The effects of vestibular system lesions on autonomic regulation: Observations, mechanisms, and clinical implications

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Abstract. The loss of labyrinthine inputs in patients or animal models has been demonstrated to affect autonomic regulation. Considerable evidence suggests that vestibular-autonomic responses serve to adjust blood pressure and respiratory activity during movement and postural alterations. However, following peripheral vestibular lesions, compensation rapidly occurs, such that autonomic disturbances are not readily evident in patients with chronic labyrinthine dysfunction. This manuscript summarizes the evidence suggesting that vestibular inputs influence autonomic regulation, but that cardiovascular and respiratory responses linked to movement recover quickly subsequent to the loss of labyrinthine signals. In addition, the clinical implications of dysfunction of vestibulo-autonomic reflexes are described. Furthermore, the mechanisms potentially responsible for the return of the ability to produce posturally-related adjustments in blood pressure and respiration following vestibular lesions are discussed. In particular, evidence that somatosensory signals can replace labyrinthine inputs to vestibular nucleus neurons that participate in autonomic regulation is provided.

Keywords: Respiration, blood pressure, labyrinthectomy, inner ear disease, 8th cranial nerve

1. Introduction

Over the past 15 years, a number of lines of evidence have demonstrated that the vestibular system contributes to autonomic regulation (see \cite{4,37,38,53,55,56,60} for reviews). The vestibular system influences both respiratory and cardiovascular control, and damage to the labyrinth or VIII\textsuperscript{b} cranial nerve has been shown to compromise the ability to adjust breathing and blood pressure during movement and changes in posture. However, these perturbations in autonomic regulation are transient, and largely dissipate over time. This review will discuss recent data regarding recovery of the capacity to produce accurate autonomic responses following lesions of the vestibular system, the mechanisms responsible for this adaptation, and the clinical implications of these transient deficits in regulating blood pressure and breathing after disruption of labyrinthine signals to the CNS.

2. Recovery from the effects of vestibular lesions on autonomic regulation in animals: Observations and mechanisms

2.1. Observations

Head-up tilts of quadrupeds, like standing in humans, typically leads to pooling of blood in the venous circu-
Fig. 1. Changes in arterial blood pressure recorded in conscious cats during 60° head-up tilts subsequent to peripheral or central vestibular system lesions. Each panel shows averaged data from a single animal. Trials were conducted such that the animal’s visual field was rotated with its body, so no visual cues reflecting body position in space were available. To simplify comparisons, the blood pressure changes were plotted relative to those that occurred before lesions. Responses recorded in the first week following lesions are depicted by solid symbols, and those monitored during the subsequent three weeks are indicated by open symbols. Error bars represent one standard error. A: responses recorded following a bilateral labyrinthectomy; data are from [19]. B: responses recorded following a combined ablation of the cerebellar uvula and a bilateral labyrinthectomy; data are from [12]. C: responses recorded following placing chemical lesions bilaterally in the caudal vestibular nuclei; data are from [30].

Stimulation of labyrinthine receptors has been demonstrated to alter the firing of vasoconstrictor efferents of the sympathetic nervous system [23], and to modify blood flow through arterial vascular beds [22], suggesting that vestibular influences on the sympathetic nervous system serve to maintain stable blood pressure during alterations in posture. Accordingly, a bilateral labyrinthectomy resulted in instability in blood pressure at the onset of head-up tilts in conscious animal models, as shown in Fig. 1(A) [19]. However, this impairment in the ability to regulate blood pressure persisted for just one week, after which time blood pressure remained stable during head-up tilts (Fig. 1A). Curiously, removal of vestibular inputs only resulted in an inability to rapidly adjust blood pressure during postural alterations when animals were tested in the absence of visual cues that could be employed to detect body position in space [19]. When animals were studied in a well-illuminated laboratory, no deficits in cardiovascular control could be detected.

In contrast, lesions of the central vestibular system can produce a prolonged impairment in posturally-related cardiovascular responses. Although ablation of the posterior cerebellar vermis did not affect regulation of blood pressure, the combination of damage to the cerebellar uvula along with a bilateral labyrinthectomy resulted in hypotension during head-up rotations, as shown in Fig. 1(B) [12]. The deficits in adjusting blood pressure were still present one month following the re-
moval of vestibular inputs, when the experiment was terminated [12]. These findings led to the conclusion that plasticity within the central nervous system was responsible for the recovery of cardiovascular responses after damage to the peripheral vestibular system, and that the occurrence of this adaptation was dependent upon the cerebellar uvula remaining intact.

