J. Physiol. (1966), **187**, *pp.* 231–246
With 7 text-figures
Printed in Great Britain

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INHIBITORY MECHANISMS IN LATERAL GENICULATE NUCLEUS OF RAT

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(*Received* 9 *May* 1966)

SUMMARY

1. An examination was made of the mechanisms responsible for the inhibition of synaptic transmission through the lateral geniculate nucleus (LGN) of the rat following a single shock to the optic nerve.

2. In the rat anaesthetized with paraldehyde we found no evidence that optic nerve stimulation produced any presynaptic inhibition in LGN. In agreement with other workers it was found that repetitive stimulation of visual cortex produced effects attributable to presynaptic inhibition. However, this was of small magnitude in the conditions of our experiments.

3. Stimulation of the optic nerve elicited an action potential in a P cell (principal cell) which was followed by a wave of hyperpolarization lasting about 150 msec (inhibitory post-synaptic potential, IPSP, wave).

4. The IPSP wave was chloride-dependent and was associated with inhibition of the P cell discharge. Occasional rippling on the IPSP wave suggests that it was produced by the repetitive discharge of I cells (interneurones).

5. These observations support the model proposed previously wherein P cells are inhibited by I cells which in turn are excited by axon collaterals of P cells. There is evidence for diffuse interconnexions between P cells and I cells.

6. The observation that the extracellularly recorded wave of hyperpolarization (P-wave) is usually negative suggests that most of the inhibitory synapses are not on the soma of the P cell.

INTRODUCTION

In the preceding paper (Burke & Sefton, 1966*b*) the thesis was put forward that the principal cells (P cells) of the lateral geniculate nucleus (LGN) of the rat send axon collaterals to interneurones (I cells) which in turn inhibit the P cells. There was also evidence that this inhibition was post-synaptic. Confirmation of this point was obtained in the experiments

reported in this paper in which intracellular records were obtained from P cells in which extracellular slow waves were also studied. However, since the existence of post-synaptic inhibition does not exclude the possibility of additional presynaptic inhibition, we have independently tested for this component. Preliminary reports have been published (Sefton & Burke, 1965, 1966).

METHODS

The general methods have been described in the previous paper (Burke & Sefton, 1966*a*). Stainless-steel insulated bipolar electrodes were positioned stereotaxically in the optic tract, approximately 6·5 mm anterior to the interaural line, 3 mm lateral to the mid line, and 7 mm deep to cortex. Their position in the optic tract was checked by recording from them while stimulating the optic nerve. These electrodes were used for stimulating and for recording antidromic field activity in the optic tract. Similar bipolar electrodes were also inserted in LGN and used for recording field responses and for stimulating optic tract nerve endings. Unit responses were recorded using a glass microcapillary electrode filled with either 3M-KCl or 2M-K citrate.

RESULTS

Presynaptic inhibition. It was shown in the preceding paper (Burke & Sefton, 1966*b*) that the inhibition of synaptic transmission through LGN produced by optic nerve stimulation was still present in the decorticate rat. Since cortical stimulation produced a similar inhibition it was suggested that axon collaterals of the principal cells might mediate this effect, Iwama, Sakakura & Kasamatsu (1965), Suzuki & Kato (1965) and Angel, Magni & Strata (1965*a*) have described cortically induced presynaptic inhibition in cat LGN. It is conceivable that this effect might be mediated through the axon collaterals. Accordingly we examined the effect of cortical stimulation on the presynaptic LGN response (t_1) produced by optic nerve stimulation and on the antidromic optic tract response produced by stimulation of optic tract endings in LGN. A decrease in the orthodromic t_1 response or an increase in the antidromic response may be regarded as evidence of a depolarization in the tract terminals and indicative of presynaptic inhibition (cf. Wall, 1958; Eccles, 1964, chapter 15).

A train of twenty shocks at a frequency of 200/sec was applied to visual cortex and a test stimulus delivered at various intervals after the train from 1 msec to 1 sec either to optic nerve or to LGN. Small effects were observed by both methods (Fig. 1). The orthodromic response was depressed to 95 %, the entire effect lasting not more than 100 msec (Fig. 1*B*). The antidromic response was increased to at most 105 % over a similar time course. After five cortical shocks at the same frequency, the antidromic response was increased for about 10 msec to 103·5 %; a single cortical shock did not lead to any increase in amplitude (Fig. 1*A*).

We also used a more general procedure and applied the conditioning stimuli (a train of twenty shocks as above) to the optic tract. Optic tract endings in LGN were again stimulated and the antidromic responses recorded in the optic nerve. A slight *decrease* in the antidromic response, of not more than 2·5 %, was observed, probably due to the slight hyperpolarization which follows repetitive activity (cf. Bishop, Burke & Hayhow, 1959). These findings suggest that presynaptic inhibition in the rat LGN is of negligible importance under the conditions of these experiments, and plays no significant part in the depressed excitability seen after a single shock to optic nerve or to cortex.

