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Short- and Long-term Modifications of Vestibulo-ocular Response Dynamics Following Unilateral Vestibular Nerve Lesions in the Cat*

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Summary. The dynamics of the horizontal vestibuloocular reflex (VOR) were determined in the dark prior to and at various time periods after unilateral removal of the vestibular nerve. One chronic group, consisting of cats that were operated at the age of 6 weeks or as adults, was studied 10.5 to 22 months later; an adult-operated group was measured 1–244 days postoperatively (p.o.). Between measurements cats were kept in a normal environment.

In control animals the VOR gain was close to unity only up to certain stimulus velocities which varied amongst cats; thereafter a sharp drop in gain occurred probably due to saturation of central and peripheral neuronal responses. Therefore, VOR gains in lesioned animals were compared to the control responses yielding high gain. It is only at these small stimulus amplitudes that the two labyrinths maximally interact and, therefore, one would expect the largest changes. The gain was computed after correction for the ocular imbalance induced by the lesion. Immediately after the lesion a drop in gain to stimulations in both directions was noted; the reduction was larger for the VOR evoked on rotation to the lesioned side. Contrary to control animals, no partial response saturation occurred in lesioned animals but, following rotation to the lesioned side, complete saturation was noted with larger stimuli. Ocular balance was greatly improved within the first 3–4 days p.o. as indicated by the strong reduction of nystagmus.

The time course of p.o. adaptive gain changes could be divided into three stages: in the initial stage (1–5 days p.o.) no improvement was visible; between p.o. days 5–10 one group of cats showed an abrupt increase in gain while it remained low in others. Response symmetry showed no consistent change in either group; the 3rd stage starting p.o. day 10 and extending throughout the observation period (22 months) is characterized by slowly developing changes reducing significantly response asymmetry. The incremental gain was higher in the young than in the adult-operated chronic cats.

Compared to controls the phase plot of the VOR of lesioned animals shows a parallel shift of ca. 10° towards larger lead over the frequency range tested (0.05–1.0 Hz) independent of direction of rotation or p.o. stages.

All lesioned animals showed a clear failure to hold eye position in the dark even in the chronic stage; a drift with an exponentially decreasing velocity of ca. 2–4°/s was typical. The direction of the drift could be to the lesioned as well as to the intact side. The eyes seem to approach a new null point which is shifted towards the lesioned side.

In conclusion on data show that while ocular balance recovers quite well and fast after unilateral lesions the VOR dynamics show some adaptive plasticity but also significant long-term deficits when measured in the dark and with the head fixed. Obviously, the striking recovery observed in the freely moving animal must be aided by other sensory systems.

Key words: Vestibuloocular reflex – Functional recovery – Vestibular nerve lesion – Nystagmus

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Introduction

Since the early work of Bechterew (1883), it has been known that the removal of one labyrinth presents a

challenge to the adaptive capacity of the central nervous system to restore function. Adaptive processes have to deal with two distinct although not independent aspects of the lesion-evoked functional deficits. Firstly, the symmetrical tonic influence exerted by the labyrinths on posture at rest is altered by the unilateral withdrawal of the resting activity of vestibular nerve fibers. This results in a strong imbalance of the output of vestibular nuclei, since the resting discharge on the lesioned side is greatly reduced (Gernandt and Thulin 1952; Trincker 1965; Shimazu and Precht 1966), while that on the intact side is considerably higher than normal, due to the removal of inhibition from the contralateral side (Shimazu and Precht 1966; Markham et al. 1977). This imbalance causes a "vestibular syndrome", basically identical in all vertebrates, consisting of a severe postural asymmetry and strong eye and head nystagmus (for ref. see Schaefer and Meyer 1974). A remarkable recovery from these deficits has been described for all species studied, although differences in time course and degree of recovery were noted.

Secondly, hemilabyrinthectomy abolishes the interaction between the two labyrinths in dynamic vestibular reflex performance, causing disturbance of response gain and symmetry. While most of the previous studies predominantly dealt with the compensation of the static imbalance of eye and head, i.e. balance control (Haddad et al. 1977), (for ref. see Schaefer and Meyer 1974; and more recently Llinas et al. 1975; Haddad et al. 1977; Robles and Anderson 1978; Jensen 1979; Petrosini and Troiani 1979; Flohr et al. 1981), little attention has been paid to the possible persistence of alterations of the dynamic vestibular reflexes. Dynamic reflex disturbances, e.g. of the vestibulo-ocular reflex (VOR), have generally been measured as the "directional predominance" of the rotational nystagmus, that is large immediately after the lesion and disappears with time (Ruttin 1926; Fluur 1960; Precht et al. 1966). An increased threshold for the elicitation of nystagmus on rotation to the lesioned side was also noted (Mittermaier 1950).

In the last decade our understanding of the normal VOR has much improved and its plastic-adaptive capacities in altered visual conditions have been documented (cf. ref. Miles and Lisberger 1981). In view of this progress it is tempting to study the VOR gain control in the unilateral vestibular lesion model more quantitatively.

Recently, a few studies have been published dealing with the VOR compensation after hemilabyrinthectomy, but they are to some extent contradictory and fragmentary. About two months after the lesion a basically complete recovery of VOR gain and phase has been reported in the cat (Courjon et al. 1977, 1982). This is in contrast with previous work showing an asymmetrical phase lead in response to low frequency sinusoidal stimuli (Moran 1974). Moreover in the rabbit (Baarsma and Collewijn 1975) and in the monkey (Wolfe and Kos 1977) lower gain and increased phase lead were shown long after hemilabyrinthectomy. Similar findings have been described in man (Wolfe et al. 1978).

The purpose of the present experiments was to study in the cat to what extent the vestibular gain control system is able to repair the defects of VOR gain and symmetry produced by unilateral section of the VIIIth nerve. To this aim, the horizontal VOR in response to velocity steps or sinusoidal rotation was measured before and at various times after the lesion in complete darkness. Between measurements animals were kept in a normally lit environment. Furthermore, we have compared the compensatory changes in the VOR occurring in cats lesioned as kittens with respect to others operated as adults. Some of the results have been already published in a preliminary form (Precht et al. 1981).

Methods

Animal Preparation and Surgical Procedure

In this study fourteen cats of both sexes were divided in two groups. The first group consisted of eight adult animals, in which the VOR was measured before and at various times (1–244 days) after unilateral vestibular neurotomy to follow the recovery course. The second group (six animals) was used to study the long-term adaptive changes occurring in the vestibuloocular system following the lesion. To this aim they underwent a unilateral lesion and were allowed to recover for 10.5–22 months before the first VOR recording was taken. Two of these cats were operated as adults (recovery time 10.5 and 15 months) and four at the age of 6 weeks (recovery time 18–22 months). After the lesion the cats were allowed to move freely in very large cages, where they could run and jump between shelves hanging from the walls. Moreover, they were kept together in groups to enhance locomotion.

All animals were lesioned on the right side. The operation was performed under Nembutal anaesthesia (35 mg/kg i.p.) and aseptic conditions, except when the VOR had to be tested the following day: In these cases an intravenous injection of Ketalar (20 mg/kg) was employed. The bulla tympanica was exposed through a ventral approach, the vestibulum opened and the membraneous labyrinth removed. The ganglion Scarpae was then destroyed by electrocauterization leaving only the short proximal stump of the VIIIth nerve in the internal acoustic meatus. Postoperatively, intramuscularly injected Penicillin was used to prevent infection. Horizontal eye movements were recorded by silver-silver chloride electro-oculogram (EOG) electrodes (Bond and Ho 1970) chronically implanted in the bone at both outer canthi of the eyes. A third indifferent electrode was implanted in the posterior part of the frontal sinus at the midline. A dental acrylic fixation device was mounted on the head. In the first group (see above), cats were prepared for control EOG recordings before the lesion; in the

second group the operation was made 3–4 days before the first recording session.

Eye Movement Recording and Calibration

During recording sessions the animals were placed in a loose restraining box, with the head securely fixed to a framework mounted on the box. Amphetamine sulfate (0.5 mg/kg) was given to keep the cat alert. The EOG signal was amplified by a DC differential amplifier and differentiated to obtain eye velocity. Eye position, eye velocity and table position or velocity were then simultaneously displayed on paper (Brush-Gould recorder). EOG measurements were calibrated by assuming that the compensatory eye movements in a normal animal following oscillations at moderate velocity in the light in front of a patterned surround had a unitary gain. This assumption is supported also by the fact that in these conditions only little or no improvement is observed with respect to responses obtained in the dark with a similar type of stimulation, in spite of the fact that the optokinetic reflex is still in its working range. Typically, stimulation frequencies of 0.1–0.25 Hz with peak velocity not exceeding 20–30°/s were used for calibration. An independent calibration was also obtained in each cat by rotating the animal at a constant velocity of 10°/s in front of a contrast rich surround. The assumption was made that the velocity of steady state optokinetic slow-phase eye velocity was equal to visual background velocity. The two methods of calibration gave in all cases similar results. Moreover, with this calibration obtained in the light, great care was taken not to test the animal in the dark for periods longer than a few minutes. After almost every trial light was switched on for a while or stimuli in the light and in the dark were alternated.

