Vestibular Signals in the Parasolitary Nucleus

N. H. BARMACK AND V. YAKHNITSA
Neurological Sciences Institute, Oregon Health Sciences University, Portland, Oregon 97201

Barmack, N. H. and V. Yakhnitsa. Vestibular signals in the parasolitary nucleus. J Neurophysiol 83: 3559–3569, 2000. Vestibular primary afferents project to secondary vestibular neurons located in the vestibular complex. Vestibular primary afferents also project to the uvula-nodulus of the cerebellum where they terminate on granule cells. In this report we describe the physiological properties of neurons in a “new” vestibular nucleus, the parasolitary nucleus (Psol). This nucleus consists of 2,300 GABAergic neurons that project onto the ipsilateral inferior olive (β-nucleus and dorsomedial cell column) as well as the nucleus reticularis gigantocellularis. These olivary neurons are the exclusive source of vestibularly modulated climbing fiber inputs to the cerebellum. We recorded the activity of Psol neurons during natural vestibular stimulation in anesthetized rabbits. The rabbits were placed in a three-axis rate table at the center of a large sphere, permitting vestibular and optokinetic stimulation. We recorded from 74 neurons in the Psol and from 23 neurons in the regions bordering Psol. The activity of 72/74 Psol neurons and 4/23 non-Psol neurons was modulated by vestibular stimulation in either the pitch or roll planes but not the horizontal plane. Psol neurons responded in phase with ipsilateral side-down head position or velocity during sinusoidal stimulation. Approximately 80% of the recorded Psol neurons responded to static and dynamic roll-tilt. The optimal response planes of evoked vestibular responses were inferred from measurement of null planes. Optimal response planes usually were aligned with the anatomical orientation of one of the two ipsilateral vertical semicircular canals. The frequency dependence of null plane measurements indicated a convergence of vestibular information from otoliths and semicircular canals. None of the recorded neurons evinced optokinetic sensitivity. These results are consistent with the view that Psol neurons provide the vestibular signals to the inferior olive that eventually reached the cerebellum in the form of modulated climbing fiber discharges. These signals provide information about spatial orientation about the longitudinal axis.

INTRODUCTION

The anatomical entity termed the Parasolitary nucleus (Psol) derives its name primarily because of its proximity to the nucleus solitarius and tractus solitarius. It is located dorsal and lateral to these structures. It extends rostrocaudally for about 2 mm and in its most rostral extent lies wedged between the medial and descending vestibular nuclei (MVN and DVN). Rather than being directly a part of a baroceptive regulation, the Psol is really the most caudal subdivision of the vestibular complex.

The Psol consists of a compact cluster of 2,300 small-diameter neurons (5–7 μm diam) extending from the nucleus solitarius to the surface of the fourth ventricle (Barmack et al. 1998). In the rabbit, the Psol is identifiable using either cytoarchitectonic or immunohistochemical criteria (Fig. 1B). All Psol neurons are labeled by an antiserum to glutamic acid decarboxylase (GAD; Fig. 1A), the synthetic enzyme for the neurotransmitter gamma amino butyric acid (GABA) (Barmack et al. 1998).

Vestibular primary afferents project to Psol, demonstrated by the distribution of neuronal degeneration following lesion of the vestibular nerve (Korte 1979). This projection is also revealed by the orthograde transport of the C-fragment of t-tetanus toxin (TTC) into vestibular primary afferents terminals in the Psol following injection of TTC into the membranous labyrinth through the oval window (Barmack, unpublished observations).

The Psol receives secondary vestibular afferent projections from neurons in the DVN and MVN (Ruggiero et al. 1996) and a bilateral descending projection from the fastigial nuclei that is shared with other vestibular nuclei (Walberg et al. 1962a,b). The Psol also receives projections from cerebellar Purkinje cells located in the ipsilateral uvula-nodulus (N. H. Barmack, Z.-Y. Qian, and J. Yoshimura, unpublished data). Unlike the nucleus solitarius, the Psol receives no sensory fibers from cranial nerves VII, IX, and X (Allen 1923; Altschuler et al. 1989).

