Korean J Physiol Pharmacol
Vol 2: 21–30, February, 1998

Chemical Coupling between Horizontal Cells in the Catfish Retina

Sung-Jong Lee, Chang-Sub Jung, and Sun-Ho Bai

Physics Section, Department of Natural Sciences, Catholic University Medical College, Seoul 137–701, Korea

The effects of GABA and glutamate on the horizontal cells were explored by an intracellular recording method to discern the mechanisms of receptive field formation by chemical coupling in the catfish outer retina. The results suggest that the horizontal cells of the catfish retina might use GABA as their transmitters and that the GABAergic system contributes to the formation of receptive fields of the horizontal cells. $GABA_C$ receptors may be involved in a chemical coupling between horizontal cells and concerned with the depolarizing actions by GABA on horizontal cells in the catfish retina. Since the chloride equilibrium potential is more positive than the dark membrane potential in horizontal cells, GABA released from a horizontal cell may depolarize the neighboring horizontal cells. Thus a chemical coupling between horizontal cells may be formed. $GABA_A$ receptors also may be involved in the negative feedback mechanism between photoreceptor and horizontal cell. And glutamate may be involved in connecting positive and negative feedback systems since it potentiated the GABA's actions. Therefore, it is presumed that large receptive fields in the catfish retina are formed not only by electrical coupling but also by chemical coupling between horizontal cells. And information travels laterally by pathways involving both electrical coupling composed of gap junctions and chemical coupling in the retinal network.

Key Words: GABA, Glutamate, Catfish retina, Horizontal cell, Receptive field, Chemical coupling

INTRODUCTION

GABA and glutamate have been identified as the major neurotransmitters in the lateral and radial synaptic pathways of the vertebrate retina. In the radial pathways, photoreceptors pass information to the ganglion cells via bipolar cells. And the responses within radial pathways are modulated by lateral input from amacrine cells in the inner plexiform layer and horizontal cells in the outer plexiform layer (Barnstable, 1993).

GABA is used by both horizontal cells and also by many amacrine cells in the lateral pathways, whereas glutamate is used by both photoreceptors and bipolar cells in the radial pathways. So, horizontal cells receive their main synaptic drive from photoreceptors via glutamatergic synapses and neighboring horizontal cells via GABAergic coupling (Djamgoz, 1995).

To date, a large amount of morphological (Naka & Garraway, 1975; Naka & Ohtsuka, 1975) and electrophysiological (Naka & Nye, 1970; Hals et al, 1986; O'Dell & Christensen, 1989) works have been done to study the synaptic mechanisms of the teleost retinal neurons. It has been shown that the horizontal cells are extraordinarily large in these retinae, which offers unique advantages in the study of transferring mechanisms of visual information, and many detailed studies of this cell type have been carried out (Murakami et al, 1972; Cammack & Schwartz, 1993; Grant & Dowling, 1995). More recently the catfish retina, with single types of cones and rods, has also yielded much useful information concerning retinal synaptic mechanisms. The horizontal cells form the most distal layer in the inner nuclear layer and are arrayed like a brick pavement; in flat mount they take the form of a starfish with many stubby arms studded with spines (Lam & Lasater, 1978; Sakai & Naka, 1986). Also, it is known that the large, monotonic receptive fields are formed by a gap junction between

Corresponding to: Sung-Jong Lee, Physics Section, Department of Natural Sciences, Catholic University Medical College, Seoul 137-701, Korea. (Tel) 02-590-1260

horizontal cells (Vaughan & Lasater, 1990; Cook & Becker, 1995).

But it has been reported that the GABAergic synapses caused a increase in coupling between horizontal cells via positive feedback system (Kammermans & Werblin, 1992; Djamgoz, 1995). If GABA is released from horizontal cells in response to depolarizing stimuli of increasing intensity, GABA autoreceptors will be activated. Since the chloride equilibrium potential appears to be more positive than the dark membrane potential in horizontal cells, this will lead to further release of GABA (that is, GABA receptors and chloride equilibrium potential form a positive feedback loop), thus increasing the sensitivity of the mechanism that controls release of GABA. Therefore, it is useful to investigate the chemical coupling between photoreceptors and horizontal cells or between a horizontal cell and the other horizontal cells.