Stability of the EOG electrodes over long periods of time is of great importance in order to use the calibration of the control also for the data recorded during the recovery. A very good stability of this type of electrodes over a period of 6 months has been already reported (Bond and Ho 1970). Furthermore, several months after hemilabyrinthectomy the eye responses following very low peak velocity sinusoidal stimulation at 0.1–0.25 Hz in the light had amplitudes very close to the control values. The fact that the responses so elicited showed a remarkable degree of regularity, a virtually perfect phase match with the stimulus, and a gain very close to that observed during pure constant velocity optokinetic stimulation at 10°/s, makes it reasonable to assume that such responses are in the chronic animal also fully compensatory and that the calibration did not undergo major changes compared to the control. In the second group of chronic animals the calibration was obtained using very low velocity sinusoidal oscillations in the light (0.1–0.25 Hz). In these conditions the gain is presumably close to one, particularly when one considers the responses during rotation to the intact side. This assumption was based on several considerations: firstly, this was observed to be the case in the first group of animals after a similar or shorter recovery time; secondly, basically no difference was present between responses obtained with low velocity pure optokinetic stimuli and with sinusoidal oscillations in the light at the same peak velocity, when the nystagmic slow phase was directed towards the lesioned side. This indicates a good match between eye and visual world velocities, since adding of the VOR did not elicit larger responses. Furthermore, it has been shown that OKN beating to the intact side (slow phases towards the lesioned side) is only very little and transiently affected by hemilabyrinthectomy (Maioli et al. 1982), i.e. its gain is very close to one with low velocity stimuli; thirdly, responses showed a remarkable degree of regularity and a very good phase match with the stimulus, i.e. they were clearly more compensatory than with pure vestibular stimulation. We trust that this calibration method, even if not giving absolutely precise measurements allowed us to have a very reliable reference point to compare the VOR performance at different stages of compensation.

Stimulation

The cats were tested on a Toennies turntable with their heads directly over the vertical axis of the table. Two kinds of stimuli were used: (1) Sinusoidal oscillations at frequencies from 0.05–1 Hz and amplitudes from 5–65°/s. Only towards the end of this study a more powerful turntable was available, with which velocities of up to 160°/s could be reached; (2) velocity step stimuli: the table was rotated with a constant acceleration of 100°/s^2 up to final velocity (20–160°/s). This velocity was then maintained constant for some 20–30 s and followed by a deceleration (100°/s^2) to zero velocity. The longest acceleration and deceleration times never exceeded 1.6 s, i.e. were far below the slow time constant of the canals in the cat (4 s) (Blanks et al. 1975). Between trials enough time was allowed to ascertain that effects from the preceding stimulus had subsided.

Data Analysis

Since the necessity to use a computer for the analysis of the sinusoidal data was realized later in the course of the present study when a large part of data was already collected, data recorded on paper were converted into digital form through an X-Y graphics table (Tektronix 4953). Data so obtained could then be stored by the computer (PDP 11/20). To this end we carefully traced with the pen the eye velocity signal, from which we extracted only the part related to the sinusoidally modulated slow phases of the nystagmus, omitting all the high velocity spikes related to the fast phases. So the obtained digital sample consisted of a series of segments relative to the slow phases, separated by empty gaps corresponding to the quick phases. This procedure, although cumbersome, allowed filtering of the fast phases, since in our frequency range it was relatively easy to determine their onset and end by looking at the eye velocity profile. Furthermore, only cycles free of evident distortions or artifacts were used so that we obtained a clean slow phase velocity signal. Several cycles were chosen for every trial at a given frequency and amplitude and fitted with the best sine according to the least mean square method. The function used for the fitting was:

$$Y = A \sin(\omega t + \Phi) + K$$

were the parameters to be found are A (amplitude), Φ (phase shift) and K (constant). The fitting of K, i.e. the DC offset caused by the spontaneous nystagmus, when present, is an important feature of our analysis method. In fact, it is almost impossible to determine a priori the value of the baseline DC displacement, either because the spontaneous nystagmus velocity is often different before and after the oscillation period, or because the stimulation by itself may alter the imbalance e.g. between the two vestibular nuclei responsible for this offset (see Results). Unfortunately, in the lesioned animals the VOR asymmetry and the distortion during rotation to the lesioned side in the presence of spontaneous nystagmus (see Results) make a simple sine wave fitting absolutely inadequate. To detect an asymmetry in the responses, the two half cycles have to be fitted separately. This is achieved by computing the best parameters which match an interval of $\pm 80°$ around the positive or negative peak eye velocity. As an indication of the validity of this procedure it was shown that in a normal animal the parameters computed from all the points or from only one hemicycle were found to be basically the same. Furthermore,

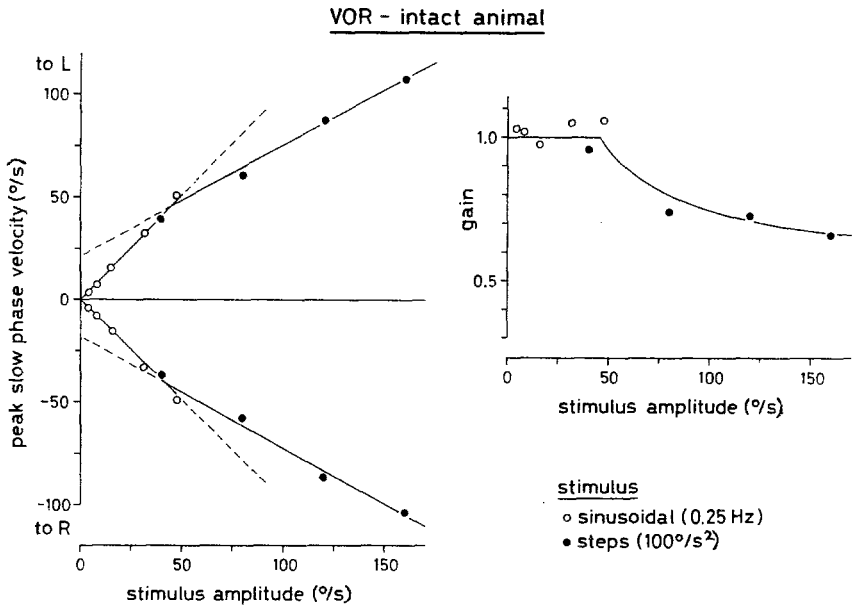

Fig. 1. VOR response amplitude in a normal cat. Left graph: relation between VOR peak slow phase velocity and stimulus amplitude. Both sinusoidal oscillations (0.25 Hz; circles) and velocity steps (*dots*) of different amplitudes were used. Right graph: same data as in left graph plotted differently to show the absolute gain drop occurring after the saturation point. The actual data match very closely the theoretical curve predicting the absolute VOR gain, assuming a gain of 1 up to 45°/s and afterwards an incremental gain of 0.54

standard errors of the parameters and statistical tests were furnished by the program.

The VOR responses to velocity step stimuli were analysed by hand. Only peak slow phase velocity was determined. It was computed by subtracting from the absolute eye velocity the value of the spontaneous nystagmus present before the stimulus onset. It is reasonable to assume that the time between the stimulus onset and the maximum eye velocity is too short to have any significant effect on the imbalance in vestibular nuclei.

Finally, two parameters were used in order to quantify VOR amplitude: the absolute gain defined as the ratio between maximum slow phase velocity ($\dot{e}$) and maximum stimulus velocity ($\dot{s}$), and, as responses were not linear over the whole range, the incremental gain defined as the ratio between the increment of the response amplitude and the corresponding increase of stimulus strength that elicited it, i.e. $\Delta\dot{e} / \Delta\dot{s}$.

Results

VOR Gain in Control Animals

It has been shown that the horizontal VOR is a linear system, at least within a certain range (Carpenter 1972; Landers and Taylor 1975; Donaghy 1980; Robinson 1976). This means that gain/phase are independent of amplitude at a given frequency. It is also well known that the canal system works in a push-pull fashion, i.e. the eye movements generated by head displacements depend on the reciprocal interaction of the two labyrinths. Whenever one canal is excited, the coplanar canal is disfacilitated. Since the magnitude of disfacilitation depends on the level of resting rate, we expect that by increasing the stimulus strength some saturation will occur.

To verify this assumption, we measured the VOR in cats before the lesion in response to velocity steps and sinusoidal stimuli. For a given stimulus amplitude the gain of the response (the ratio between peak nystagmic slow phase velocity and stimulus velocity) was the same for both stimulation types, as one would expect if the system were linear. This indicates that even with step stimuli the maximum slow phase velocity is proportional to the head velocity, provided the acceleration pulse does not last too long (in our cases < 1.6 s). The reason to pool together the data from the two types of stimuli was that it was by far easier to measure responses to sinusoids when small amplitude stimuli were used. On the other hand strong stimuli were easier to obtain with steps. A good matching between VOR gain measured with step and sinusoidal stimuli has been described also by Robinson (1976).