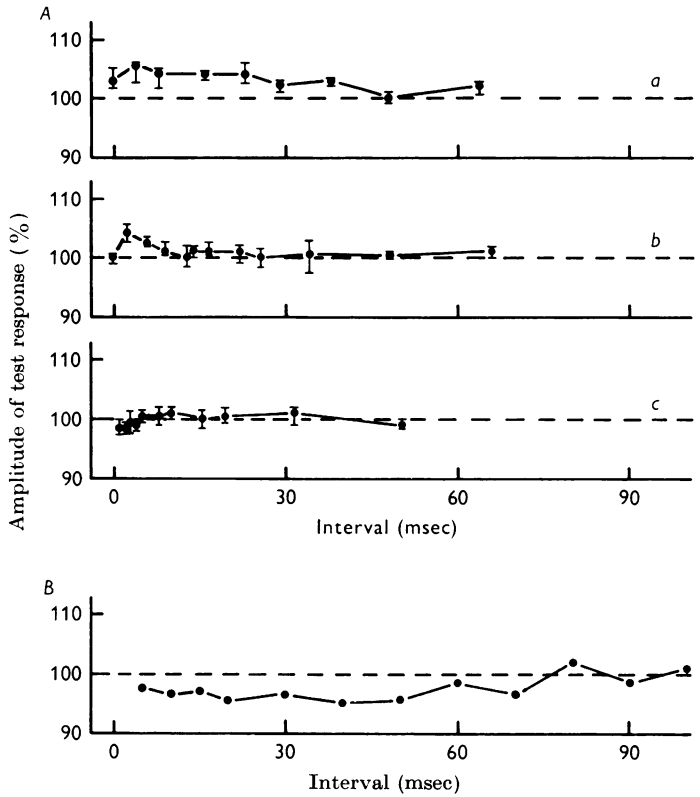

Fig. 1. Evidence for presynaptic inhibition in LGN. *A*. Test for depolarization of optic tract endings by Wall's (1958) method. Percentage increase in amplitude of antidromic field response in optic nerve to stimulation of optic tract endings (ordinate) plotted against interval from end of train of shocks to visual cortex (abscissa). (*a*): 20 shocks; (*b*): 5 shocks; (*c*): 1 shock. Each point is the mean of five observations, bars indicating the range. *B*. Percentage change in amplitude of orthodromic tract field response (t_1) in LGN to stimulation of optic nerve (ordinate) plotted against interval from end of train of 20 shocks applied to visual cortex (abscissa). Each point is the mean of 100 observations averaged on a CAT computer (Nmemotron).

Slow potential changes and intracellular recording. Evidence for post-synaptic inhibition was sought by intracellular recording. In the process of obtaining intracellular records from these small cells the electrode was advanced very slowly. Opportunity was therefore provided to examine the extracellular response and particularly the occurrence of slow potential waves. Extracellular records of slow waves were obtained from forty-one cells; intracellular records were obtained from twenty-four cells.

Penetration of a cell always caused damage; the greatest resting potential recorded was 40 mV. The spike potential was rarely present longer than a few seconds after impalement and few responses remained longer than 2 or 3 min. Apart from this, the rat LGN is a particularly convenient preparation in which to study these responses because slow waves and spike discharges unrelated to the nerve stimulus are virtually absent. When present following a stimulus, they can be satisfactorily recorded extracellularly. Furthermore, the slow waves to be described here were from single cells, and disappeared when the cell was killed. Field slow waves were usually of negligible amplitude, probably because of the small size of the LGN. By way of contrast, large slow waves and spike discharges occur in cat LGN in the absence of overt stimulation (Bishop & Davis, 1960).

Extracellular records. A stimulus to the optic nerve or to the visual cortex elicited a response in a P cell, the extracellular record of which usually consisted of a diphasic (positive/negative) spike followed by a negative slow wave lasting about 150 msec (Fig. 2*a*). A slow wave was frequently observed not preceded by a spike (Fig. 2*b*). It must be emphasized, however, that this negative slow wave was a response of the cell and disappeared when the cell was lost. The field slow wave following a stimulus was always positive within the LGN, as in cat LGN (Bishop & Davis, 1960) and was always of small amplitude (less than 0·5 mV), whereas the unit slow wave frequently exceeded several millivolts (Fig. 2*c*, *d*, *e*). This wave was followed by a succession of other waves, of similar polarity and duration but usually smaller than the first, in a fairly rhythmical sequence at intervals of 100–200 msec (Fig. 2*c*, *d*, *e*). The entire sequence usually lasted several seconds. As we shall show presently these waves had the properties of the positive field slow waves recorded in the ventro-basal nucleus of the thalamus in the cat by Andersen, Brooks, Eccles & Sears (1964), and therefore we will follow the terminology of these authors and call them P-waves. An explanation of the difference in polarity between the two sets of waves will be put forward later. No extracellular slow waves were recorded from I cells.