In another series of experiments, chemical lesions were placed bilaterally within the area of the vestibular nuclei that mediates autonomic responses [30]. In a variety of species, this “autonomic region” of the vestibular nucleus complex is comprised of portions of the medial and inferior vestibular nuclei located caudal to the lateral vestibular nucleus [33,39,43,47,51,58,61]. These vestibular nucleus lesions produced a permanent loss of the capacity to rapidly adjust blood pressure during head-up tilts of the animal, as shown in Fig. 1(C) [30]. Similar deficits in producing posturally-related cardiovascular responses were noted when visual cues reflecting body position in space were provided, and when visual signals were eliminated. The differences between these data and the results collected subsequent to a bilateral vestibular neurectomy [19] suggest that the adaptive plasticity that is responsible for recovery of compensatory cardiovascular responses following removal of labyrinthine inputs is mediated through the caudal vestibular nuclei.

Changes in posture can also affect the resting length of respiratory pump muscles, requiring alterations in the activity of these muscles if ventilation is to be unaffected. For example, nose-up tilt of quadrupeds or standing in humans from a supine position can result in the diaphragm sinking into the abdominal cavity [25,32,48]. Compensation for the effects of gravity on diaphragm length during head-up body tilts includes both an increase in diaphragm activity and a co-contraction of the abdominal muscles, although increases in abdominal muscle activity appear to be more important in this postural response [7]. Following a bilateral labyrinthectomy, spontaneous diaphragm and abdominal muscle discharges increased significantly (by ~170%), and augmentation of abdominal muscle activity during nose-up body rotation was diminished, as illustrated in Fig. 2 [7]. However, spontaneous muscle activity and responses to tilt began to recover within a few days after the lesions, presumably because of plasticity in the central nervous system [7]. These findings show that although labyrinthine inputs ordinarily contribute to regulation of respiration, other sensory signals can substitute for the vestibular inputs if they are lost.

![Fig. 2](image-url)

Fig. 2. Effects of a bilateral labyrinthectomy on the activity of an abdominal muscle, rectus abdominis. Data from 6 animals were pooled; error bars represent one standard error. Muscle activity recorded in the first week following the labyrinthectomies and during the subsequent three weeks is shown in different columns. A: Percent increase in baseline abdominal muscle activity after removal of vestibular input. To perform this analysis, prelesion rectus abdominis activity in each animal was standardized at 100%, and the percent change in muscle activity after the lesion was determined for each animal. Subsequently, the values from each animal were averaged. B: Effects of removal of vestibular inputs on increases in rectus abdominis activity during $60^\circ$ nose-up tilts. Data are from [7].

2.2. Mechanisms

As noted above, disturbances in the capacity to rapidly adjust blood pressure and respiration during alterations in body position in space occurred following damage to the peripheral vestibular system, but these deficits dissipated rapidly [6,7,19]. In contrast, lesions of caudal portions of the vestibular nucleus complex or ablation of the cerebellar uvula prior to a labyrinthectomy resulted in a prolonged impairment of compensatory autonomic adjustments during movement and changes in posture [12,30]. These findings led to the hypothesis that plastic changes that occur in the caudal vestibular nuclei subsequent to removal of labyrinthine signals are responsible for the recovery of autonomic responses, and that this plasticity is dependent on the presence of inputs from the cerebellar uvula [56,57]. A number of experiments have been conducted to test this hypothesis.
In one study, the activity of vestibular nucleus neurons was recorded in decerebrate cats that had undergone a bilateral vestibular neurectomy 1–3 months previously and were allowed to recover [59]. Responses of neurons were recorded during tilts in multiple vertical planes at frequencies ranging from 0.05 to 1 Hz and amplitudes up to 15°. Many spontaneously active neurons were present in the vestibular nuclei of these animals; the mean firing rate of these cells was 43 ± 5 (SEM) spikes/s. The firing of 27% of the neurons was modulated by tilt; examples of the responses of one neuron are shown in Fig. 3. For all cells, the plane of tilt that elicited the maximal response was usually within 25° of pitch. The response gains for these units were approximately 1 spike/s/° across stimulus frequencies, and their response phases were typically near stimulus position at low frequencies, but lagged position slightly at higher frequencies (average of 35 ± 9° at 0.5 Hz). Vestibular-elicited responses recorded from sympathetic and respiratory nerves had similar dynamic properties [39,61]. These data show that non-labyrinthine inputs can modulate the firing of vestibular nucleus neurons during vertical rotations, and suggest that signals from the muscle, skin, or viscera can substitute for vestibular inputs to these cells following damage to the inner ear. Previous studies have also demonstrated that nonlabyrinthine inputs can be substituted for labyrinthine signals following peripheral vestibular system damage [9,45].