Evidence from both orthograde and retrograde tracer studies indicates that the Psol is the source of the GABAergic projections to the β-nucleus and dorsomedial column (dmcc) of the inferior olive and the nucleus reticularis gigantocellularis (NRGc) (Barmack et al. 1998; Fagerson and Barmack 1995; Kaufman et al. 1996) (Fig. 1). Single-neuron recordings from the β-nucleus, dmcc, and NRGc indicate that neurons in these nuclei respond to vestibular stimulation with increases during contralateral static and dynamic roll-tilt about the longitudinal axis (Barmack 1996; Barmack et al. 1993a; Fagerson and Barmack 1995). The β-nucleus and dmcc send climbing fiber projections to the contralateral uvula-nodulus where vestibular-related climbing fiber responses are mapped onto sagittal strips (Barmack and Shojaku 1995; Fushiki and Barmack 1997). These strips encode ipsilateral static and dynamic roll-tilt. In the uvula-nodulus, as in the β-nucleus and dmcc, no modulation of activity is evoked by vestibular stimulation in the plane of the horizontal semicircular canals.

Since the anatomical evidence indicates that the Psol is involved in the processing of vestibular information, in this experiment we have examined how Psol neurons encode natural vestibular stimulation. We have sought answers to three questions: are Psol neurons modulated by physiological vestibular stimulation, do signals from all vestibular end organs drive Psol neurons, and do Psol neurons receive convergent optokinetic signals? We answered these questions by using the...
technique of extracellular microelectrode recording from Psol neurons in anesthetized rabbits.

METHODS

Anesthesia and surgery

Twenty pigmented rabbits (weight 0.8–1.7 kg) were anesthetized intravenously with α-chloralose (50 mg/kg) and urethan (500 mg/kg) or intramuscularly with ketamine hydrochloride (50 mg/kg), xylazine (6 mg/kg), and acepromazine maleate (1.2 mg/kg). Rectal temperature was monitored and maintained at 37°C. The adequacy of anesthesia was evaluated using the corneal reflex as an indicator.

In a preparatory operation, a dental acrylic plug was formed to the calvarium of each rabbit. This plug held two inverted stainless steel screws (8–32) to the dorsal surface of the calvarium. Five smaller stainless steel screws (2–56) were screwed into the calvarium and helped to anchor the acrylic plug. The larger inverted screws mated with a metal rod that was used to maintain the head rigidly fixed in the center of a vestibular rate table.

Glutamic acid decarboxylase immunocytochemistry

Two rabbits were deeply anesthetized (as described in the preceding text) and perfused transcardially with physiological saline followed by a fixative consisting of 4% formaldehyde, 0.2% zinc salicylate, and 0.9% NaCl, pH 6.5 (Mugnaini and Dahl 1983). The brain stems rostral to the obex and caudal to the dorsal cochlear nuclei were removed and cryo-protected in graded sucrose in saline prior to being frozen and sectioned on a cryostat at 30 μm. The sections were processed for glutamic acid decarboxylase (GAD) immunocytochem-
istry as previously described using a double-peroxidase–anti-peroxi-
dase protocol (Barmack et al. 1998).

Vestibular stimulation

The head of the rabbit was held rigidly in the center of rotation of
a three-axis vestibular rate table with the plane of the horizontal
semicircular canals maintained in the earth horizontal plane. The body
of the rabbit was encased in foam rubber and fixed with elastic straps
to a plastic tube aligned with the longitudinal axis of the rate table.
The rate table was sinusoidally oscillated about its vertical axis (yaw),
about its longitudinal axis (roll), or about its interaural axis (pitch)
(±10°, 0.005–0.800 Hz). During vestibular stimulation the vision of
the rabbit was occluded by hemispherical ping pong balls.

Static vestibular sensitivity

Static vestibular stimulation was used to test for the otolithic origin
of vestibularly evoked discharges. The rabbit was tilted 5–10° about
the longitudinal axis. After an adaptation period of 20–30 s, the
average discharge frequency was measured for the next 20–30 s. The
rabbit was then tilted in the opposite direction. A difference in mean
discharge frequency of 20%, evoked for roll tilts in the two opposite
directions, indicated sensitivity to linear acceleration. Based on the
predominant mediolateral polarization vector of hair cells within the
utricular maculae, as opposed to the predominant ventral-dorsal po-
larization vectors for hair cells within the saccular maculae (Fernan-
dez and Goldberg 1976), we presume that a static roll stimulus evoked
activity originating primarily from utricular hair cells.