Figure 1 shows an example of VOR responses recorded from one animal. It turns out clearly that eye velocity can match the stimulus velocity with a gain close to unity up to 50°/s. Further increase in stimulus amplitude still elicits linearly related responses, but with a much lower slope. In this particular example the superimposition of trials with both types of stimulation at the same stimulus amplitude is not shown. However, such an overlap was a consistent finding in all animals. So we can divide the VOR responses in two ranges, characterized by a different "incremental gain", i.e. the ratio between the variation of response amplitude and the increase of the stimulus strength that elicited it. In Fig. 1 the incremental gain, computed as the slope of the best line fitting the data, above 50°/s is 0.54. With stimulus velocities below 50°/s, the system behaves linearly at all frequencies tested (0.05–1.0

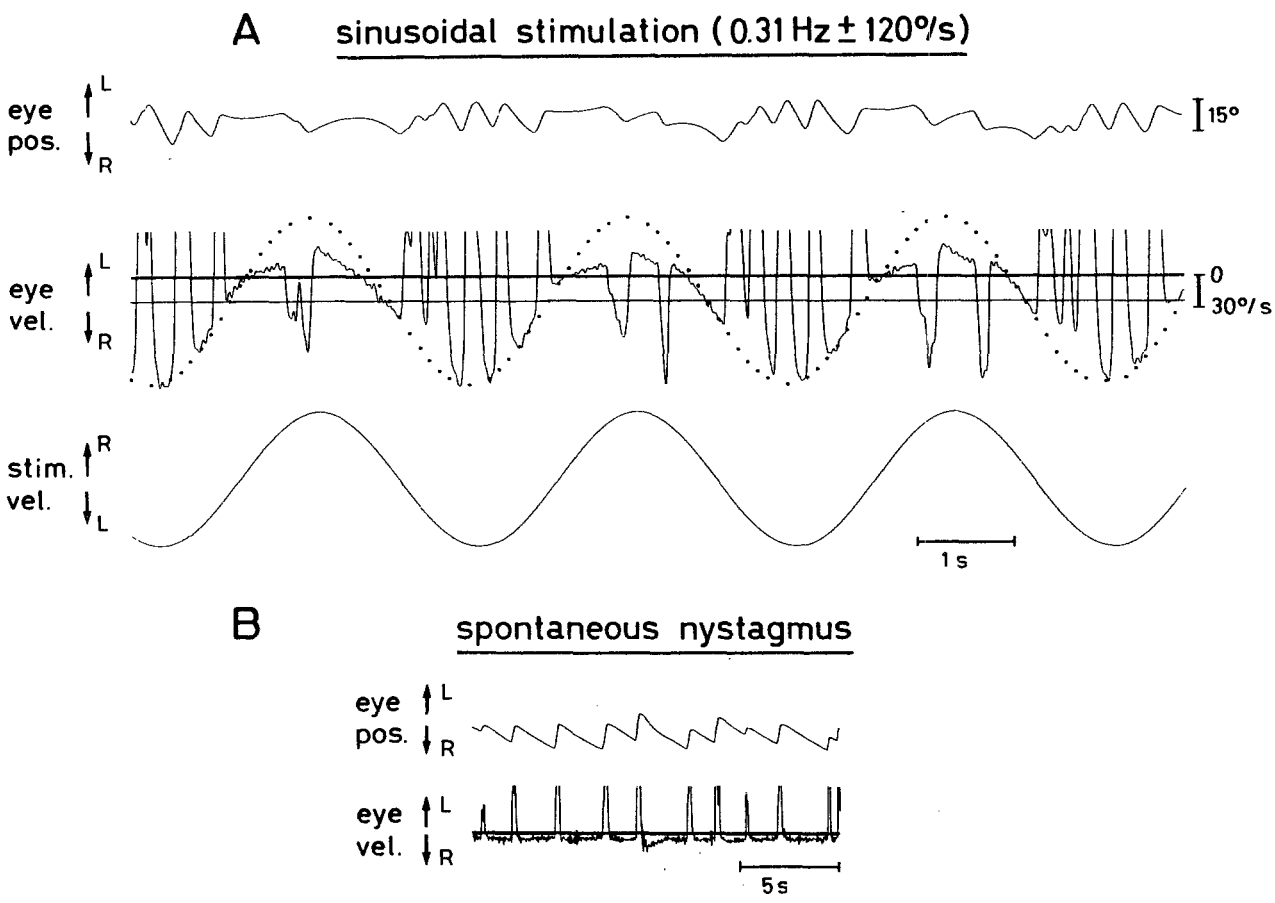

Fig. 2A, B. Actual eye movements recorded 5 days after right labyrinthectomy. **A** Response to sinusoidal oscillation at 0.31 Hz ± 120°/s. In the middle trace eye velocity is plotted together with the sinusoid (*dotted line*) better fitting the hemicycle of the nystagmic slow phase velocity profile relative to rotation towards the intact side. This sine closely matches the slow phase eye velocity also when the animal is rotated towards the opposite direction, but only up to the zero crossing level (*thick line*). Then a flattening of the response is evident. The *thin line* represents the DC shift computed with the fitting procedure (23°/s). **B** Spontaneous nystagmus recorded from the same animal. Note that the slow phase velocity of the spontaneous nystagmus is much lower than the computed DC shift during stimulation

Hz). Above 50°/s the partial saturation leads to a progressive decrease of the absolute gain (Fig. 1). The actual data match very closely the theoretical curve predicting the absolute VOR gain, assuming a gain of 1 up to 45°/s and afterwards an "incremental gain" of 0.54.

In a population of eight control cats, the following observations were made: (1) A high degree of symmetry is present both for the non-saturating and for the saturating responses. (2) Prior to the partial saturating point the gain is close to unity (mean = 0.93; SD = 0.08) and does not change with amplitude or frequency of stimulation in the tested range (0.05–1.0 Hz). (3) The incremental gain after the partial saturation point varies from animal to animal; in the four cats in whom stimuli strong enough for its computation were used, the values were 0.47, 0.54, 0.63 and 0.76. (4) The partial saturation point also varied among the five animals in whom it could be measured (15, 20, 35, 45 and 55°/s). In the other three cats stimulation up to 55, 70 and 80°/s did not show any sign of saturation. (5) In none of the cats complete saturation was reached, at least not up to a stimulus velocity of 160°/s.

From these control measurements it appears clear that stimuli of small amplitude have to be used to study the effects of removal of one labyrinth, because it is only at these small amplitudes that the two labyrinths maximally interact, and therefore, the largest changes may be expected.

VOR Gain in the Acute Postoperative Stage

It is important to assess the impairment of the VOR as soon as possible after the lesion in order to detect early adaptive changes. Such changes are not so unlikely since in the cat spontaneous nystagmus

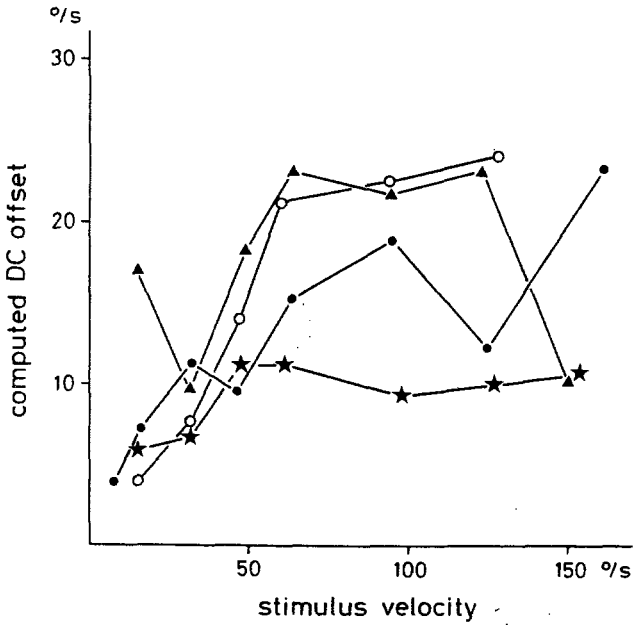

Fig. 3. Computed DC shifts during sinusoidal oscillations versus maximum stimulus velocities at different times after lesion in the same animal shown in Fig. 2. *Circles* = 3 days p.o.; *triangles* = 5 days p.o.; *dots* = 8 days p.o.; *stars* = 23 days p.o. The computed DC level is increasing together with the stimulus intensity up to the attainment of the plateau shortly after the peak stimulus velocity reaches 50°/s. The plateau level decreases with time elapsing after the lesion

largely disappears within the first 3–4 postoperative days (Carpenter et al. 1959; Precht et al. 1966; Haddad et al. 1977; Courjon et al. 1977). The present study largely confirms previous findings concerning the compensation of imbalance: after one week, cats were able to stand and walk even if the gait was still insecure and lateropulsion with occasional falls to the lesioned side was present. Head tilt was still clearly visible. Although the spontaneous nystagmus strongly decreased within the first 3–4 days it must be stressed that nystagmic beats were still observed in chronic states (see later). At the end of the first week gaze stabilization was usually very good in the light, whereas in the dark a drift of 2–10°/s (mean = 5°/s; SD = 2.6) was present.