Another study defined the nonlabyrinthine inputs that modulate the firing of vestibular nucleus neurons during changes in posture [20] The majority (72%) of vestibular nucleus neurons in labyrinth-intact animals whose firing was modulated by vertical rotations responded to electrical stimulation of limb and/or visceral nerves. The activity of even more vestibular nucleus neurons (93%) was affected by limb or visceral nerve stimulation in chronically labyrinthectomized preparations. Some neurons received non-labyrinthine inputs from several peripheral sources, including antagonist muscles acting at the same joint, whereas others received more limited inputs. These data suggest that a variety of non-labyrinthine inputs elicited during movement modulate the processing of information by the central vestibular system, and following peripheral vestibular lesions contribute to the recovery of spontaneous activity of vestibular nucleus neurons and the responses of these cells during tilts. A subsequent experiment was conducted to determine the afferent pathways that relay nonlabyrinthine signals to the functionally distinct subdivision of the vestibular complex that participates in autonomic regulation; this study combined monosynaptic mapping with viral transneuronal tracing [18]. First order afferent projections to the vestibular nuclei were defined by retrograde transport of the β-subunit of cholera toxin (CT/β), and the extended polysynaptic circuitry was ascertained in the same animals by injection of a recombinant of pseudorabies virus Bartha (PRV) into the contralateral vestibular nuclei. Neurons containing CT/β or infected by retrograde transneuronal transport and replication of PRV were distributed throughout the spinal cord, but were ten times more prevalent in the cervical cord than the lumbar cord. The labeled spinal neurons were most commonly observed in Rexed’s laminae IV–VI and the dorsal portions of
laminae VII–VIII. Both the CTβ and PRV injections also resulted in labeling of neurons in all four vestibular nuclei, the prepositus hypoglossi, the reticular formation, the inferior olivary nucleus, the medullary raphe nuclei, the trigeminal nuclei, the facial nucleus, and the lateral reticular nucleus. Following survival times \( \geq 3 \) days, PRV-infected neurons were additionally present in nucleus solitarius and the gracile and cuneate nuclei. These data show that an anatomical substrate is present for somatosensory and visceral inputs to influence the activity of cells in the autonomic region of the vestibular nuclei, and suggest that these signals are primarily transmitted through brainstem relay neurons.

Figure 4 summarizes the putative inputs that affect the excitability of vestibular nucleus neurons that influence autonomic regulation. Neurons in the region of the vestibular nuclei that participates in cardiovascular and respiratory regulation integrate a variety of sensory signals reflecting body position in space. These cells have been directly demonstrated to receive inputs from receptors in muscle, skin, and the viscera [20], and physiological evidence suggests that they also receive visual signals [19]. With this balance of inputs, some vestibular nucleus neurons regain the ability to respond to changes in body position in space following chronic bilateral removal of labyrinthine inputs [57], as they still receive considerable information regarding spatial orientation. Physiological studies have additionally shown that following the loss of vestibular signals, recovery of autonomic responses related to postural alterations is dependent on the cerebellar uvula remaining intact [12]. This cerebellar region could potentially be involved in ‘shaping’ the responses of vestibular nucleus neurons to multiple sensory inputs, since it is known to participate in sensory-motor transformations [1,2,49,50], and projects to the area of the vestibular nuclei that mediates vestibular influences on autonomic regulation [34,44].

3. Studies in humans and clinical implications

Distressing symptoms in patients with acute vestibular lesions, such as nausea, vomiting, occasionally diarrhea, sweating, tachycardia and palpitations, vividly illustrate the existence of vestibulo-autonomic projections. Recent questions include a possible connection between vestibular disorders, anxiety and autonomic symptoms, and putative neuro-anatomical sites capable of mediating a vestibulo-autonomic interaction. Specifically, the parabrachial nucleus, in connection with limbic areas, appears to be ideally placed to mediate vestibular influences on the level of anxiety, as this nucleus is involved in vestibular, autonomic and neuro-behavioral processes [3]. Attention has also been drawn to the possibility that some ill-defined symptoms in chronic vestibular lesion patients, such as orthostatic intolerance or lightheadedness, may represent disordered vestibular-autonomic control [10]. Thus, there are many reasons why diagnosis and management of vestibular patients would improve if we understood human vestibular-autonomic control better than we do at present. There are, however, many obstacles to overcome; these challenges will be discussed below, but first, insights into vestibulo-autonomic interactions gained through studies in humans during the last 15 years will be presented.