Vestibular null plane measurement

A “null technique” was used to characterize the peripheral origins
of the vestibular signals that modulated the activity of Psol neurons.
While the rabbit was rotated about the longitudinal axis of the rate
table, the angle of the rabbit’s head was changed about the vertical
axis until a minimum in stimulus-modulated neuronal activity was
detected (null plane). On either side of this null plane, the phase of
modulated activity again appeared but with a phase shift of 180° with respect to the sinusoidal stim-
ulus. The location of the recorded neuron within the
Psol is illustrated in D. Amb, nucleus ambiguus; Cu,
cuneate nucleus; dmcc, dorsomedial cell column of the
inferior olive; icp, inferior cerebellar peduncle; LPC,
RAC, left posterior and right anterior semicircular ca-
nals; DVN, descending vestibular nuclei; NPH, nu-
cleus prepositus hypoglossi; NRGc, nucleus reticularis
gigantocellularis; SpV, spinal trigeminal nucleus.
Optokinetic stimulation

The rate table was located at the center of a large sphere (1.45 m diam). A 120° segment was cut out of the sphere to allow convenient access to the animal. Nonetheless it was possible to orient the rabbit so that the visual field of a single eye was completely encompassed by the interior surface of the sphere. A perforated aluminum globe (4 cm diam), with a 50-W tungsten filament microscope bulb on the inside, was positioned just over the head of the rabbit. The globe was mounted on a small pen motor. Movement of this globe was controlled by voltage ramps to the pen motor. The globe-pen motor could be aligned with any axis to create movement about that axis. The optokinetic sensitivity of Psol neurons was tested for stimulation about the vertical, longitudinal, and oblique axes.

Microelectrode recording

The Psol was approached by reflecting the muscles overlying the cisterna magna and enlarging the dorsal aspect of the foramen magnum. The dura mater was carefully removed exposing the dorsal surface of the brain stem and folia 9c of the cerebellum. The meningeal attachments of the cerebellum were carefully cut, allowing the cerebellum to retract 1–2 mm rostrally. A hydraulic microdrive, attached to the head-restraint bar, advanced tungsten microelectrodes toward a region of the dorsal brain stem just caudal to the medial vestibular nucleus about 1.8 mm lateral to the midline. The microelectrodes had an extended taper so that the diameter of the final 4 mm was <50 μm. The tip impedance was ~4 MΩ.

Action potentials were discriminated with a window-slope discriminator-Schmitt trigger. Discriminated action potentials were analyzed by computer using Spike 2 software (Cambridge Electronic Design). Evoked single-unit activity was displayed on-line as a peristimulus histogram. Peristimulus histograms were constructed using different numbers of stimulus cycles at different stimulus frequencies. During data acquisition, each stimulus cycle was divided into 180 bins. Interspike intervals for spike occurrences were stored in these bins. The reciprocal of these interspike intervals, spike frequency, was averaged for the number of spike occurrences in each bin.

Histological verification of recording sites

The location of each neuron from which recordings were obtained was marked electrolytically (~8 μA, 30 s). At the conclusion of the experiment each rabbit was deeply anesthetized and perfused transcardially with 0.9% saline, followed by 10% paraformaldehyde. The brain was removed and cryoprotected with 10, 20, and 30% sucrose in 0.1 M PBS, pH 7.2. The brain stem was blocked sagittally, mounted onto cork with OCT compound, and frozen in isopentane cooled with dry ice. Sagittal frozen sections (35 μm) were cut and collected in cold 0.1 M PBS and mounted serially. The location of each recorded neuron was reconstructed from the locations of the marking lesions. These locations were analyzed in transverse histological sections and

---

**FIG. 3.** Responses of a Psol neuron to static roll. Step-roll stimulation was used to characterize the otolithic sensitivity of Psol neurons. A: this neuron, recorded from the left Psol increased its rate of discharge when the rabbit was rolled onto its left side. The step response at the bottom of the figure indicates step-roll about the longitudinal axis. An upward deflection indicates step-roll onto the left side. B: cartoon indicates the optimal response plane for the Psol neuron whose responses are shown in A. C: the peristimulus histogram for this neuron illustrates 2 complete cycles of vestibular step roll-tilt. D: this neuron was located in the Psol ~-500 μm rostral to its caudal pole. The rectangle demarcates the area of the photomicrograph in E. ↓, microlesion that marked the location of the neuron. X, dorsomotor nucleus of the vagus.
RESULTS