As the electrode was advanced the P-waves increased in amplitude but signs of cell damage also appeared, such as loss of the negative phase of the spike, injury discharges and failure of the B (soma-dendrite) com-

ponent of the spike. It is important to note, however, that the negativity of the P-waves was not the result of such damage. The P-waves were negative in polarity at a time when the spike response showed a good negative phase (Fig. 2*a*, *b*), indicating an undamaged membrane (cf. Bishop, Burke & Davis, 1962).

At the termination of a P-wave there was frequently a burst of firing from the cell, provided damage to the cell was not too great (Fig. 2*b*, *c*). The P-waves were always associated with inhibition of spikes. This was clearly shown on many occasions when the cell was giving an 'injury' discharge; this was suppressed during the P-waves (Fig. 2*d*, see also

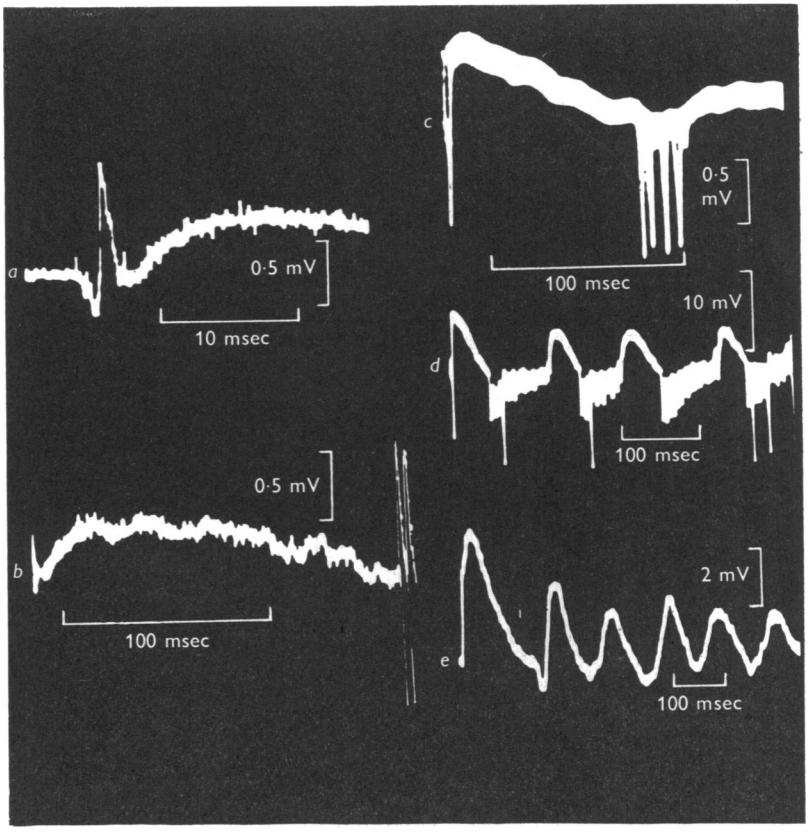

Fig. 2. Extracellular records of P-waves from five P cells, (*a*)–(*e*). (*a*): P-wave is negative when action spike has large negative phase. (*b*): P-wave need not be preceded by action spike; discharge at termination of P-wave. (*c*): Single spike preceding P-wave, discharge at termination; spikes positive phase only and occasional failure of B component. (*d*): Succession of P-waves to single stimulus: injury discharge (mostly A spikes) suppressed by P-wave. (*e*): Spike discharge has ceased but P-waves continue. Time base triggered by stimulus except in (*a*). Letters placed at level of base line. Negative upwards.

Fig. 6*b*). As mentioned earlier, the P-waves did not depend on the presence of a spike and when the spike mechanism had been inactivated by injury the sequence of P-waves could still be elicited (Fig. 2*e*).

We recorded one example (from forty-one units) of an extracellularly positive P-wave (Fig. 3). The positive waves in this example exhibited all the properties described for the more common negative P-waves. An explanation of this finding will be put forward in the Discussion. An additional feature in this cell was that the P-waves terminated in a negative wave, usually but not always associated with a burst of spikes,