3.1. Vestibulo-respiratory interactions

The respiratory system is a good candidate through which to study the complex vestibular-anxiety-autonomic interrelations. Patients with panic disorder hyperventilate and this makes them dizzy. The reciprocal also appears to be true, in that vestibular patients often hyperventilate and feel ‘panicky’. The latter is often observed during caloric vestibular testing, and many patients cannot complete their vestibular tests due to anxiety-panic symptoms. As a starting point we have examined two questions:

1) Does hyperventilation affect balance and if so, how?
2) Does vestibular input affect breathing?

In order to investigate whether hyperventilation affects balance, Sakellari and Bronstein [41] asked subjects to overbreathe voluntarily for specified lengths of time and then to stop. At this point, i.e. during the subsequent phase of normal breathing or hypopnoea but with subjects still in hypocapnia, different variables were measured. It was found that normal subjects become posturally unstable, with large amplitude and low frequency body sway movements. Patients with bilateral severe loss of peripheral vestibular function (‘labyrinthine defective subjects’ or LDS) became equally unstable during hyperventilation, suggesting that the unsteadiness was more likely to be mediated by non-vestibular than by direct vestibular mechanisms [41]. Additional experiments, for instance measuring click-elicited, vestibular-evoked myogenic potentials that remained unchanged after hyperventilation, confirmed this view [42]. Thus, hyperventilation mostly interferes with somatosensory mechanisms and central processes mediating vestibular compensation [42].

These experimental observations carry some implications for clinical practice. Therapists need to be vigilant of patients developing hyperventilation during rehabilitation since this, as discussed above, interferes with vestibular compensation. Should hyperventilation occur, compensatory breathing exercises should be prescribed. Another point concerns the diagnosis of dizziness due to hyperventilation. Many physicians, in the absence of clinical findings in a dizzy patient, ask the patient to hyperventilate in order to see if this induces dizziness or reproduces the patient’s symptoms. It is our advice that physicians should not rely excessively on the voluntary hyperventilation test for diagnosis of hyperventilation-related dizziness. After all, voluntary hyperventilation induces dizziness and objective loss of balance in all individuals as well as nystagmus in patients with a pre-existing vestibular abnormality [26, 42].

The question of whether vestibular stimulation influences breathing has been examined with the use of caloric and rotational stimuli. A general problem in this area of research is determining how much of an observed effect is actually vestibular in origin, although this can be partly overcome by incorporating LDS as controls. Both caloric [17] and rotational stimuli [15, 46] induce a slight increase in respiratory frequency that is not detected in LDS. The findings could indicate that the vestibular organs, as specialized motion transducers, synchronise or ‘entrain’ body musculature, including respiratory muscles, to similar frequencies as the ongoing movement [46]. More generally, body movements, particularly active movements, are likely to increase oxygen consumption, and the vestibular system could provide an early signal to the CNS to increase ventilation accordingly.

An important clinical implication is that these findings provide the physiological basis for ‘vestibular induced’ panic attacks, in which respiratory symptoms and hyperventilation can feature prominently. Indeed, vestibular patients reporting respiratory-autonomic symptoms do exhibit increased heart and respiration rate during head movements [52]. Physicians need to be aware that panic symptoms preceded by ‘true’ rotational vertigo may indicate an underlying vestibular disorder as a trigger for the panic episode. Similarly, evidence suggests that patients with vestibular lesions may suffer from a form of ‘vestibulo-respiratory ataxia’ (M.A. Gresty, personal communication) due to disruption of the vestibulo-respiratory drive. Although this is somewhat speculative and no clear definition of this putative syndrome yet exists, physical therapists need to be vigilant and, if in doubt, include breathing retraining during vestibular exercises.