Activity evoked in Psol neurons by vestibular stimulation: optimal and null response planes

We recorded from a total of 97 neurons, 74 of which were localized to the Psol. Sinusoidal oscillation of the rabbit about its longitudinal axis modulated the activity of Psol neurons (Fig. 2). When the rabbit was rotated onto the side that was ipsilateral to the recorded Psol neuron, an increase in discharge rate was evoked. When the rabbit was rolled onto the side contralateral to the recorded Psol neuron, there was a decrease in discharge rate. Rotation of the rabbit about its vertical axis (yaw stimulation) failed to modulate Psol activity.

The average discharge rate during sinusoidal stimulation of 74 Psol neurons was 13.3 ± 9.5 (SD) imp/s. The average resting discharge rate for a smaller sample (n = 21) of Psol neurons was 9.6 ± 10.5 imp/s. The discrepancy between these two discharge rates reflects the stimulus-driven activity of many otherwise quiescent Psol neurons.

We measured the null plane of 47/74 Psol neurons from which we recorded and inferred the optimal response planes from these null planes. During sinusoidal vestibular stimulation about the longitudinal axis, the orientation of the head of the rabbit was systematically changed until a minimum in the evoked modulation of Psol activity was reached (Fig. 2B). On either side of the null plane the modulation of activity was phase shifted by 180° (Fig. 2, A and C). The optimal plane for the neuron illustrated in Fig. 2 aligned with the ipsilateral posterior and contralateral anterior semicircular canals (Fig. 2A).

Absence of Psol responses to horizontal vestibular stimulation

Only one neuron responded optimally to horizontal vestibular stimulation. This neuron was localized to the border between the Psol and the MVN.

Absence of optokinetic modulation of Psol neuronal activity

The activity of none of the neurons localized to Psol could be modulated by optokinetic stimulation. The absence of a modulated optokinetic response was not dependent on the particular alignment of the optokinetic stimulation. There was no modulation of Psol activity when the optokinetic stimulation axis was coaxial as well as orthogonal to the optimal axis of vestibular stimulation.

Static roll responses of Psol neurons

In addition to testing each suspected Psol neuron with vestibular sinusoids, we examined the static responses of Psol
neurons using static roll-tilt (see METHODS). More than 80% of recorded Psol neurons had a positive static roll-tilt response. A subset of these neurons was also tested with periodic vestibular step stimulation. The optimal response plane for evoking activity from these neurons was based on previous testing with vestibular sinusoids. An example of a neuron that tested positive for static roll is illustrated in Fig. 3. This neuron responded when the rabbit was stepped onto its left side (Fig. 3A). A peristimulus histogram illustrating two cycles of step roll-tilt indicates that the response did not adapt during the brief (10 s) step (Fig. 3C). This neuron was localized to Psol at a level that was 1,000 μm rostral to the caudal pole of the Psol (Fig. 3, D and E).

Another Psol neuron, with a positive static roll-tilt test, was examined with a series of sinusoidal frequencies (Fig. 4). The evoked discharge of this neuron lead head position by ~40° at a stimulus frequencies of 0.02–0.10 Hz (Fig. 4D). However, at the highest two frequencies, the gain of the response was reduced and the phase of the response lagged head position by 20–30°. This neuron was localized to the most rostral part of the Psol, 2,000 μm rostral to the caudal pole of the Psol (Fig. 4C).

The phase of 47 Psol neurons, each with a static roll response, was compared using vestibular sinusoids at 0.30–0.40 Hz (Fig. 5A). The mean phase lead of this population was 39.5 ± 5.1°. Only four neurons had a phase lag at the frequencies tested.

A full range of vestibular sinusoids was used to examine the phase of the evoked discharge in a subset of 13/47 Psol neurons (Fig. 5B). The phase lead with respect to head position decreased by ~40° as the frequency of stimulation was increased from 0.10 to 0.80 Hz.

