint requests and other correspondence: E. C. Cropper, Dept. Neuroscience, Box 1065, Mt. Sinai Medical School, One Gustave L. Levy Place, New York, NY 10029 (E-mail: elizabeth.cropper@gmail.com).
To record from processes, microelectrodes were generally ~50 MΩ, and the tip was filled with 3% 5(6)-carboxyfluorescein dye in 0.1 M potassium citrate. Carboxyfluorescein was injected to verify recording sites. During physiological experiments processes were visualized for impalement by injecting Fast Green dye into the B21 soma (Evans et al. 2003b).

In lesion experiments, processes were mechanically severed using a glass micropipette. In current-clamp experiments, we measured the input resistance of the intact cell, and the input resistance of the cell after the medial lesion. Neurons were only tested for excitability if an increase in input resistance was observed. On average cells originally had an input resistance of 3.2 ± 0.3 MΩ. After lesions the input resistance was 6.2 ± 1.2 MΩ; n = 7). Voltage-clamp experiments were only conducted on neurons with an input resistance above the mean observed in current-clamp experiments.

TTX (Sigma-Aldrich, St. Louis, MO) was focally applied to the medial process at a concentration of ~10-4 M. In some experiments (n = 2), the TTX was pressure applied via a micropipette with a large tip diameter. Fast Green was included in the TTX solution to monitor the injection. In other experiments (n = 5), the TTX solution was added to a subchamber that pharmacologically separated the ASW perfusing the medial process from the ASW perfusing the rest of B21. Fast Green was used to test for subchamber leaks. Controls did not show any affect of Fast Green on excitability.

To evoke afferent activity, the subradula tissue (SRT) was peripherally stimulated using a mini-speaker controller by a stimulator (Grass Instruments) (Cropper et al. 1996).

Statistical tests were performed with Kaleidagraph (Synergy Software, Essex Junction, VT). Unless otherwise noted, two group comparisons utilized a paired t-test and n's provided indicate the number of preparations in which data were obtained. Data are reported as means ± SE.

RESULTS

B21 has major medial and lateral processes (Fig. 1A1B). The medial process acts as an input region, innervating the periphery (Rosen et al. 2000b). The lateral process acts as an output region, being the primary point of contact with motor neurons (the B8 cells) (Borovikov et al. 2000; Gardner 1971). Peripherally triggered spikes are therefore transmitted from the medial process of B21 through the soma to the lateral process (Fig. 1A2). When B21 is peripherally activated at its resting potential, spikes fail to propagate to the lateral process (Fig. 1A1) (Evans et al. 2003b). To determine why the propagation failure occurs, we sought to determine whether there are regional differences in B21 excitability.

When the lateral process of B21 is mechanically isolated, it resists and is excitable (Evans et al. 2003b). We found that the same is true for the isolated medial process (Fig. 2A1, right, and A2; n = 3; average spike amplitude 48.7 ± 1.9 mV). The somatic region is, however, different. We mechanically isolated this region of B21 progressively, removing the medial process first and the lateral process second. In most (6/7) cells, medial lesions virtually eliminated spiking. In one preparation, small depolarizations were still apparent (Fig. 2B2) that resembled impulses previously observed when spikes were triggered in the lateral process (Evans et al. 2003b). As expected, these depolarizations were eliminated when the lateral process was severed (Fig. 2B3). These data suggest that the somatic region of B21 (including the proximal medial process) is relatively inexcitable. Consistent with this idea are data we obtained in SEVC experiments in lesioned neurons. Net currents evoked by depolarizing steps in the somatic region were outward in normal saline (Fig. 3A; n = 6).

A potential paradox, however, is that spike-like depolarizations are recorded when current is injected into somata of intact B21 neurons (Fig. 2B1) (Rosen et al. 2000a,b; Shetreat-Klein and Cropper 2004). We hypothesized that these impulses were triggered in the medial process and electrotonically conducted to the soma (Fig. 2B1). [Previous characterizations of the lateral process length constant preclude the possibility that spikes were laterally initiated (Evans et al. 2003b).] To determine whether impulses were medially initiated, we simultaneously recorded from both the soma and the medial process and triggered spiking by injecting current into the soma. Consistent with the idea that spikes were medially triggered, impulses recorded in the medial process were observed prior to impulses recorded from the soma (Fig. 3B1). (The time difference between peak depolarizations was 1.4 ± 0.2 ms; n = 6.) Impulses in the medial process also had greater peak amplitudes (46.1 ± 2.1 vs. 38.1 ± 3.1 mV; t-test, P < 0.05; t = 2.58; df = 5; n = 6). In a second type of experiment, spikes were triggered via somatic current injection, and TTX was selectively applied to the medial process (Fig. 3B2, top). TTX application blocked spike initiation (Fig. 3B2, bottom; n = 7).