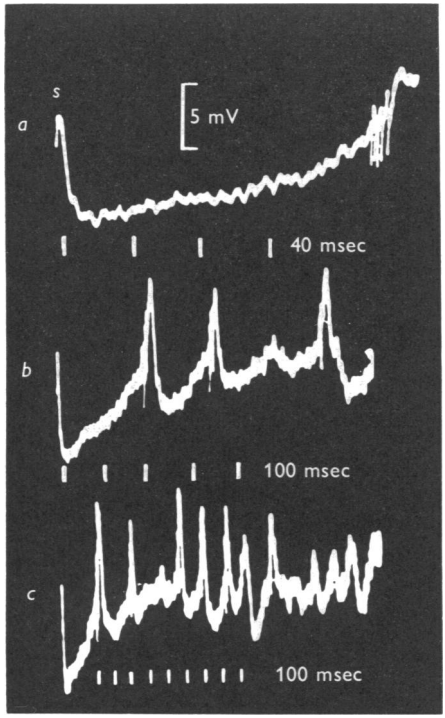

Fig. 3

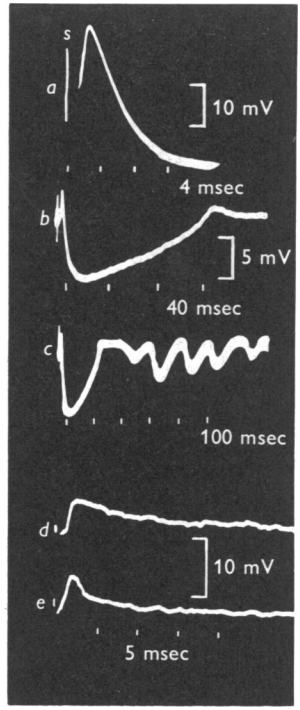

Fig. 4

Fig. 3. Unusual positive P-wave recorded on successively slower time bases. Note: absence of spike preceding P-wave but burst of spikes at termination (*a*); negative waves at ends of P-waves with burst discharge superimposed on some. See also Fig. 5*a–c*. Sweeps triggered by stimulus (*s*); letters at level of base line. Negative upwards.

Fig. 4. Intracellular records using K citrate electrode. (*a*)–(*c*): Records from P cell on successively slower time bases. Initial brief positive wave is either failing spike or EPSP and is followed by IPSP wave. Note small positive hump at end of IPSP wave (*b*). Voltage calibration in *b* applies to *c*. (*d*), (*e*): From another P cell after loss of spike. (*d*): EPSP alone to weak optic nerve stimulus. (*e*): Larger stimulus elicits small IPSP wave which subtracts from EPSP. Sweeps triggered by stimulus (*s*), letters at level of base line. Positive upwards.

mainly positive-going. The negative wave was not seen in extracellular records from other cells (Fig. 2) but a small wave of depolarization was seen in some intracellular records (e.g. Fig. 4*b*). A second optic nerve stimulus applied 70 msec or more after the first shock prolonged the first slow wave and delayed the negative wave and burst occurring at its termination (Fig. 5).

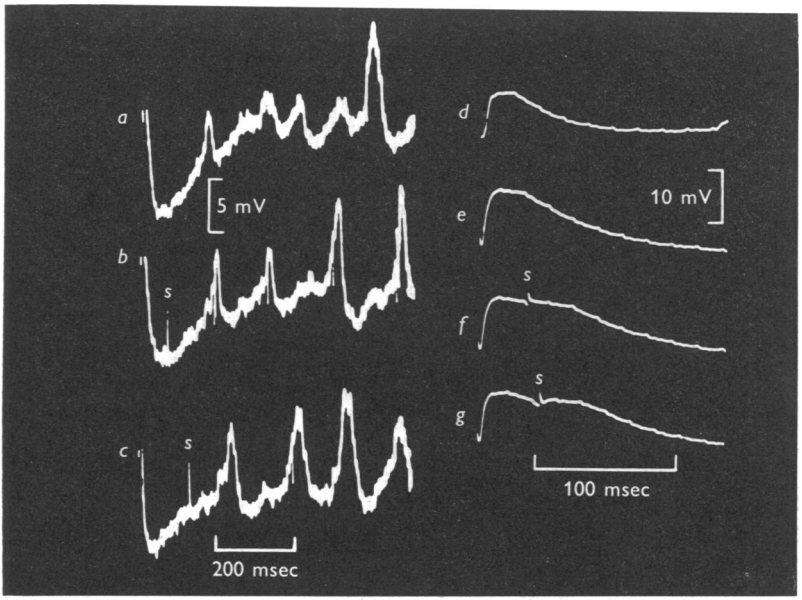

Fig. 5. Prolongation of slow wave by second shock to visual cortex. (*a*)–(*c*): Positive P-wave as in Fig. 3. Second shock (*s*) in (*b*), (*c*) prolongs P-wave and delays negative wave and burst discharge. Negative upwards. (*d*)–(*g*): Intracellular IPSP wave (depolarizing). (*d*): Optic nerve stimulus, (*e*). (*f*), (*g*): Stimulus to visual cortex. Second shock (*s*) in *f*, *g* prolongs IPSP wave. Positive upwards. Time bases triggered by stimulus in all records; letters at level of base line in (*a*)–(*c*), but above it in (*d*)–(*g*). Calibrations at left apply to (*a*)–(*c*), at right to (*d*)–(*g*).