**Frequency dependence of null plane analysis**

The foregoing data suggested that Psol neurons receive convergent vestibular information. At least some of this convergence could be attributed to signals arising from the utricular otoliths and vertical semicircular canals. If this were true, then it should be possible to obtain a frequency-dependent shift in the null plane of a neuron. We measured the null plane at two different frequencies (0.02 and 0.30 Hz) for the neuron illustrated in Fig. 6. This neuron had a positive response to static tilt, demonstrating that it received otolith information. In such neurons, it was not feasible to conclude that the response at higher frequencies was driven by either otoliths, semicircular canals or combinations of these inputs. The null plane for the higher frequency corresponded to a null plane of 45° counterclockwise (CCW; Fig. 6B). The null plane at the lower frequency corresponded to a head orientation of 17° CCW.
These data suggest convergence of at least two different vestibular primary afferents at the level of the Psol neuron.

**Distribution of optimal response planes for Psol neurons**

We measured the null planes in 47 Psol neurons at stimulus frequencies of 0.20–0.40 Hz. The optimal response planes of these neurons clustered about the anatomical orientation of the ipsilateral anterior and posterior semicircular canals. The numbers adjacent to each bracketed set of optimal response planes indicate the mean for that cluster and the number, n, of Psol neurons included in the average.

(Fig. 6C). These data suggest convergence of at least two different vestibular primary afferents at the level of the Psol neuron.

**Topographic distribution of optimal response planes mapped onto the Psol**

For each neuron from which we recorded, a microlesion was made to mark its location. The location of these marking lesions was reconstructed from transverse histological sections through the Psol and plotted onto standard transverse schematics spaced 500 μm apart (Fig. 8). The locations of 97 recorded neurons are represented. Of these neurons, 21 were unresponsive to vestibular stimulation about the longitudinal axis (*). Most of these unresponsive neurons (20/21) were found outside of the Psol. Only one Psol neuron was unresponsive to vestibular stimulation about the longitudinal axis. The null planes of seventeen neurons were not measured (▫). Of these neurons, 15/17 were within the Psol and were sensitive to vestibular stimulation about the longitudinal axis. Twenty-six neurons were localized within the Psol and had optimal response planes consistent with stimulation of the ipsilateral anterior semicircular canal (○). These neurons were concentrated in the most rostral region of Psol (Fig. 8D). Twenty-nine neurons had optimal response planes consistent with stimulation of the ipsilateral posterior semicircular canal (●). A topographic concentration of these neurons within the Psol was not evident. Finally, four neurons were found with a Type 3 response (◼). These neurons responded to sinusoidal rotation onto the left and right sides.

**Vestibularly evoked oscillations in Psol neurons**

In most Psol neurons vestibularly evoked discharges were stationary. They were repeatedly evoked, for tens of minutes, during sinusoidal rotation of the rabbit about the longitudinal

![Fig. 7. Distribution of optimal response planes for Psol neurons. Null planes were measured in 47 Psol neurons at sinusoidal stimulus frequencies of 0.20–0.40 Hz. The optimal response planes of these neurons clustered about the anatomical orientation of the ipsilateral anterior and posterior semicircular canals. The numbers adjacent to each bracketed set of optimal response planes indicate the mean for that cluster and the number, n, of Psol neurons included in the average.](image)

![Fig. 8. Localization of vestibularly responsive neurons within Psol. The left dorsal brain stem is illustrated in transverse sections, spaced ~500 μm apart in A–D, left. The numbers to the right of each section indicate the distance from the caudal pole of the Psol. The area that includes Psol in each section is indicated. This area is shown at higher magnification in the right column. The locations of Psol neurons, confirmed by recovery of microlesions, are plotted in the higher magnification sections. *, location of neurons that lacked a vestibularly driven response; ○, neurons whose optimal response planes corresponded to the orientation of the left anterior-right posterior semicircular canals; ●, neurons with optimal response planes corresponding to the orientation of the left posterior-right anterior semicircular canals; ◼, neurons that responded to rotation onto both the left and right sides; ▫, neurons that were vestibularly responsive, but in which null planes were not measured.](image)
axis. When the vestibular stimulus was stopped, the discharge of these responses returned to nonperiodic spontaneous levels. However, the vestibularly evoked discharge of ~5% of Psol neurons was not stationary. In these neurons, sinusoidal vestibular stimulation about the longitudinal axis evoked increased discharge when the rabbit was rotated onto the side that was ipsilateral to the recorded Psol neuron (Fig. 9A). However, when the sinusoidal vestibular stimulation was stopped, the neuron continued to oscillate at a frequency that reflected its stimulus history (Fig. 9, B and C). These slow oscillations lasted 100–300 s.