FIG. 1. Spike propagation in B21 at resting potential (A1) and with central depolarization (A2). B21 is illustrated with camera Lucida drawings in which regions in which active spike initiation occurs are indicated by black, and regions in which electrotonic transmission occurs are indicated by gray. Traces are intracellular recordings simultaneously obtained in a physiological experiment in which B21 was peripherally activated. At resting membrane potential (A1), spikes are actively generated in the medial process but thereafter propagation fails. Impulses are electrotonically transmitted through the somatic region to the lateral process. When B21 is centrally depolarized (A2), spike propagation in the medial process is unchanged, and impulse transmission through the somatic region is again electrotonic. Currents generated by medial spike initiation are, however, now sufficient to trigger spiking in the lateral process. B: physiological consequence of a mechanism whereby spike propagation is regulated by altering the membrane potential of an excitable region in a neuron. B1: when B21 is centrally depolarized, peripherally evoked activity is reinitiated in the lateral process and peripheral encoding is not altered. B2: if central depolarization triggered spiking in B21 peripheral encoding could be altered.
Our results suggest that when B21 is peripherally activated at its resting potential, spikes actively propagate in the medial process but that propagation fails in the relatively inexcitable somatic region (Fig. 1A2). Although the lateral process is capable of active spike generation (Evans et al. 2003b), it does not occur, presumably due to the fact that currents generated by medial spike initiation are insufficient to trigger lateral action potentials. When B21 is centrally depolarized prior to peripheral activation, active spiking again occurs through the branch point in the medial process (the T-junction region) and transmission in the somatic region is electrotonic. Events in the lateral process, however, are changed. Currents generated by medial spike initiation are sufficient to trigger active spike initiation.

**DISCUSSION**

In previous work, we demonstrated that spikes fail to actively propagate to the lateral process (an output region) when B21 is peripherally activated at its resting membrane potential (Evans et al. 2003b). In this study, we demonstrate that this propagation failure is in part a result of the somatic region of B21 being inexcitable. Thus the conduction failure is not simply a result of the impedance mismatch between the medial process and soma. Cells with excitable somata have been described in *Aplysia*, as have neurons with inexcitable somata (e.g., Alving 1968; Hurwitz et al. 1994; Tauc 1962a,b). It is therefore currently not clear whether an inexcitable soma is the rule or exception in this mollusk. In general, it is often difficult to localize sites of spike initiation in *Aplysia* because length constants in neurons can be surprising long. Consequently, somatic current injection often evokes relatively large-amplitude spike-like impulses, but without further analysis, it cannot be determined whether these impulses are remotely triggered.

Our current data do not implicate a specific mechanism as the underlying cause of the somatic inexcitability in B21. It is likely, however, that the soma is characterized by a low density of voltage-gated sodium channels as has been demonstrated in other sensory neurons (e.g., Safronov et al. 2000). Channels may also have an unfavorable distribution. Thus clustering of voltage-gated sodium channels has been demonstrated in axons.
of Aplysia and is likely to decrease the number of channels required for spike initiation important for propagation (Johnston et al. 1996). In the B21 soma, channel distribution may be uniform. It is important to point out, however, that our voltage-clamp data indicate that the somatic region of B21 does not simply function as a passive load, i.e., outward currents in the soma are activated within presumably physiological ranges. This phenomenon has been described, and implicated as being an important determinant of neuronal excitability (Graubard and Hartline 1991).

The regional biophysical differences in B21 produce a situation where excitable input and output processes are separated by a relatively inexcitable part of the cell. Although this arrangement is a result of a bipolar morphology in B21, unipolar or pseudo-unipolar neurons can be similar if they are characterized by a relatively short “stem” process exiting from the soma (i.e., if electrical affects of the soma are not masked) (Luscher et al. 1994; Weiss et al. 1986). An interposed inexcitable region may be of functional significance in a sensory neuron like B21 because it permits the regulation of afferent transmission without disrupting peripheral encoding (Fig. 1B, 1 vs. 2). Thus when B21 is peripherally activated at its resting potential, spikes are actively initiated in the input process, but currents generated are insufficient to trigger spiking in the next region capable of spike generation, the output process. In contrast, when B21 is centrally depolarized prior to and during peripheral activation, spikes in the input process do trigger spiking in the output process. Somatic depolarization therefore promotes initiation of peripherally triggered spikes. Importantly, however, somatic depolarization does not in itself induce additional spikes. Thus we characterize a mechanism whereby synaptic input can regulate afferent transmission without altering the encoding of peripherally generated signals.

Regulation of spike propagation in B21 is likely to be important for sensori-motor integration during feeding. When Aplysia feed, the food grasping organ (the radula) is protracted and retracted and opened and closed (Cropper et al. 2004). Phase relationships between protraction/retraction and opening/closing determine the nature of the behavior. If the radula closes during protraction, food is pushed out (i.e., behavior is egestive). In contrast, if the radula closes during retraction, food is pulled in (i.e., behavior is ingestive). Studies of spike propagation in B21 have focused on afferent transmission to radula follower neurons. This conduction failure can, however, be relieved if B21 is centrally depolarized prior to peripheral activation. Under physiological conditions, this can occur when the somatic region receives electrical synaptic input during feeding motor programs. Because the soma is inexcitable, central depolarizations do not initiate spiking and therefore do not alter the peripherally determined encoding pattern. Somatic depolarizations do, however, promote conduction in B21. The inexcitable B21 soma is therefore used to control transmission of afferent information without altering it.

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