Intracellular records. The intracellularly recorded spike was followed by a slow wave of hyperpolarization which reached its maximum amplitude at about 20 msec. An example is shown in Fig. 4*a–c*, in which the response to a single optic nerve stimulus was recorded on successively slower time bases, using a K citrate filled electrode. The first wave was followed by a succession of waves at intervals varying from about 100 to 200 msec. It was occasionally possible to compare extracellular and subsequent intracellular slow waves in the same unit (e.g. Fig. 6). It was then possible to establish the correspondence of the P-waves to the intracellular waves of hyperpolarization which we refer to as IPSP waves (cf. Andersen, Eccles & Sears, 1964).

Using KCl-filled electrodes, the IPSP wave was negative-going immediately after impalement of the cell (Fig. 6*b*, *c*). Subsequent potential changes depended upon the extent of damage caused by the electrode. If injury was considerable, as indicated by loss of resting potential and injury discharge, the IPSP wave could first become larger, then smaller, finally reversing to a depolarizing wave (Fig. 6*b*–*e*). On the other hand, if the resting potential was well maintained, the IPSP wave decreased in amplitude from the moment of impalement until it reversed after about 90 sec.

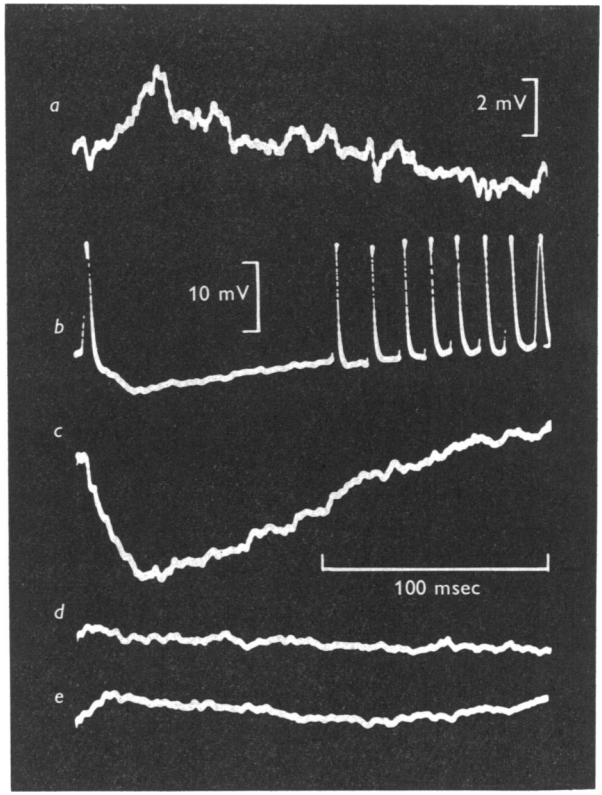

Fig. 6. Comparison of P-wave and IPSP wave in P cell. KCl electrode. (*a*): extracellular record (P-wave), negative upwards. (*b*)–(*c*): Intracellular, positive upwards, obtained at these times after impalement of the cell: (*b*): 5 sec; (*c*): 25 sec; (*d*): 55 sec; (*e*): 60 sec. IPSP wave in (*b*), (*c*) disappears in (*d*) and is reversed in (*e*). Injury discharge in (*b*) is suppressed during the IPSP wave. Sweeps triggered by stimulus; letters above level of base line. Voltage calibration in (*a*) applies to (*c*)–(*e*)

In this case the reversed IPSP was of larger amplitude (Fig. 7) than in the first case (Fig. 6). No such reversal of potential occurred if a K citrate electrode was used (Fig. 4). Thus the ionic mechanism underlying the IPSP wave in LGN P-cells seems to be chloride-dependent, as in other

C.N.S. cells (cf. Eccles, 1964, chapter 11). The sequence of potential changes may be explained in terms of the difference between the resting potential and the equilibrium potential for the inhibitory transmitter (in which the chloride concentration ratio is a significant factor) at any given moment.