**DISCUSSION**

**Psol and its transmitter-specific circuitry**

In the rabbit the Psol consists of a cluster of 2,300 neurons that lies dorsolateral to the tractus solitarius in its caudal most aspect and wedged between the MVN and DVN at its most rostral aspect (Fig. 10) (Barmack et al. 1998). In this study we have shown that Psol neurons respond to vestibular stimulation. In particular we have shown that most Psol neurons are modulated during static and dynamic roll-tilt about the longitudinal axis. Psol neurons have optimal response planes that are consistent with stimulation of either the ipsilateral anterior or posterior semicircular canals and the utricular otoliths. Psol neurons are not modulated by rotation about the vertical axis nor are they modulated by optokinetic stimulation.

The identity of the Psol as the exclusive source of the vestibular GABAergic projection to both the β-nucleus and the dmcc is reinforced by observations concerning the retrograde and transneuronal transport of the α-herpes virus following infection of the uvula-nodulus of gerbils (Kaufman et al. 1996). Forty-eight hours after a postuvula-nodulus infection, the α-herpes virus was found only in the dmcc and β-nucleus. However, after a 50-h survival period, the virus labeled a cell group that corresponded to the location of Psol, contralateral to uvula-nodulus injection site. Of equal interest, following the 50-h survival period, other neurons within the vestibular complex were only sparsely labeled.

The Psol is embedded in neuronal circuitry that provides an important source of vestibular climbing fiber inputs to the cerebellum. This transmitter-specific circuitry is illustrated in Fig. 10. Stimulation of the vertical semicircular canals or the utricular otoliths activates glutamatergic primary vestibular afferents that synapse on ipsilateral Psol neurons (Raymond et al. 1984). Psol neurons are GABAergic and project to the ipsilateral NRGc and to the dmcc and β-nucleus (Barmack et al. 1998). The dmcc and β-nucleus, in turn, project to the contralateral cerebellar uvula-nodulus (Barmack 1996; Brodal 1976; Eisenman et al. 1983; Kaufman et al. 1996; Sato and Barmack 1985; Whitworth et al. 1983). The transmitters for this projection include aspartate or glutamate (Wiklund et al. 1982; Zhang and Ottersen 1993) and corticotropin-releasing factor (Barmack and Young 1990; Mugnaini and Nelson 1989; Young et al. 1986). The Purkinje cells of the uvula-nodulus project onto the ipsilateral Psol (N. H. Barmack, Z.-Y. Qian, and J. Yoshimura, unpublished results).

**Comparison of the physiology of Psol neurons with the physiology of other neurons receiving projections from Psol neurons**

The optimal response planes for neurons in the nucleus reticularis gigantocellularis (NRGc) (Fagerson and Barmack 1995), β-nucleus (Barmack et al. 1993a), dmcc (Barmack 1996), and climbing fiber responses of Purkinje cells in the uvula-nodulus (Barmack and Shojaku 1995; Fushiki and Barmack 1997), like those of Psol neurons, were consistent with stimulation of the vertical semicircular canals and utricular otoliths. In each of these structures, the optimal response planes correspond to the anatomical planes of the vertical semicircular canals or utricular otoliths. In none of the Psol, NRGc, β-nucleus, dmcc, or uvula-nodulus was there any physiological evidence of activity modulated by vestibular stimulation in the plane of the horizontal semicircular canal.

There are differences as well as similarities in the evoked neuronal activity in each of these locations. For example, we found that Psol neurons lacked optokinetic sensitivity. However, in the β-nucleus and uvula-nodulus, many of the neurons driven by vestibular stimulation are also responsive to vertical...
optokinetic stimulation (Barmack and Shojaku 1995; Barmack et al. 1993b; Fushiki and Barmack 1997). Optokinetic information from the medial terminal nucleus converges directly onto neurons in the β-nucleus (Giolli et al. 1984).