In this study, the effects of GABA and glutamate on the horizontal cells were explored by an intracellular recording method to discern the mechanisms of receptive field formation by chemical coupling in the catfish retina.

METHODS

Retina-eyecup preparation

Experiments were performed using the channel catfish (*Ictalurus punctatus*) retina-eyecup preparation. The animals were maintained under normal day and night light cycles, and dissections were done under bright light. The cornea, iris, lens, and vitreous were removed by absorption with Kimwipe tissues under the dissection microscope thereby exposing the retina in a hemi-eyecup. The retina eye-cups were then placed in a dark Faraday cage where they adapted to a mesopic state. A perfusion pipette was placed at the rim of the retina allowing the eyecup to be filled with Ringer's solution which could be switched to a solution containing pharmacological agents.

Solutions and drugs

A Ringer's solution with or without pharmacological agents was aerated by 100% O_2 gas. The oxygenated Ringer's solution consisted of 126 mM NaCl, 4 mM KCl, 3 mM $CaCl_2$, 1 mM $MgCl_2$, 15 mM dextrose, and 2 mM 5N-2-hydroxyethylpiperazine-ethanesulfonic acids-N'-2 (HEPES; Sodium Salt type), and was titrated to pH 7.4. For studies on sodium substitution, 126 mM NaCl was replaced by equimolar $HOCH_2CH_2N(CH_3)_3Cl$ (choline chloride). For studies on chloride substitution, Ringer's solution was modified to the following: 63 mM Na_2SO_4, 2 mM K_2SO_4, 3 mM $CaSO_4$, 1 mM $MgSO_4$, 2 mM HEPES, 15 mM dextrose.

The following pharmacological agents (concentrations specified in test) were added to the above Ringer's solution. GABA, glutamate, cobalt chloride, muscimol ($GABA_A$ receptor agonist), baclofen ($GABA_B$ receptor agonist), trans- aminocrotonic acid (TACA; $GABA_C$ receptor agonist), picrotoxin ($GABA_A$/$GABA_C$ receptor antagonist), N-methyl-D-aspartate (NMDA), kainate, quisqualate. TACA and quisqualate were obtained from Tocris Cookson Co. (U.K.). All other chemicals were purchased from Sigma Chemical Co. (St. Louis, MO, USA).

Stimulation and recording

Full-field, spot or annular light stimuli were generated on a computer monitor and focused onto the retina. Electrophysiological recordings were made using standard intracellular electrodes which in turn were made by the microelectrode puller of an omega dot shaped capillary filled with 2 M potassium acetate and 1 mM ethylene glycol-bis (b-aminoethyl ether) N,N,N',N'-tetraacetic acid (EGTA). The resistance of the electrode was approximately 100~200 MΩ. The microelectrode was moved by means of a micromanipulator into the eyecup. Cells were identified based on light response and retinal depth. No distinction was made between amacrine and ganglion cells, which were simply identified as third-order neurons. The electrical signal was amplified by electrometer and was viewed on an oscilloscope. Regular signals from the cells were recorded with a penwriter and digitized on a Digidata 1200A A/D board using Axoscope software.

RESULTS

Equilibrium potentials of the catfish horizontal cells

Both glutamate and GABA depolarized the catfish

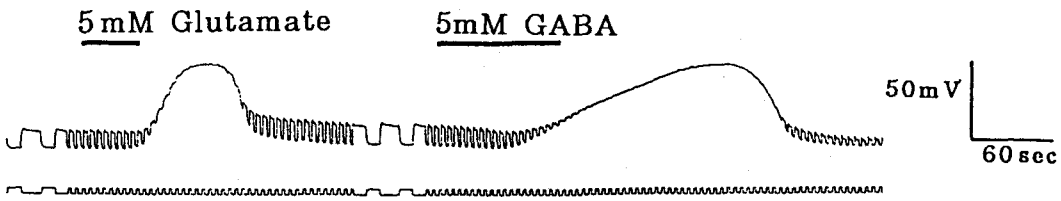

Fig. 1. Intracellular recording from retinal horizontal cells which were stimulated by red diffuse illumination having a duration of 2 sec and an interstimulus interval of 3 sec as indicated by the square-wave pulses at the bottom of the voltage trace (red: upward). Glutamate (5 mM) or GABA (5 mM) depolarized the horizontal cell with a loss of a light responses. The depolarization rate of glutamate (5 mM) was ~2 mV/sec and that of GABA (5 mM) was ~0.5 mV/sec. The responses were recovered after returning to the control solution. The dark bar above the voltage trace indicates the duration of drug application. In drug application, there was usually about 30 sec delay from time the drug was switched on until it reached the retina because of dead space in the perfusion system.