### 3.2. Vestibulo-cardiovascular interactions

An important aspect of the experiments mentioned in the previous section was the demonstration that some vestibular-cardiovascular effects are secondary to primary vestibulo-respiratory effects. For instance, caloric irrigation [17] induced an increase in the high frequency (0.15–0.40 Hz) component of heart rate variability. This response, however, was only present if subjects breathed freely and disappeared if respiration was synchronized with a metronome. In this circumstance, changes in heart rate and blood pressure variability were apparently secondary to a caloric-elicited increase in respiration frequency. We will now review the evidence suggesting the presence of direct, non-respiratory mediated, vestibulo-cardiovascular responses in humans.

In experiments with subjects seated on a linear sled, facing the direction of motion, Yates et al. [54] observed an increase in blood pressure and heart rate soon after the onset of acceleration. The response occurred instantaneously, sometimes within one heartbeat, which is too rapid to be secondary to breathing changes (see Fig. 5). This rapid effect was not observed in LDS. In order to more precisely determine the latency between head acceleration and cardiovascular responses,
Radtke et al. [35] devised an experiment in which the stimulus (head acceleration) was triggered by the R-spike of the subject’s electrocardiogram (ECG). The experimental design, illustrated in Fig. 6, employed the ‘head drop’ paradigm, in which the head is suddenly released into free fall. From previous experiments it was known that this sudden head acceleration, which stimulates both semicircular canals and otolith organs, is capable of activating short latency vestibulo-spinal mechanisms in normal subjects but not in LDS [14,31]. Head drops reduced the interval between the triggering R-wave and the next R-wave; by varying the delay between the R-wave and the head drop, the latency of the vestibulo-cardiac reflex was estimated to be approximately 500 ms. The early modulation of heart rate was not consistently observed in LDS, confirming the view that vestibular inputs contribute to generating a fast cardiac response to rapid head-body reorientations. Changes in blood pressure and peripheral blood flow were observed 2–3 heartbeats later both in normal and LD subjects [36], indicating that non-vestibular signals contributed to producing these cardiovascular responses.

Other researchers have investigated the influence of vestibular activation on muscular sympathetic nerve activity (MSNA) in the lower limbs by performing microneurography. Caloric irrigation of the ear increases MSNA in a manner that is proportional to the intensity of the vestibular stimulus and the resulting nystagmus [8]. Otolith activation also increases MSNA, and this has been demonstrated with two techniques. The first method is by inverting the normal upright position of the head, achieved by having subjects supine and then flexing their neck such that the top of the head points down to the ground (referred to as ‘head down rotation’ (HDR) by the authors of the study) [13,37,38]. Recordings were performed when the head position was stable, however, and not during the dynamic component of the rotation that also activated semicircular canals. The increase in MSNA elicited by this maneuver was observed consistently, but two problems remain with these data: a) it is not known whether the findings were the result of selective activation of vestibular endorgans, as LDS have never been tested and b) the functional significance of such an otolith-sympathetic reflex is unclear. An increase in peripheral arterial vasoconstriction, presumably leading to an increase in cerebral blood flow, would not appear to be necessary when the head is upside-down. In spite of these caveats the findings are of potential clinical relevance, as dysfunction in this reflex may partly explain orthostatic intolerance in vestibular patients or the elderly [29].

Kaufmann et al. [21] studied the otolith-sympathetic reflex by measuring MSNA during off-vertical axis rotation (OVAR). The authors were able to estimate that the delay or latency at which this mechanism operates, particularly during the nose-up phase of rotation, is approximately 400 ms. This latency is compatible with that determined by the experiments of Yates et al. [54] and Radtke et al. [35,36] during forward acceleration and ‘head drop’, respectively. Here again, however, the fact that LDS were not studied does not allow one to be confident as to whether the findings observed during OVAR were the result of stimulating vestibular receptors or other graviceptors such as visceral receptors [27,28].

4. Recovery from the effects of vestibular system dysfunction on autonomic regulation in patients

A considerable obstacle in understanding vestibular-autonomic control in humans is posed by the rapid development of vestibular compensation after acute peripheral lesions. A recent clinical study by Jauregui-Renaud et al. [16] illustrates this point. In this study, a battery of simple clinical tests of autonomic cardiovascular control was applied to a group of patients with acute vertigo due to unilateral vestibular neuritis. These tests occurred within 48 hrs of vertigo onset, and a complete semicircular canal paresis was documented in all cases. In the acute stage there was evidence of reduced
Fig. 6. Design of an experiment to determine the latency of vestibulo-cardiovascular influences in human subjects. Tests were done with subjects in a supine position with the head suspended 10 cm above a cushion in a sling with an electromechanical release. Release of the head was triggered at a predetermined delay after an R-spike of an ECG and resulted in an abrupt acceleration (about 0.8 g for about 140 ms) as the head returned to its normal alignment from a flexed posture with little neck extension. The latency of the effect of vestibular stimulation on the cardiac cycle length was estimated by considering the delays in the stimulus (time interval between a triggering R-spike and onset of the head drop) and the changes in the R–R interval.