Vestibularly evoked oscillations in Psol neurons

Some Psol neurons were driven into oscillations by repetitive sinusoidal roll stimulation. In this regard, these Psol neurons are similar to, and maybe responsible for, climbing fiber oscillations that we have previously recorded from Purkinje neurons in the uvula-nodulus (Barmack and Shojaku 1992). There are two classes of explanations that could account for these oscillations: the oscillations represent intrinsic membrane properties of certain neurons and the oscillations represent network properties of the vestibular primary afferent → Psol → β-nucleus → uvula-nodulus → Psol circuit. In either case, these oscillations comprise an adaptive function that could account for the persistence of periodic reflexive eye movements that last 1–2 min after the cessation of long-term periodic vestibular stimulation (Kleinschmidt and Collewijn 1975). These vestibularly evoked oscillations may reflect a fundamental system response to periodic motion.

Comparison of Psol with “classical” vestibular nuclei

The Psol is the one vestibular nucleus for which we can identify a clear encoding function. Psol neurons encode vestibular spatial orientation about the longitudinal axis. The characteristics of Psol neurons differ from the more “classic” vestibular neurons in several respects: 1) the Psol is composed exclusively of an homogenous group of small GABAergic, principal neurons, without evidence of inhibitory interneurons (Barmack et al. 1998). Other vestibular nuclei are composed of a mixture of non-GABAergic principal neurons and inhibitory neurons that may be GABAergic or glycnergic (Behar et al. 1994; Kumoi et al. 1987). 2) The Psol lacks a commissural projection. Other vestibular nuclei (with the exception of Deiter’s nucleus) have a com-
missural projection (Gacek 1978; Ito et al. 1985; Newlands et al. 1989). 2) The Psol receives afferents from other vestibular nuclei but does not project to these nuclei. The MVN, DVN, and SVN have reciprocal projections with other vestibular nuclei (Epema et al. 1988). 3) The Psol is the exclusive origin of the GABAergic vestibular projection to the inferior olive and perhaps the nucleus reticularis gigantocellularis. Other vestibular nuclei have a wider array of ascending and descending projections (Büttner-Ennever 1992; Deecke et al. 1977). 5) Psol neurons do not project as mossy fibers to the cerebellum. Rather the Psol cerebellar projection is mediated exclusively by the vestibular climbing fiber projections of the inferior olive. Other vestibular nuclei (MVN, DVN, and SVN) project bilaterally to the cerebellum as mossy fibers. At least a subset of this mossy fiber projection is cholinergic (Barmack et al. 1992; Epema et al. 1990). 6) The Psol, like other vestibular nuclei, receives a direct projection from the ipsilateral cerebellum (Barmack 1999). This cerebellar projection to the Psol and other vestibular nuclei is not uniform. Parts of each of these vestibular nuclei receive no cerebellar projection (N. H. Barmack, Z.-Y. Qian, and J. Yoshimura, unpublished data).

Functional implications of Psol circuitry

It is interesting to speculate about the possible function of the circuitry in which the Psol is embedded. Primary vestibular inputs, say on the left side, would activate left Psol neurons. These neurons would in turn inhibit neurons in the left β-nucleus and dmc. This would decrease the climbing fiber signals to the right uvula-nodulus. Because the modulation of the simple spikes of cerebellar Purkinje cells is antiphasic to climbing fiber signals, a decrease in climbing fiber input would cause an increase in simple spike discharge (Fushiki and Barmack 1997). This increased simple spike discharge in the right uvula-nodulus would activate the activity of neurons in the right Psol. Thus activation of neurons in one Psol by primary vestibular afferents would lead to a reciprocal reduction in activity in the contralateral Psol mediated by: left Psol → left β-nucleus and dmc → right nodulus → right Psol.

There is little doubt that this circuitry is critical for providing information about spatial orientation about the longitudinal axis. It remains for future experiments to determine the behavioral significance of this circuitry. Experiments that link its role to otohelic function, vestibular adaptation and possible vestibular-autonomic interactions seem most promising.

We thank M. Westcott-Hodson for expert histological, technical, and artistic assistance. We thank S.-H. Park for technical and graphic assistance. The antiserum to GAD was provided by the Laboratory of Clinical Science, National Institute of Mental Health. The antiserum was developed by Dr. I. J. Kopin in association with Ds. W. Oertel, D. E. Schmechel and M. Tappaz. This research was supported by National Eye Institute Grant EY-04778. Address for reprint requests: N. H. Barmack, Neuronal Plasticity Group, L111, Oregon Health Sciences University, 3181 SW Sam Jackson Park Rd., Portland, OR 97201.

Received 4 January 2000; accepted in final form 6 March 2000.

REFERENCES