In the acute stage, the analysis of the VOR is difficult due to presence of the balance impairment. A "directional predominance" in the frequency of beats and slow phase velocity of the elicited nystagmus is clearly visible during sinusoidal rotation (Fig. 2A). But it is difficult to tell to what extent this is due to the spontaneous nystagmus or to a real asymmetry of the VOR. An obvious solution of the problem would be to subtract the spontaneous nystagmus from the actual data. But this procedure presents two main difficulties. Firstly, the spontaneous nystagmus is often different before and after the stimulation. Secondly, the imbalance between the vestibular nuclei may be affected by the stimulus itself during the sinusoidal rotation. Evidence for the last point comes from the analysis of the best sine fitting of the actual data (see Methods). In the eye velocity signal, the imbalance of the vestibulo-ocular system is represented by a DC displacement of the baseline about which the sinusoidal modulation occurs. This DC level can be computed as a parameter fitting the response hemicycle relative to rotation towards the intact side (Fig. 2A, thin line in the eye velocity trace). Interestingly, in some animals the values so found are directly proportional to the stimulation amplitude. Figure 3 shows measurements from a cat in which this behavior is prominent. Stimuli consisted of sinusoidal oscillations at 0.3 Hz of different amplitudes. The computed DC level is increasing together with the stimulation intensity, until turn table peak velocity reaches 50–60°/s. The plateau that follows correlates inversely with the time passed after the lesion. Figure 2A shows an actual record taken from the same animal 5 days after the lesion. At rest the spontaneous nystagmus measures about 6°/s (Fig. 2B), and during oscillation the best sine fitting the slow phase eye velocity trace towards the lesioned side (dotted line) has a DC shift of 23°/s (thin line). Obviously, the above fitting procedure is reliable only if, for the averaging, responses were selected that showed little distortion from a sinusoid (see Methods).

The reliability of this procedure is supported by several observations: firstly, the computed DC offset turns out to be the base line that divides the whole period into two hemicycles of about the same duration. This is not often the case when the spontaneous nystagmus at rest is used as a reference. Secondly, linearity is preserved, i.e. subtracting the computed baseline, the response gain at a given frequency does not change with stimulus amplitude whereas subtracting the spontaneous nystagmus gain increases with larger amplitudes. Thirdly, the response amplitudes so computed overlap very nicely with the values obtained from step stimuli as in normal animals (Fig. 4). To measure the dynamics of the VOR in the acute stage we, therefore, subtracted the DC offset from the recorded absolute eye velocity generated by sinusoidal stimuli.

Up to now we have taken into account only responses to stimuli directed to the intact side. Following rotation to the lesioned side, responses are different depending on whether the stimulus is strong enough to reverse the spontaneous nystagmus or not. The record of Fig. 4 was taken 1 day after the lesion; the slow phase velocity of the spontaneous nystagmus

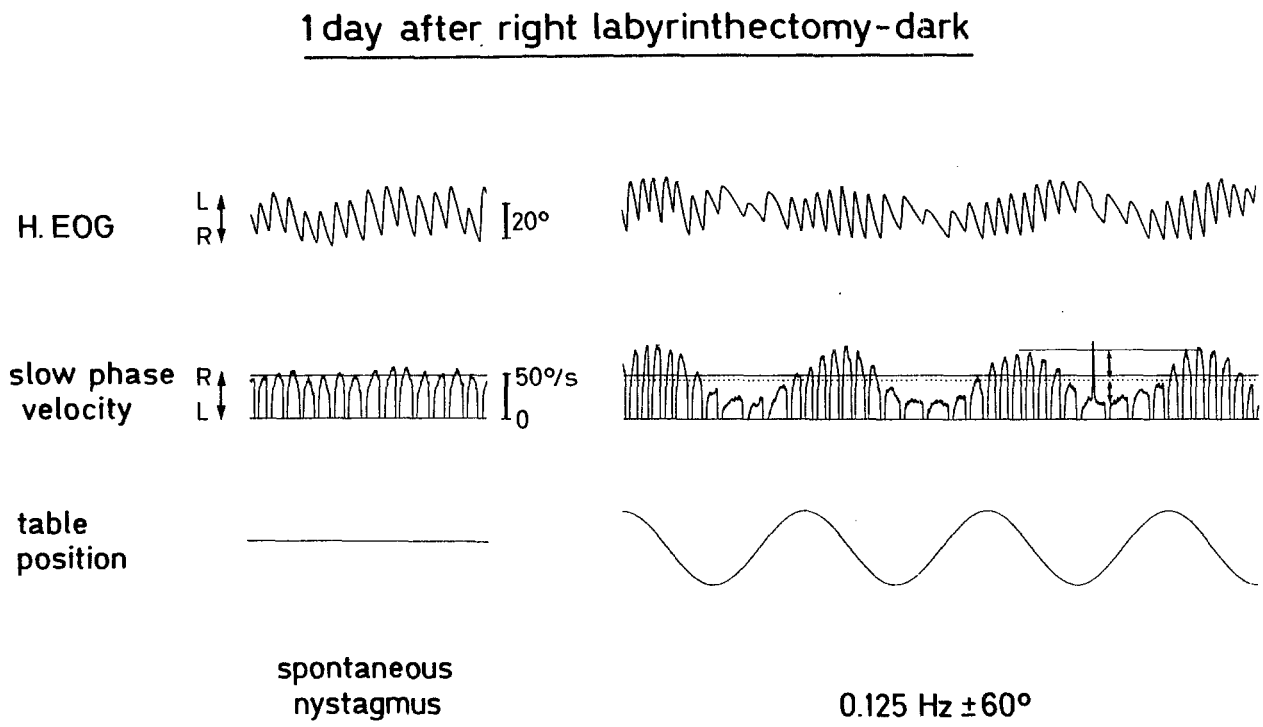

Fig. 4. Spontaneous nystagmus and response to sinusoidal oscillation one day after the lesion. Horizontal eye position, rectified eye velocity, and turntable position are reported. At rest, the slow phase velocity is about 50°/s; the computed DC-shift has a similar value (*dotted line*). The slow phase modulation is roughly symmetrical around the level of the computed DC offset

is sinusoidally modulated but nystagmus is not reversed. Note the small difference between the computed DC offset (dotted line) and the value of the spontaneous nystagmus velocity measured at rest in this very acute stage. The slow phase velocity deflection towards zero (rotation to the lesioned side) is almost as large as the half cycle relative to rotation to the intact side. In other cases, the modulation was often symmetrical around the level of the computed DC offset. Already 1 or 2 days after the lesion a reversal of the spontaneous nystagmus can be obtained by increasing the amplitude of the stimulation. Interestingly, then the gain of the responses to rotation towards the lesioned side becomes lower as shown in Fig. 2A. The dotted line represents the best sine fitted by the computer through the half cycle corresponding to rotation to the intact side. This sine matches closely the eye velocity even during rotation to the opposite direction, but only up to the zero crossing level. Thereafter, a flattening of the response is evident. This non-linearity prohibits a sine fitting of responses obtained by rotation towards the lesioned side.

From the above analysis of the VOR in the acute postoperative stage it appears clear that balance impairment and dynamic responses interact in a quite complex way. To compare the dynamic VOR performance at different levels of vestibular imbalance, we need a parameter which is independent from the intensity of the spontaneous nystagmus. This is particularly true when we want to measure the capacity of the spared labyrinth to drive the eyes to the ipsilateral side through a decrease of its resting discharge, occurring during rotation to the lesioned side. In fact, when the slow phase of the response is in the same direction as that of the spontaneous nystagmus, the VOR gain can be obtained by subtracting the computed DC offset. Because of the described dependence of the absolute gain on the spontaneous nystagmus, with stimuli in the opposite direction this parameter would be affected more by the recovery of balance than by the eventual adaptive changes of the dynamic responses. Thus, to quantify the VOR during rotation to the lesioned side, we considered the "incremental gain" only of the responses to stimuli strong enough to move the eyes in the direction opposite to the slow phase of spontaneous nystagmus. In addition, since the DC offset varied together with the amplitude of sinusoidal stimulation, only step stimuli were used here, both because the spontaneous nystagmus before each trial was found to be pretty constant, and the time between the stimulus onset and the peak slow phase velocity was probably too short to alter the imbalance