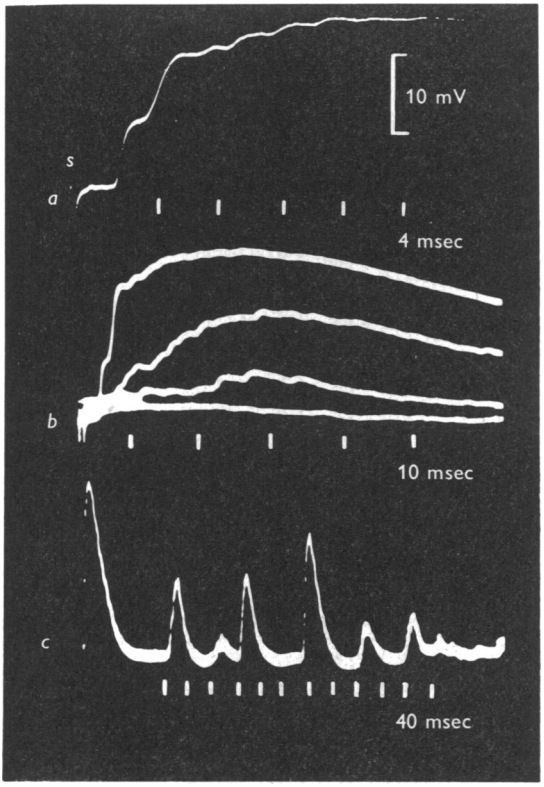

Fig. 7. Intracellular records of IPSP waves, obtained after reversal of IPSP (KCl electrode). Positive upwards. (*a*): Fast sweep. Initial step of response is EPSP (about 7 mV). (*b*): Superimposed records obtained during the response to a single stimulus to optic nerve; the largest wave was the short-latency response. Note rippling in (*a*) and (*b*). (*c*): Slow sweep; note large initial wave and some similarity in amplitude between certain of the later waves. Sweeps triggered by stimulus (*s*) except that the three smaller IPSP waves in (*b*) themselves triggered the time base.

Occasionally rippling was seen on an IPSP wave. The best example is shown in Fig. 7. The superimposed records are of successive IPSP waves to a single stimulus, and were made after penetration of the cell with a KCl-filled electrode. By the time the records were obtained, the spike had disappeared and the IPSP waves had become depolarizing (Eccles, 1964, chapter 11). The first IPSP wave is preceded by an excitatory post-synaptic potential (EPSP) of 7 mV. The EPSP had been identified immediately on penetration as it was depolarizing while the IPSP wave was

hyperpolarizing. In all records, the first IPSP wave is the largest and commences with a large initial step, while later IPSP waves start much less abruptly. The frequency of rippling averaged 400/sec in the cell from which Fig. 7 was prepared. Rippling became faster and less obvious on the larger waves (e.g. the largest in Fig. 7*b*). Rippling on a wave of hyperpolarization is shown in Fig. 6*c*, in which the frequency of rippling was about 225/sec.

Stimulation of cortex produced similar trains of slow waves. A second cortical stimulus applied at an interval of 30 msec or longer prolonged the duration of a P-wave (Fig. 5*a–c*) or an IPSP wave (Fig. 5*d–g*), and delayed the onset of burst discharges which occur at the waning of the slow wave.

Occasionally it was possible in a low-threshold P cell to elicit an EPSP without an IPSP. Figure 4*d* shows what is probably a pure EPSP; a slight increase in stimulus strength in Fig. 4*e* produced an IPSP which commenced just after the peak of the EPSP and considerably reduced the depolarization.

DISCUSSION

There is now good evidence for the occurrence of presynaptic inhibition in LGN of cat as a result of stimulating visual cortex (Iwama *et al.* 1965; Suzuki & Kato, 1965; Angel *et al.* 1965*a*). However, Iwama *et al.* (1965) showed that this effect was abolished by barbiturate. Because presynaptic inhibition in the spinal cord is enhanced by barbiturate (Eccles, 1964, chapter 15) it is possible that the effect of cortical stimulation is mediated through the reticular formation; there is also evidence that stimulation of this region produces presynaptic inhibition in LGN (Angel *et al.* 1965*a*, *b*). The effects we observed on stimulating visual cortex in the rat may have been small because of the anaesthetic used, paraldehyde. Andersen, Brooks, Eccles & Sears (1964) found increased excitability of afferent nerve endings in the ventro-basal nucleus of the thalamus of the anaesthetized cat as a result of conditioning through the same fibres. We found that stimulation of the optic nerve produced only a slight *decrease* in excitability. Whatever the situation in the unanaesthetized rat, it is evident that the strong inhibition observed in the LGN of the anaesthetized animal can be only to a small extent due to presynaptic inhibition.

The results clearly indicate that inhibition of a P cell was associated with a slow wave of potential change which was generated in the cell membrane, because it disappeared when the cell was killed. This wave was recorded intracellularly as a wave of hyperpolarization if a K citrate filled electrode was used and we may presume that in the intact cell this wave was also hyperpolarizing. The work of Fuster, Creutzfeldt & Straschill (1965) on rabbit LGN has demonstrated the occurrence of IPSP waves both with the animal in the dark and in response to flashes of light. There is good

reason to think, therefore, that these IPSP waves have an important role to play in normal vision.