Fig. 7. Mean and standard deviation of the systolic blood pressure response to immersion of the hand in cold water (cold hand test) of 7 patients with vestibular neuritis and 7 age-matched healthy subjects. Patients were tested near the onset of vertigo (acute phase of their vestibular dysfunction) and at a two-week follow up. Courtesy of K. Jauregui-Renaud, adapted from reference [16].

Since the discovery of vestibular vascular sympathetic reactivity during orthostatic challenges and during immersion of the hand in cold water, but these abnormalities had dissipated when tests were conducted again two weeks later (see Fig. 7). A potentially important clinical implication of this study [16] is that dosages of vasoactive medications, e.g. antihypertensive drugs, may have to be reduced during the acute phase of an acute vestibular episode as patients may be prone to suffer orthostatic hypotension.

Whether these findings indicate a specific dysfunction of vestibulo-sympathetic mechanisms, or whether they just reflect a generalized loss of sympathetic reactivity during acute, distressing symptoms, needs further investigation. However, the fact that recovery of vestibulo-ocular and vestibulo-postural responses occurred over a similar time course as which deficiencies in autonomic responses resolved suggests that a common mechanism is involved [16]. Yet, little is known about the mechanisms responsible for potential recovery of autonomic responses following disease or damage of the vestibular system in humans. On the basis of animal experiments [12], however, the cerebellar uvula and parafloccular region appear to be good candidates for mediating central vestibular-autonomic compensation. It is therefore interesting to note that these cerebellar areas have been identified as possible sites for vestibular processing underlying motion sickness [5].

As briefly discussed above, a major limitation of most studies of vestibulo-autonomic control is the fact that they were conducted in chronic, usually well-compensated, patients. According to the animal experiment literature (see Section 2 above) and the only study in acute human patients [16], the process of compensation for vestibulo-autonomic dysfunction is rapid and effective. Studies in patients with acute bilateral vestibular disorders, e.g. subsequent to ototoxicity or meningitis, would be particularly useful although most of these patients are too ill to undergo research experiments. Due to this limitation, we do not as yet know the magnitude of the contribution of the vestibular system to cardio-respiratory control in man. The experiments performed so far suggest that the contribution is small and variable but, as mentioned, this may be due to compensation processes. In contrast, vestibular input into gastric motility [24] and nausea mechanisms seems large and, according to patients’ reports, clinically relevant. However, apart from a consideration of motion sickness, little research effort has been devoted to this potentially important area.
5. Summary and conclusions

Vestibular system lesions produce a number of deleterious effects, including a disruption in the ability to rapidly adjust blood pressure and respiratory muscle activity during movement and changes in posture. Following damage to the labyrinth or VIIIth cranial nerves, these deficits resolved over time. However, it should be noted that the testing conditions employed in the studies that produced these observations were somewhat artificial. It is probable that the animal and human subjects expected to undergo experimental procedures, and were particularly vigilant during data collection sessions. It is unlikely that such a high level of attention to environmental cues regarding body position in space was maintained outside of laboratory conditions. Thus, peripheral vestibular dysfunction could result in long-lasting deficits in correcting blood pressure that only become apparent when the level of alertness diminishes. Further experiments will be required to examine this possibility. Central vestibular system lesions can also elicit pronounced and prolonged dysfunction of autonomic responses that are required during changes in posture. Studying animals with such disturbances in cardiovascular and respiratory regulation has provided insights regarding the process of sensory integration within the vestibular nuclei, and has led to the conclusion that under some conditions nonlabyrinthine signals are substitutted for labyrinthine inputs. However, the cellular and molecular basis of this adaptive plasticity is not currently known, and additional experiments will be needed to provide these data. Furthermore, studies of patients in the acute phase of recovery from vestibular dysfunction, particularly those with bilateral loss of labyrinthine inputs, should provide valuable information regarding the processes involved with compensation.

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