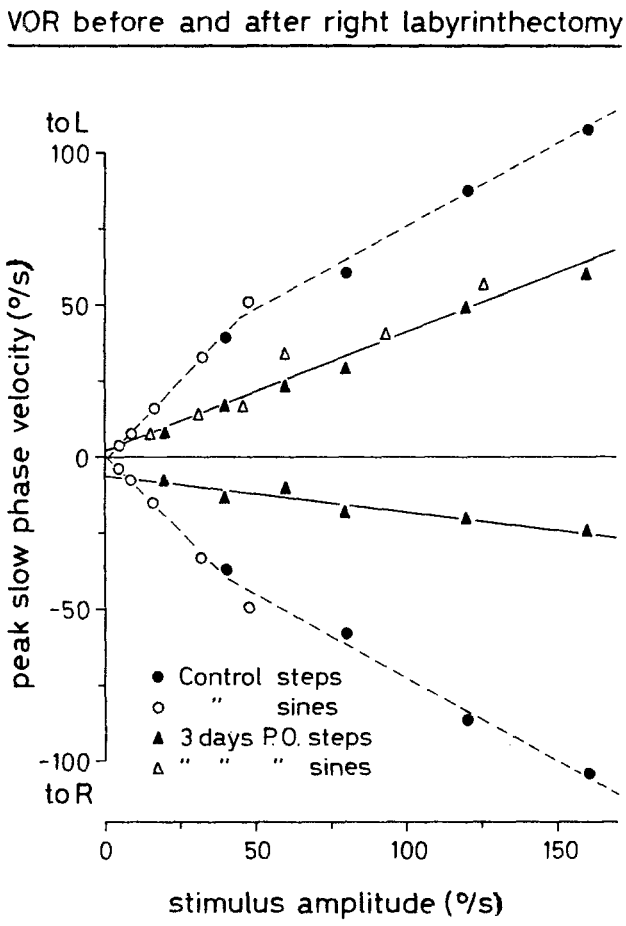

Fig. 5. Representative examples of the VOR changes occurring after right labyrinthectomy. Data were recorded 3 days after the lesion. *Circles* correspond to control data (the same ones shown in Fig. 1); *triangles* indicate the responses in the acute stage. A good match between sines and step data is always present, except acutely after the lesion for stimuli towards the lesioned side because of the described interaction with the spontaneous nystagmus (see text). A gain drop for responses in either direction and a marked asymmetry are the most prominent effects induced by the lesion

between the vestibular nuclei. However, we saw a good overlapping between data obtained with sinusoidal and step stimuli in the cases where the computed DC offset and the spontaneous nystagmus intensity at rest had similar values.

A representative example of the VOR gain measured acutely after lesion is shown in Fig. 5 together with control data. Measurements were taken from the same animal shown in Figs. 1 and 2. The slow phase velocity of the nystagmus at rest and the computed DC offset were subtracted from the absolute values of the responses to step and sinusoidal stimuli, respectively. Thus, the Y-axis intercept of the line fitting the points relative to rotation to the lesioned side reflects the presence of the spontaneous nystagmus. The effects of the lesion on the VOR can be summarized as follows: (1) a drop of VOR gain to stimuli to both directions is present in all animals; (2) the decrease of the incremental gain is larger for stimuli to the lesioned side, resulting in a marked VOR asymmetry; (3) the decrease of the gain following rotation to the intact side is typically ca. 50% or less compared to the gain of the non-saturating responses in the controls. In no case does it exceed the incremental gain of the saturating part of the control curve. (4) No signs of partial saturation, of the kind seen in control animals, are visible during stimulation to both directions. (5) A complete saturation of the responses is present when the animal was rotated towards the lesioned side at sufficiently high velocities. In these cases the slow phase velocity of the elicited nystagmus is never higher than 50–60°/s presumably because vestibular unit activity on the lesioned side is silenced. The stimulation amplitude at which such a saturation occurs depended on the VOR incremental gain for that particular animal.

Time Course of Adaptive Changes of VOR Gain

Before describing the adaptive changes of the VOR, it is worthwhile to briefly comment on the recovery of posture and motor coordination. Both recovered so well that it was difficult to distinguish chronic from intact animals. On close inspection a slight preference to deviate towards the lesioned side when running and a small head tilt were occasionally observed. These signs were, in general, more difficult to detect in the young operated animals. The recovery of vestibuloocular balance control was not complete even more than one year after the lesion. In fact, by recording eye movements in the dark, a drift of 2–4°/s towards the lesioned side was almost always present in our chronic cats (see below). The frequent occurrence of resetting fast saccadic movements often produced a "nystagmic modulation".

Recovery of the dynamic performance of the vestibuloocular system, however, was different. Figure 6 shows the modifications of VOR gain as a function of time after section of the right vestibular nerve in ten adult cats. The post-operative adaptive changes can be divided in three periods. In the first 4–5 days no clear improvement is visible. The VOR gain following rotation to the intact side remains at around 0.4–0.5 with remarkably little scatter of gain among animals. Responses to rotation to the lesioned side show a larger variability, but in all cases the gain is distinctly lower than that for rotation to the intact side. Between 5 and 10 days the experimental data

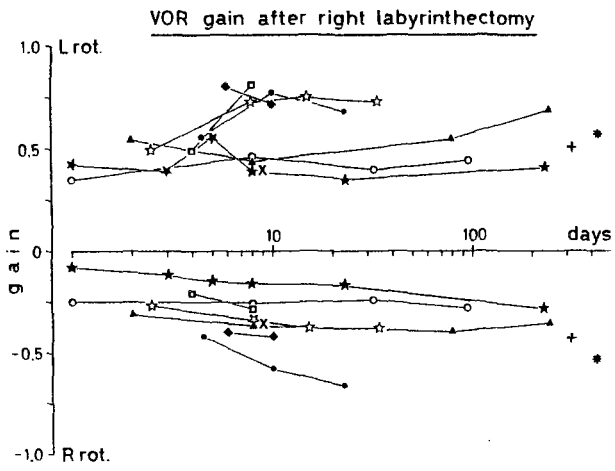

Fig. 6. Time course of VOR incremental gain in ten adult cats that underwent a lesion on the right side. Gain was computed after subtracting from the responses the slow phase velocity of the spontaneous nystagmus (when present). Note the marked VOR asymmetry lasting for many months after the lesion

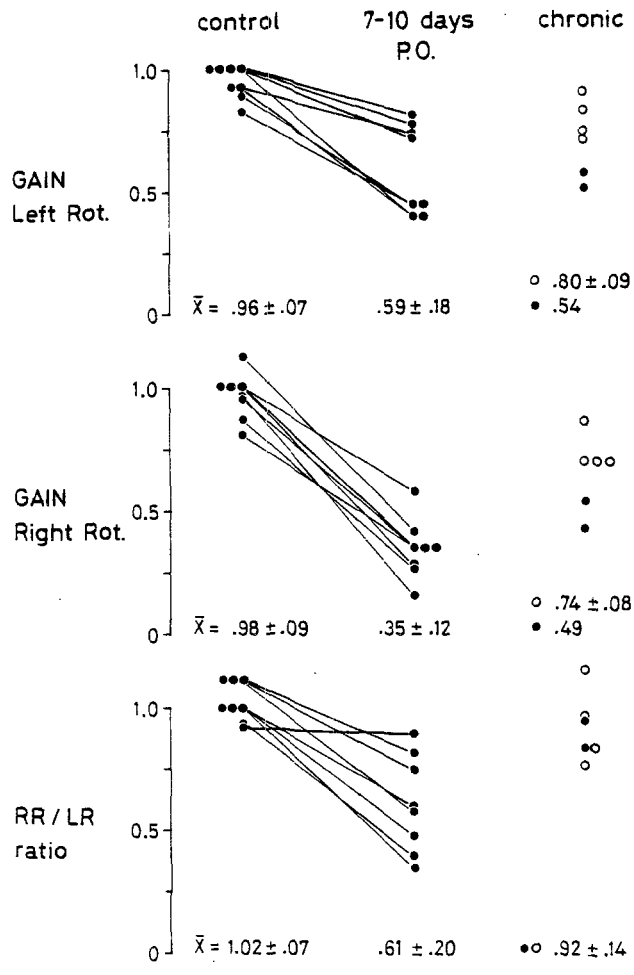

Fig. 7. Comparison between VOR responses recorded in the same group of cats before and 7–10 days after lesion, and in another group of chronic cats (10.5–22 months p.o.). Incremental gain of responses during rotation towards the intact (left) and lesioned (right) side and the ratio between responses to right and leftwards stimuli (symmetry) are shown together with mean values and standard deviations for each group. *Dots* represent adult operated animals, *circles* animals operated at the age of 6 weeks. Note the decrease of all the parameters acutely after the lesion and their partial recovery in the chronic stage. Young operated cats, on the average, compensate better than adult ones

fall into two populations. In one group the gain on stimulation to the intact side increases to ca. 0.75 rather abruptly around day 5, while in the other one it remains low. The ratio between the gain of bilateral responses shows no consistent trend: In some animals the ratio slightly increased, whilst it decreased in others. This means that within the first 10 days the gain changes occurring in some cats are not accompanied by an improvement in symmetry. The VOR performance in terms of gain and symmetry present 10 days after lesion is summarized in Fig. 7 and compared to control values.