In favourable recordings (Figs. 6*c*, 7), rippling was seen on the IPSP wave and the frequency and duration of rippling corresponded to the discharge pattern of an I cell (see Fig. 3 in the previous paper (Burke & Sefton, 1966*a*)—this was from another animal but is quite typical of all I cell discharges). The first IPSP wave was always the largest and this may have been due to the synchronous discharge of a number of I cells. Rippling was seen only occasionally (three cells) on IPSP waves of rat LGN cells and was not reported at all in the LGN of the rabbit (Fuster *et al.* 1965) nor in the ventro-basal nucleus of the cat thalamus (Andersen, Eccles & Sears, 1964) where analogous circuits are believed to be present. Rippling would be expected only if a small number of I cells discharged on to the P cell or if all I cell discharges were fairly synchronous. There is considerable variation in the pattern of successive IPSP waves. Occasionally, the smallest IPSP wave appears to result from a single I cell spike, as shown by the smallest wave in Fig. 7*b*; slightly larger waves show rippling suggestive of the burst discharge of a single I cell as in the third largest wave in Fig. 7*b*, which can be compared with the fifth burst shown in Fig. 3*a* of the previous paper (Burke & Sefton, 1966*a*). In the largest wave of Fig. 7*b* the rippling is faster and is a little blurred, suggestive of the convergence of a number of I cells whose discharges are not quite synchronous. Thus this evidence further strengthens the validity of the model proposed in the preceding paper (Burke & Sefton, 1966*b*).

Also confirmatory of the model were the observations that a second shock to visual cortex after an interval of 30 msec or more prolonged a P-wave or an IPSP wave and delayed the burst discharge (Fig. 5). I cells could be reactivated from cortex at a similar interval (Burke & Sefton, 1966*b*). Therefore the time relations are correct for the I cell to be responsible for the slow wave.

The variations in amplitude of IPSP waves is probably due to the different numbers of I cells discharging and to the different numbers of spikes in the successive discharges of a single I cell, an example being shown in Fig. 3 of the previous paper (Burke & Sefton, 1966*a*). If successive IPSP waves are superimposed as in Fig. 7*b* they appear to fall into 5 or 6 discrete groups; other records such as that in Fig. 4*c* exemplify this statement. Extracellular records (e.g. Fig. 2*d*, *e*) convey a similar impression. These observations suggest that a small number (perhaps five or six) I cells converge on to each P cell.

Conversely, about eight P cells were found for every I cell (Burke & Sefton, 1966*a*), although too much reliance must not be placed on this ratio because of the possibility that a given electrode may record more

favourably from one type of cell than from another. The Discussion in the preceding paper (Burke & Sefton, 1966*b*) led to the conclusion that there was an extensive innervation of I cells by P cells. Hence we have a closely cross-innervated system of cells, each type of cell capable of exciting powerful synaptic effects on the other group. The suggestion has been made (Ratliff & Hartline, 1959) that a system of lateral inhibition may serve to accentuate contrast in a sensory pathway. However, we do not know enough about the organization described here to say whether this is such a system or not. The functional relation of P and I cells should become clearer when the effects of photic stimulation are examined. It is also not clear whether the groupings of cells and nerve endings in cat LGN termed 'glomeruli' (Tello, 1904; Taboada, 1927) bear any relation to the functional association of cells described here.

As an IPSP wave subsides, there may be a burst of spikes from the P cell which would reactivate the associated I cell or cells. In turn a further IPSP wave would be produced in all the P cells to which the I cells project, whether or not the P cells had discharged. IPSP waves of different amplitudes in the same cell all had very similar duration, and variation in duration from cell to cell within any one animal was small. Leaving aside the possibility of excitatory axon collaterals between P cells it is not difficult to see how the IPSP waves could be of similar duration. The I cell can be reactivated a short time after its initial burst, and is therefore ready to be excited by the next P cell discharge. If there are extensive interconnexions between groups of P and I cells then the I cell discharges would be synchronized and so would the onset of IPSP waves. However, any individual P cell or I cell discharges infrequently, not being activated at the end of every IPSP wave.

What induces the P cell to discharge with the waning of the IPSP? Andersen, Eccles & Sears (1964) suggest the presence of excitatory collaterals from neurones, themselves phased by the rhythmic discharges, but we have not seen any synaptic potentials prior to the burst discharges of P cells. This mechanism cannot account for the initiation of the first discharge of the earliest-recovering P cell. Excitatory collaterals could, however, be important in synchronizing P cell bursts and thus I cell discharges. Another possibility is that there is a constant bombardment of P cells by afferent impulses which initiate a spike only when the IPSP wanes; we have never seen the synaptic potentials that might be expected to accompany such bombardment. We suggest that the termination of hyperpolarization leads into a phase of depolarization which initiates spike discharges. The phase of depolarization might result from a decrease in K permeability and an increased activation of the Na mechanism during hyperpolarization.