horizontal cells. Glutamate (5 mM) depolarized the dark membrane potentials of the horizontal cell by ~ 52 mV with a loss of light responses and GABA (5 mM) depolarized the dark membrane potentials by ~ 50 mV with a loss of a light responses on the same cell (Fig. 1). In this case, the depolarization rate of the membrane potential caused by glutamate was ~2 mV/sec and that caused by GABA was ~0.5 mV/sec.

The equilibrium potentials for glutamate depolarization (~15 mV) and GABA depolarization (~26 mV) were more positive than the dark membrane potential (~51 mV), though muscimol equilibrium potential (~62 mV) was more negative than the dark membrane potential in the catfish retina (Table 1).

As all of the synaptic interactions in the retina were blocked by cobalt (3 mM) administration, membrane potentials of the cells were hyperpolarized and light responses were abolished. Subsequently, agonists of GABA and glutamate were added to the cobalt administration. GABA (10 mM) and TACA (5 mM) produced a large depolarization (Fig. 2A, D). But muscimol (100 μM) and baclofen (1 mM) did not cause any change of the membrane potential (Fig. 2B, C). Glutamate and its receptor agonists, kainate (100 μM), quisqualate (100 μM) and NMDA (1 mM), depolarized the cell in the presence of cobalt (Fig. 3).

Fig. 4 demonstrates that the depolarizing actions by GABA is affected by endogenous glutamate release. The recovery from the depolarization by GABA was delayed in a dark environment. To estimate the interaction between an endogenously released transmitter and an exogenously perfused one, glutamate and GABA were applied in the long duration of

Table 1. Equilibrium potentials of the horizontal cells in the catfish retina

Perfusate	Equilibrium potential (mV)
normal (n=70)	−51±11.8
glutamate (n=36)	−15± 7.1
GABA (n=40)	−26±12.6
muscimol (n=14)	−62±10.0

Values are expressed as mean±standard deviation

darkness or light. GABA (10 mM) depolarized the membrane potential by ~50 mV in darkness and by ~60 mV in light. The membrane potential did not recovered after returning to the control in darkness (Fig. 4A). Glutamate (10 mM) depolarized the membrane potential by ~22 mV in darkness and by ~75 mV in light. The recovering aspects from the actions of glutamate in light were similar to those in darkness. The membrane potential returned to its original level after it was returned to the control solution whether in light or in darkness (Fig. 4B).

Ionic mechanisms of depolarization by glutamate and GABA

For the investigation of ionic mechanisms of the GABA and glutamate actions on the horizontal cells, chloride-free (Sulfate was substituted.) and sodium-free (Choline was substituted.) Ringer's solution were introduced. Fig. 5A shows that GABA (5 mM) depolarized the light membrane potential by ~52 mV and