The third period is characterized by slowly developing modifications, probably still continuing beyond the end of our observation time. These modifications become more evident if we compare the responses recorded 7–10 days after the lesion with those of chronic cats (10.5–22 months p.o.) (Fig. 7). Symmetry clearly improved, and the values in the chronic stage are only slightly lower than those of the controls (difference statistically not-significant $P > 0.05$; one tailed T-test). Moreover, within the chronic group, young (open circles) and adult (filled circles) operated animals reach the same degree of VOR symmetry. As for the incremental gain, it is clear that the lesion-induced deficit is better compensated when the lesion is made in kittens. In fact, on rotation to the lesioned side adult operated cats never show responses as large as those present in young operated animals, with only one exception (filled dots in Fig. 6). However, this animal is unique in showing such a distinct improvement within the first month. Following rotation to the intact side, the responses elicited in the young operated animals are all comparable to those seen in that adult group which reveals an abrupt gain increase during the first week. Also, the two chronic animals operated as adults seem to improve gain slightly above 0.5 after 10.5 and 15 months, so that they may belong to the low gain group of Fig. 6. However, our data do not tell if the good compensation typical of the young operated animals is not reachable by the adult operated ones, since it is possible that particularly the high gain group, when recovering for 1.5–2 years, could attain a similar degree of VOR symmetry.

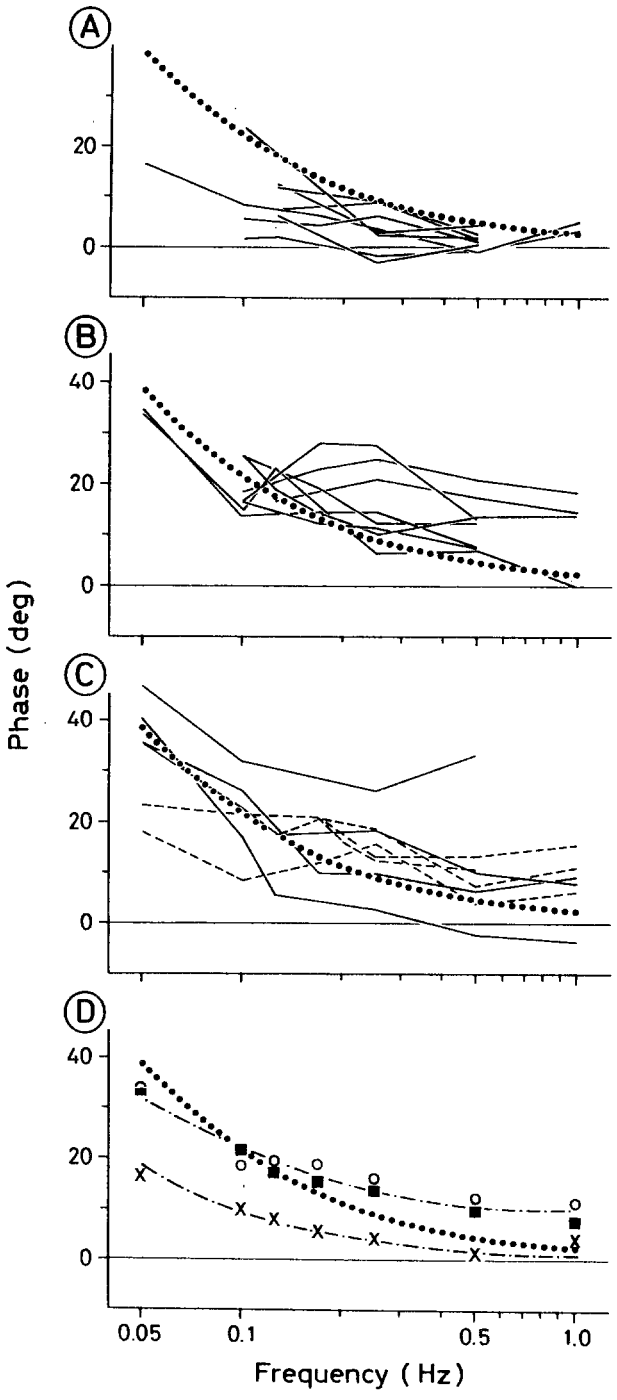

Fig. 8A–D. VOR phase in relation to frequency of sinusoidal oscillations measured at different times before and after lesion. The *dotted lines* indicate in all the panels the theoretical values that we would observe if the VOR were dominated by the time constant of the canals (4 s). **A** Control values. **B** Values measured 7–10 days after the lesions in the same animals as shown in **A**. **C** Values measured 10–22 months p.o. The animals are different from **A** and **B** except for two. *Dashed lines* represent cats lesioned at the age of 6 weeks. **D** Mean values for each frequency for each group of animals. *Crosses,* control; *squares,* 7–10 days p.o.; *circles,* 10–22 months p.o. The curves fitting the experimental data are also plotted. Values from acute and chronic cats were pooled together

VOR Phase in Normal and Lesioned Animals

The phases of VOR responses to sinusoidal stimuli were also computed by means of the fitting procedure described in the Methods. Figure 8A shows the VOR phase lead measured in the dark in eight control animals as a function of stimulation frequency. The dotted line (drawn in all the panels) serves as a reference and indicates the theoretical phase values that we would observe if the VOR were dominated by the longer time constant of the semicircular canal (4 s; Blanks et al. 1975). The mean values measured at each frequency (crosses in Fig. 8D, closely match the values predicted for a first order high pass filter with a time constant of 9.5 s (broken line between crosses).

The phase values obtained from the same eight animals 7–10 days after neurotomy are plotted in Fig. 8B. Phases computed by fitting separately the hemicycles relative to rotation towards the intact and lesioned side were not significantly different, so a mean of the two was plotted in the figure. The scatter of the points is even larger than in the controls, but a shift towards larger leads over the whole frequency range is consistently present. After computation of the mean values for each frequency (circles in Fig. 8D) a parallel shift of ca. 10° is observed. This larger phase lead does not seem to return to control values after the lesion. In Fig. 8C the phase values measured in the second group of six chronic cats (10–22 months p.o.) and in two of the animals of panels A and B (about 7 months p.o.) are shown. The dashed lines represent the cats lesioned at the age of 6 weeks. In spite of a considerable variability, there is a clear tendency towards a larger phase lead with respect to control data, in fact, the mean values for each frequency (squares in Fig. 8D) are identical to those measured one week after the lesion.

Eye Drift in the Dark in Chronic Cats

Normal cats are able to hold their eyes quite steady in the dark (Robinson 1974). Lesioned animals, however, still show a clear failure to hold eye position in absence of visual cues one year after lesion, i.e. a drift of 2–4°/s towards the lesioned side was a common finding. Examples of spontaneous eye movements in chronic cats are shown in Fig. 9. Records in Fig. 9A and B were obtained from an adult cat 23 days after the lesion. Gaze is perfectly stable in the light, whereas in the dark a drift towards the lesioned side is present. Figure 9C and D show other examples of spontaneous eye movements in the dark recorded from two different cats lesioned at the