The only clue we have concerning the site of this triggering depolarization is provided by Fig. 3. These records were unusual in that they were the only extracellular records to show a positive P-wave. They were also the only extracellular records to show a negative wave associated with spikes. The suggestion is made later that the electrode may have been in the vicinity of the inhibitory synapses either on dendrites or possibly on axon hillock. To this we may add the hypothesis that the same areas are the trigger zones for re-excitation of the cell. Spencer & Kandel (1961) have suggested that two trigger zones exist in hippocampal pyramidal cells, one on the initial segment, the other on the bifurcation area of the apical dendrites. They consider that rebound excitation following hyperpolarization may arise in the latter region. A hyperexcitable phase following hyperpolarization has been demonstrated in the motoneurone (Coombs, Curtis & Eccles, 1959; Araki, Ito & Oshima, 1961) and following IPSPs in motoneurones (Coombs, Eccles & Fatt, 1955); and has been suggested for hippocampal cells (Kandel & Spencer, 1961) and pyramidal tract neurones (Stefanis & Jasper, 1964).

When the P cell fires late it does so in a burst of 2–5 spikes. We suggest that this is the natural response of the cell in isolation to a threshold depolarization. This response is cut back to a single spike when evoked by electrical stimulation of the optic nerve because of the powerful recurrent inhibition. The rapid onset of the IPSP wave is well seen in Figs. 4*e* and 6*e*. Photic stimuli might elicit a burst discharge as in rabbit (Fuster *et al.* 1965). A short-latency burst discharge in cat LGN is reduced to a single spike as the stimulus strength is increased (Bishop, 1960).

The rhythmical slow wave and spike discharges cease within about 5 sec of the initial stimulus. It is difficult to understand how the discharges cease since, as discussed earlier, there is a strong synchronizing action capable of pulling in cells which have missed a round. A progressive dropping out of cells in groups might account for the effect. This explanation is not entirely satisfactory.

The slow waves recorded intracellularly were represented in extracellular records as negative waves in forty of forty-one examples. The rat LGN is a particularly favourable preparation in which to study the polarity of unit slow waves, because there are no significant field slow waves as described for cat LGN by Marshall, Talbot & Ades (1943), Chang (1950), Vastola (1957, 1959) and Bishop & Davis (1960). A negative extracellular wave means that the electrode is recording from a part of the membrane which is a sink of current. Since in the present case the slow wave corresponds to a wave of hyperpolarization, the implication is that the hyperpolarization is remote to the electrode. If we assume that in most cases the electrode is recording from the soma of the cell (being the largest 'target')

then the inhibitory synapses must be on dendrites or perhaps on axon hillock (Tömböl, 1965). It is possible that the electrode had damaged a part of the membrane and destroyed its hyperpolarizing mechanism. However, in several instances, absence of damage was indicated by the presence of a good negative phase on the spike potential (Fig. 2*a*, *b*; cf. Bishop *et al.* 1962). In the example with positive-going P-waves, the recording electrode may have been close to the inhibitory synapses on a cell process. Field slow waves in LGN are positive because they represent the flow of current from somas to axons; the large field waves in cat may obscure the small P-wave from an individual cell.

Spindles, a series of slow waves, waxing and then waning in amplitude and often with spikes on their peaks, have been described in the LGN of cat (Bishop & Davis, 1960) and rabbit (Fuster *et al.* 1965) and in other thalamic regions in cat, including medial geniculate nucleus (Galambos, Rose, Bromiley & Hughes, 1952), mid-line thalamic nuclei (Verzeano & Calma, 1954; Verzeano, Naquet & King, 1955; Verzeano & Negishi, 1960) and in ventro-basal complex (Andersen & Sears, 1964; Andersen, Eccles & Sears, 1964). It is probable that an inhibitory circuit similar to that proposed in the preceding paper (Burke & Sefton, 1966*b*) forms the basis of the slow waves, both spontaneous and induced by orthodromic or cortical stimulation, seen throughout the thalamus. Evoked slow rhythms and spindles were also shown to be unaffected by removal of cortex (Adrian 1941, 1951; Bremer & Bonnet, 1950; Galambos *et al.* 1952; Bremer, 1953; Andersen, Brooks, Eccles & Sears, 1964). These observations were confirmed in the present studies (Burke & Sefton, 1966*b*).

Spontaneous spindling was not seen in the LGN of the rat under the conditions of the present series of observations but has been reported in rabbit LGN (Fuster *et al.* 1965). The lack of spontaneous spindles in the rat LGN may reflect a difference in its anatomy, perhaps with few connexions between groups of interrelated P and I cells.

Photic stimuli in the barbiturate-anaesthetized rat evoke a series of slow waves in visual cortex, recurring at intervals of 160–240 msec (Kimura, 1962). It is possible that these result from the late bursts of P cells in the LGN. Spontaneously occurring cortical rhythms (as seen in the electroencephalogram) in the rat have a frequency of 4–7/sec (Morris & Glaser, 1959), and are probably driven by the thalamic rhythm.

This study was supported by a grant from the National Health and Medical Research Council of Australia. We wish to thank Dr R. W. Rodieck for valuable criticism of the manuscript. We are grateful to Miss Sylvia Johnson for clerical assistance and to Mr O. Gerke, Mr R. M. Tupper and Mr R. Brailey for technical assistance.

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