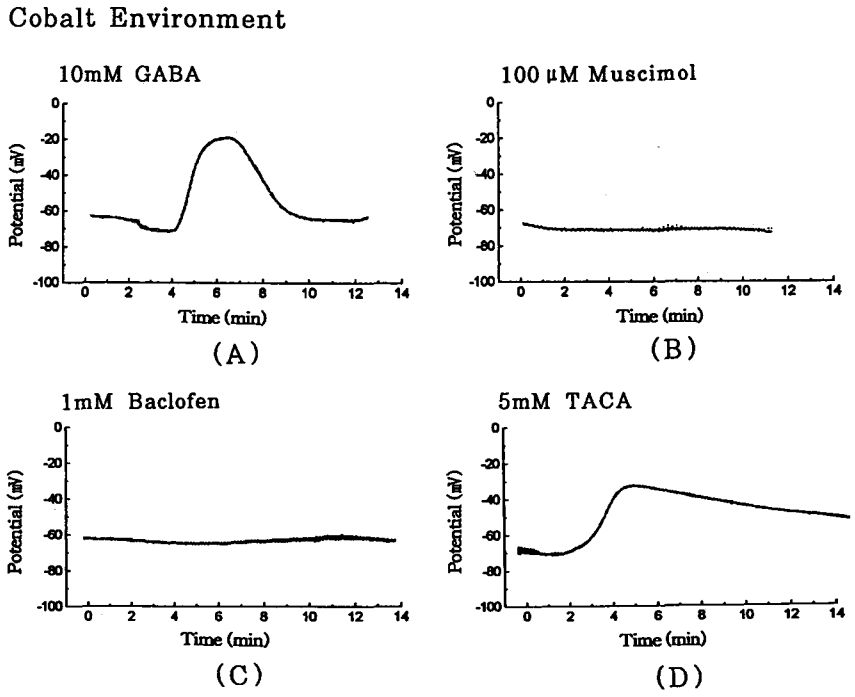

Fig. 2. In order to evaluate whether the actions of GABA agonists on the horizontal cells were direct or indirect, cobalt (3 mM) was introduced. GABA (10 mM) and TACA (trans-4-aminocrotonic acid; 5 mM), the $GABA_C$ receptor agonists, produced a large depolarization, in the presence of 3 mM cobalt. But muscimol (100 μM), the $GABA_A$ receptor agonists, and baclofen (1 mM), the $GABA_B$ receptor agonists, did not cause any change in the membrane potential.

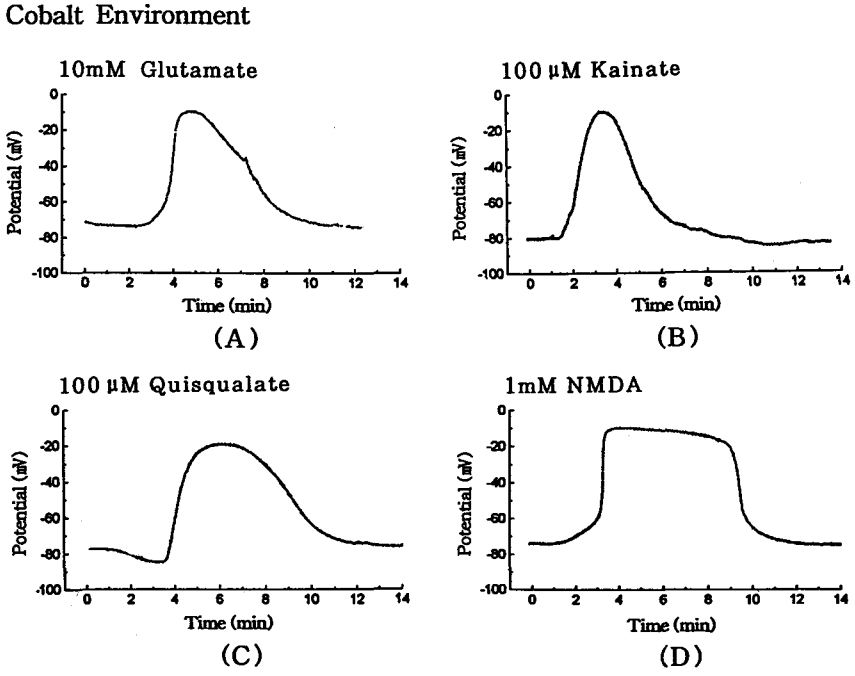

Fig. 3. Under the cobalt (3 mM) environment, horizontal cells were depolarized by glutamate and its receptor agonists, kainate (100 μM), quisqualate (100 μM) and NMDA (1 mM).