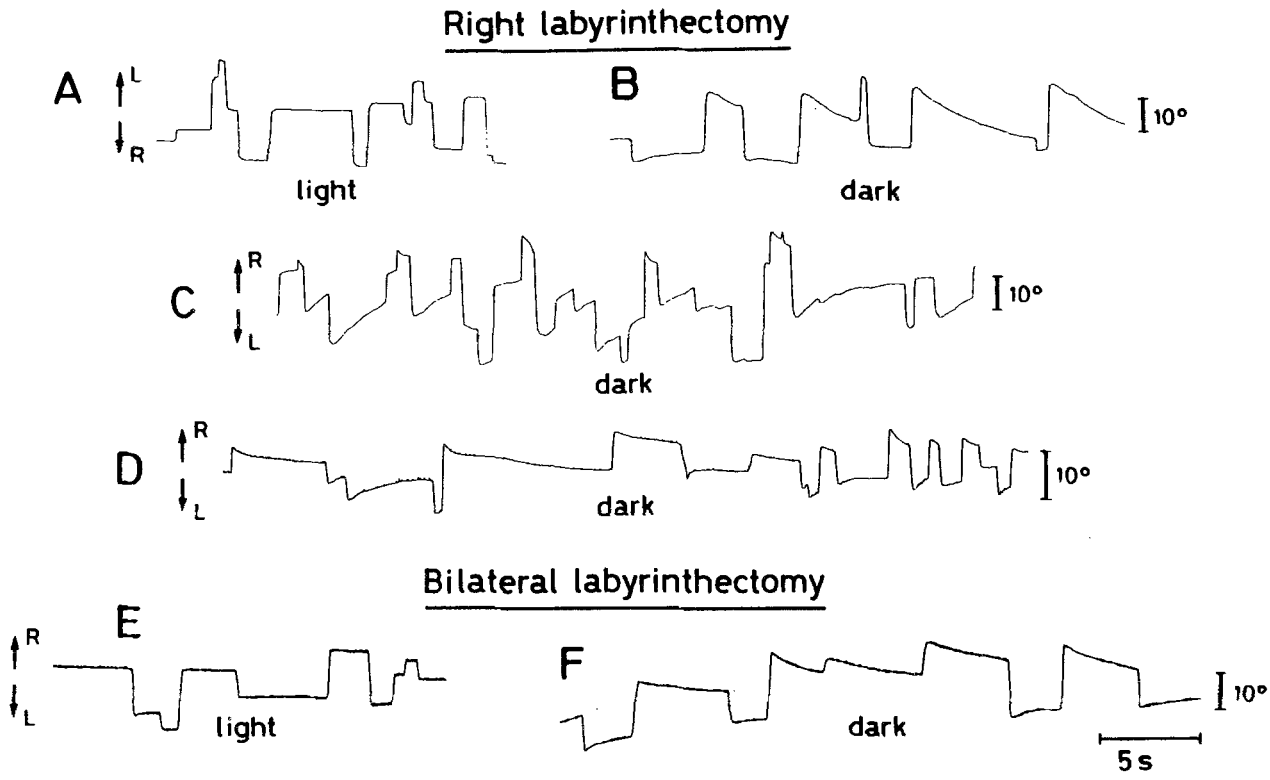

Fig. 9A–F. Actual eye movement recordings obtained from cats that underwent unilateral and bilateral lesion. **A, B** Records taken in the light and in the dark from an adult animal 23 days after unilateral lesion. **C, D** Records taken in the dark 18 months after right labyrinthectomy from two different cats lesioned at the age of 6 weeks. **E, F** Records taken 5 months after bilateral labyrinthectomy in an adult cat in the light and in the dark. Note the curvilinear drift present in all animals when kept in the dark

age of 6 weeks and recorded 18 months later. As it has been already described for the spontaneous nystagmus in the acute stage (Precht et al. 1981) the drift has a curvilinear shape with velocity decreasing in an exponential-like way. Furthermore, there is a position in the orbit (null point) where no more drift is noticeable. Our recording technique did not allow us to ascertain absolute eye position, but in several cases we used a video-camera to establish a rough correspondence between EOG signal and eye position in the orbit. In all cases the null point was shifted away from the center of gaze towards the lesioned side. Because of this marked eccentricity, it is rare to see the eyes move beyond the null point, especially in adult operated cats (the eccentricity is smaller in the animals lesioned at the age of 6 weeks; Fig. 9D). However, when such an event occurs, the eye drifts back towards the null point (Fig. 9B–D), i.e. to the intact side. Thus, we have to conclude that in the absence of spontaneous saccades the eyes would stay in an off-center position shifted towards the lesioned side without reaching the farthest corner of the orbit.

From this series of observations, it seems that the eye drift is not simply a residual spontaneous nystagmus due to an incomplete rebalance of the vestibulo-ocular system, but rather represents a deficit in the eye position holding function in the absence of visual cues. If the gaze holding failure were to result from the lesion independently of the presence of vestibular imbalance, one would expect a similar deficit after bilateral lesions in which no spontaneous nystagmus or any other kind of postural asymmetry is induced. Representative examples obtained from bilaterally lesioned cats are shown in Fig. 9E and F. These records were taken from an adult cat, about 5 months after the lesion. Also in this case, gaze stabilization is perfect in the light (Fig. 9E), but a clear failure to keep eyes steady in the dark is present (Fig. 9F). The null position is now near the center of gaze and every time a saccade towards the periphery occurs in either direction, the eye drifts back exponentially to the center.

Discussion

VOR in Control- and Acutely Lesioned Cats

The present results show that VOR gain is non-linear, i.e. partial saturation of responses occurs with

strong stimuli (Fig. 1). Landers and Taylor (1975) report non-linearity starting at 25°/s, Donaghy (1980) at 200°/s, and Robinson (1976) found no saturation up to 80°/s. In our more extensive study large individual variations in the saturation points ranging from 15°/s to more than 80°/s were observed. How could one account for this non-linearity on the basis of single unit studies performed under various experimental conditions?

Firing of vestibular nuclear neurons (Vn) during head rotation is controlled by the action of the bilateral semicircular canals. Most Vn responding to angular acceleration are excited by the ipsilateral and inhibited by the synergistic contralateral canal. The inhibition is mediated by the contralateral vestibular nucleus via commissural fibers (Shimazu and Precht 1966; Markham 1968; Mano et al. 1968; Kasahara and Uchino 1974). As a result of this bilateral convergence the acceleration sensitivity of Vn is greatly increased when compared to primary neurons (Precht 1979). The importance of the contralateral input on Vn was shown in experiments in which the canals on one side were plugged to block endolymph circulation (Abend 1977, 1978). This procedure renders primary afferents insensitive to head rotation, without altering the tonic excitatory input to the ipsilateral Vn. In these conditions, the mean acceleration sensitivity of Vn is decreased by half with respect to the control.

Since the canals work in a push-pull fashion, i.e. whenever one is excited, the parallel canal is disfacilitated, and the magnitude of disfacilitation depends on the level of resting discharge, we expect that as stimulus amplitude increases, more Vn will be silenced. That this, indeed, occurs has been demonstrated both in primary neurons (Goldberg and Fernandez 1971; Blanks et al. 1975) and in Vn (Shimazu and Precht 1965; Melvill Jones and Milsum 1970; Shinoda and Yoshida 1974; Abend 1978). Furthermore, since commissural inhibition has an important contribution in determining Vn firing rate, silencing on the disfacilitated side should induce some saturation in the nucleus on the excited side. In fact, the relation between increase in firing rate and stimulus amplitude in Vn has been shown to exhibit a downward concavity for large stimuli (Shimazu and Precht 1965; Melvill Jones and Milsum 1970; Shinoda and Yoshida 1974; Abend 1978). This non-linearity should be the basis of the above described saturation in the VOR. However, this interpretation is not sufficient, since silencing does not occur synchronously in all Vn. Progressive silencing should lead to a gradual VOR saturation with a smooth transition from a high to a low gain. Instead, a sharp transition was observed (Fig. 1). Groen et al. (1952) pointed out that non-linearities in single neurons may be cancelled when one considers the overall neuronal pool. Thus, the saturation of low threshold units may be balanced by a recruitment of high threshold units, thereby extending the linear range of the system's response. Vn, indeed, have been shown to exhibit a wide range of thresholds (Shimazu and Precht 1965; Melvill Jones and Milsum 1970). Our data support this argument, as the linear range of the VOR may extend to 80°/s, far beyond the values at which units start to be silenced. The described VOR saturation (Fig. 1) may, therefore, occur when: (1) all neurons on the excited side are recruited, or/and (2) all neurons on the opposite side are silenced. A comparison between the incremental gain after the saturation point in control animals and that of acutely lesioned cats suggests that the first possibility is the most likely one. After removal of one labyrinth the resting discharge on the deafferented vestibular nucleus is very close to zero (Gernandt and Thulin 1952; Trincker 1965; Shimazu and Precht 1966). Thus, in case the second aforementioned hypothesis were true, the gain for rotations towards the intact side should be very similar to the incremental gain of the partially saturated responses shown by the same animal before the lesion. Instead, the gain measured in the acute stage is very often lower. While a large variability exists in the incremental gain of control cats, that of acutely lesioned cats dropped consistently to ca. 0.5. Interestingly, after unilateral labyrinthine lesion also the sensitivity of Vn on the intact side dropped by half (Markham et al. 1977).

The VOR responses on rotation to the lesioned side depend on whether the slow phase of the elicited nystagmus is in the same or opposite direction to that of the spontaneous nystagmus. In fact, we have seen that in the latter case the incremental gain is lower (Fig. 2), probably because contraction of eye muscles is stronger when induced by excitation of motoneurons via excitatory VORs, rather than by disinhibition caused by decrease of the inhibitory VORs. In addition, it has not been possible to demonstrate the existence of a direct inhibitory pathway to the contralateral medial rectus subdivision of the III. nucleus (Baker and Highstein 1978). An indirect proof that the VOR slow phase velocity is mainly determined by the vestibular nucleus which is excited by the stimulus, is given by the close match between VOR gain drop and decrease in Vn sensitivity on the intact side following the lesion. In fact, both are roughly half of the normal values, in spite of the complete loss of the contribution of the vestibular nucleus on the lesioned side. In the acute stage the lesioned vestibular nucleus is basically silent, causing an imbalance that gives rise to a spontaneous nystag-

mus. When stimuli are not strong enough to reverse the direction of the spontaneous nystagmus, one expects symmetrical modulation of the strength with which eyes are pulled towards the lesioned side resulting in symmetrical eye movements (Figs. 2–4). A gain decrease is observed when the eyes are moving towards the intact side, as the contribution of the deafferented vestibular nucleus is very small and the efficacy of the intact nucleus in this task is low. As we will see later, poor functioning of the deafferented vestibular nucleus persists even after the disappearance of the spontaneous nystagmus, as indicated by the persistence of asymmetric VOR.

Compensation of VOR Deficits

A remarkable finding that emerges from this study is the complete absence of any correlation between recovery of the static asymmetries and of dynamic VOR deficiencies. For instance, in the first 3–4 days after the lesion the spontaneous nystagmus is almost completely compensated even when measured in the dark, whereas at the same time no appreciable improvement in VOR gain or symmetry occurs. The VOR gain never recovered to control values and even the gradual recovery of VOR symmetry took much longer than any of the postural asymmetries. Furthermore, VOR phase was impaired over the whole time period. These findings are surprising at least for two reasons. Firstly, effective adaptive gain control was shown for the VOR under various experimental conditions (cf. Miles and Lisberger 1981). In particular, cats wearing reversing prisms are able to reduce very quickly VOR gain to a maximum of 80% (Robinson 1976; Melvill Jones and Davies 1976; Melvill Jones 1977; Keller and Precht 1979), and in humans and monkeys, using 2 × magnifying lenses the gain could be increased up to 1.7 (Gauthier and Robinson 1975; Miles and Eighmy 1980). However, in most of our adult-lesioned cats these adaptive capabilities seem to be severely impaired as gain adjustments are much smaller than in normal animals and occur much more slowly. As shown in Fig. 6 some animals revealed a clear gain increase starting around day 5, i.e. after spontaneous nystagmus was largely compensated, and with a time course similar to that observed in intact cats wearing prisms. Apparently, if that critical time period is missed, possibly by reduced locomotor activity, only a very slow gain enhancement occurs. Changes in gain were not necessarily associated with an improvement in symmetry.

It should be emphasized, however, that the VOR gain modifications reported here were measured in the dark and with the head fixed. A freely moving animal does make use of its optokinetic system and the neck-ocular reflexes both of which support the VOR. In fact, in lesioned animals the neck-ocular reflex was demonstrated to increase significantly (Dichgans et al. 1973). If such an improvement had also occurred in our animals it may have been sufficient – together with OKN – to compensate VOR deficiencies. Thus, at present it is not clear whether the animals could not or did not need to change their VOR gain to stabilize gaze.

The finding that compensation processes of static and dynamic vestibular symptoms are independent confirms the important distinction made by Haddad et al. (1977) between gain and balance control. There is good evidence that the two control systems are functionally and structurally separate, since they are altered differently in lesion experiments (Haddad et al. 1977; Harris and Cynader 1981). For example, lesion of the vestibulo-cerebellum impairs the gain control (Ito et al. 1974; Robinson 1976), without much affecting the balance control (Schaefer and Meyer 1973; Llinas et al. 1975; Haddad et al. 1977). On the other hand, section of the optic chiasm impaired balance, but not the gain control (Harris and Cynader 1981).

The second conflict that arises from the different time courses of dynamic and balance control relates to the current view about the mechanisms leading to compensation of postural asymmetries, i.e. that rebalancing of the resting activity in bilateral vestibular nuclei is important (Precht 1974). This latter condition would be then very similar to the already mentioned canal-plugged paradigm. In both cases VOR would be generated by the stimulation of only one labyrinth, driving bilaterally the activity of vestibular nuclei with a normal firing level at rest. After canal plugging, VOR was symmetrical although at half gain (Money and Scott 1962; Zuckermann 1967; Barmack and Pettorossi 1981) and no major difference in the percentage of units responding to angular acceleration in the plugged versus the unplugged side was found, nor was the incidence of responding units in plugged animals different from that in controls (Abend 1977, 1978). However, bilateral sensitivity to natural stimulation was about half that of intact animals, showing that in normal animals almost all Vn receive an input from the contralateral labyrinth and that the two labyrinths have about the same weight in driving them. It follows from the above that if just rebalancing of the vestibular nuclei activity were responsible for the compensation of the spontaneous nystagmus, a considerable improvement in VOR symmetry should be observable rather early after the lesion. Since this

was not the case the assumption that during the recovery resting discharge in the deafferented vestibular nucleus comes back to a level comparable to the one on the intact side may be questioned. If it did come back to symmetrical levels Vn on the lesioned side would have to be less readily activated by rotation. That the latter deficiency, indeed, occurs is shown in some recent single unit work (Maioli et al. 1982). Compensation of spontaneous nystagmus may occur also outside the vestibular nuclei. That such a possibility exists is indicated by the CNS' capacity to compensate for nystagmus induced by a number of unilateral central lesions not necessarily affecting the vestibular nuclei activity (Jeannerod et al. 1981; Flandrin and Jeannerod 1981; O-Uchi et al. 1981).

Comparision with Other Studies

Similar deficiencies in dynamic VOR compensation have been found in different species [cat (Moran 1974); rabbit (Baarsma and Collewijn 1975); monkey (Wolfe and Kos 1977); human (Wolfe et al. 1978)]. Whereas a greater difficulty to compensate dynamic than static symptoms seems to be a common feature of higher mammals, rabbits compensate poorly both postural and dynamic asymmetries. Unfortunately, all these studies describe the VOR only at a certain time postoperatively rather than giving its recovery time course. In the rabbit, 6 months after labyrinthine removal, VOR gain is still 50% that of control animals and asymmetrical. Phase is advanced with respect to normal values by about 20° for the whole frequency range tested (0.05–1.8 Hz) compared to 10° in our study. Interestingly, a tonic deviation of the eyes towards the lesioned side remains as a permanent deficit. In the cat such a deviation is also present in absence of spontaneous saccades (Fig. 9). In the monkey, a low gain and symmetric VOR showing a parallel phase shift of 20° persists up to one year after the lesion. Similar findings are observed in humans 6 years after lesion (Wolfe et al. 1978). Besides our work, only Moran (1974) considered VOR phases in the cat and found asymmetric phase lead of 10–20° at low frequencies (0.06 and 0.03 Hz), whereas at 0.12 Hz the lead showed no asymmetry. Such an asymmetry has not been found in the rabbit and in the monkey, as well as in the cat in the present study. Most likely the asymmetry is due to the bias introduced by the eye position drift, since phases were computed by Moran from the eye position rather than from the eye velocity trace as in the present paper. We noted a similar asymmetry in gain and phase using cumulative slow phase position (Precht et al. 1981).

Contrary to all the above data, Courjon et al. (1977, 1982) reported a recovery of gain and phase already two months after the lesion and significant improvement of symmetry during the first week. The discrepancies are probably due to the fact that they did not subtract the spontaneous nystagmus (Courjon et al. 1977, Fig. 3A) and, therefore, their improvement in symmetry may reflect the compensation of the spontaneous nystagmus. Furthermore, they used very large stimuli which surely saturated Vn responses. Also control data are missing.

Lesions in Young Animals

It is a common notion that neuronal plastic changes occur more readily in young animals. Berthoz et al. (1975) reported, however, that young kittens compensate very poorly after hemilabyrinthectomy in absence of vision. In contrast it has been shown that in guinea pigs (Schaefer and Meyer 1973) and in Xenopus (Horn 1981) young animals compensate vestibular lesions faster than older ones. Our data show that young operated cats compensate on the average better than adults. In fact, not only do they recover a good level of response symmetry, but reach also a higher gain (Fig. 7). It must be concluded that in the study by Berthoz et al. visual deprivation after lesion was the reason for the poor compensation.

Eye Drift in the Dark

A curvilinear eye drift in the dark is another long-lasting deficit after labyrinthine lesion. The defects shown in Fig. 9 are similar to the eye movement deficits noted following cerebellectomy in that the animal is unable to hold postsaccadic eye position, resulting in an exponential drift towards a null point Robinson (1974). The interpretation given by Robinson was that the central velocity-to-position integrator (Skavensky and Robinson 1973) became leaky as a result of the lesion. Another important outcome of that study was that both vestibuloocular and saccadic systems share the same neuronal integrator. In our study, both post-saccadic drift and abnormalities in VOR phases occurred. Thus, it has been proposed that a positional integrator deficiency is also produced by vestibular lesion (Baarsma and Collewijn 1975; Precht et al. 1981). However, if that were true, the resulting VOR phase shift would not be uniform over all the frequency range, as shown in Fig. 8. Thus, we either assume two different integrators, one for the saccadic and one for the VOR, but evidence is against this hypothesis (Robinson

1974) or other mechanisms are responsible for the observed deficiencies. One purely speculative possibility could be that some persisting imbalance between bilateral vestibular nuclei is counteracted by a signal encoding eye position in the orbit so that an eccentric null point is established where drift is absent, although this would not explain the results obtained with bilateral lesions (Fig. 9). That proprioceptive input from the eyes is possibly involved in drift suppression in normal cats has been already suggested (Robinson 1974). As concerns the larger phase lead, we know that oculomotor neurons have to receive both eye velocity and eye position signals to overcome the orbital mechanics which begin to play a role in the frequency range of our study (Shinoda and Yoshida 1974). If the relative contribution of eye velocity had increased, some parallel shift towards larger leads were to be expected.

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