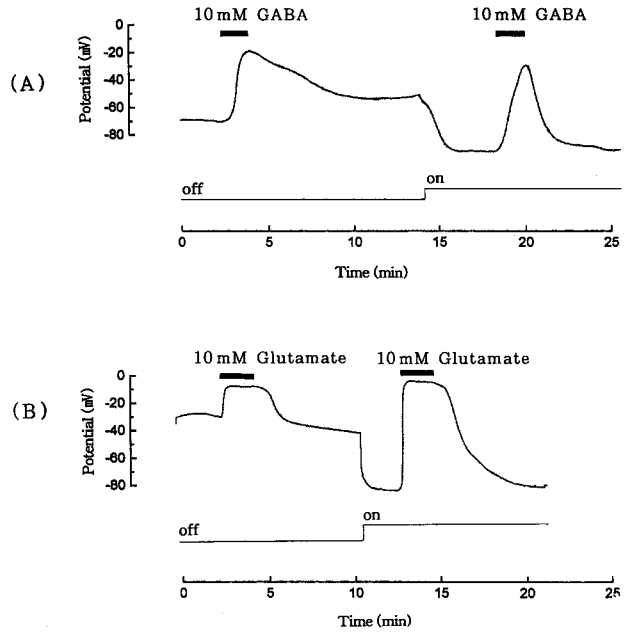

Fig. 4. Intracellular recording obtained from a horizontal cell. *A* : GABA (10 mM) depolarized the membrane potential by ~50 mV in the dark and by ~60 mV in the light. The membrane potential did not recover after being returned to the control solution in the dark. *B* : glutamate (10 mM) depolarized the membrane potential by ~22 mV in darkness and by ~75 mV in light. The membrane potential was recovered after returning to the control solution in both light and darkness.

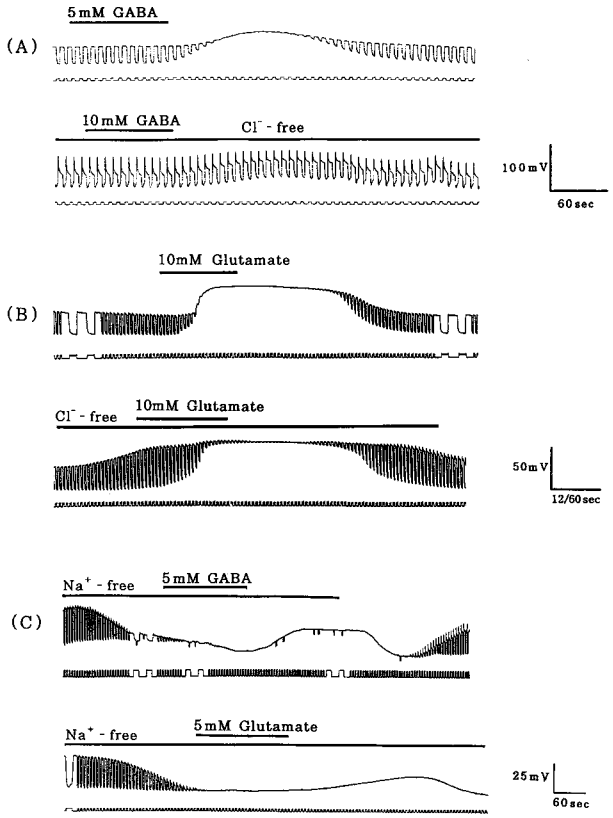

Fig. 5. Effects of chloride and sodium ions on the ionic mechanisms of the GABA and glutamate actions on the horizontal cells. *A* : GABA (5 mM) depolarized the light membrane potential by ~52 mV and eliminated the light responses. After 10 minutes administration of chloride free Ringer's solution, 10 mM GABA depolarized the light membrane potential only by ~18 mV and did not eliminate the light responses. *B* : glutamate (5 mM) depolarized the light membrane potential by ~70 mV and eliminated the light responses. Under the chloride free environment, 5 mM glutamate depolarized the light membrane potential by ~69 mV and the elimination of the light responses was delayed by about a minute more than that of the normal condition. *C* : when the Ringer's solution was changed with sodium free Ringer's solution, the membrane potentials of horizontal cell were hyperpolarized by ~30 mV and the light responses were abolished. Under the sodium free environment, 5 mM GABA depolarized the membrane potential by ~22 mV with equilibrium potential of −59 mV (below the dark membrane potential) and 5 mM glutamate depolarized the membrane potential by ~16 mV with depolarizing rate of ~0.05 mV/sec.

eliminated the light responses. After 10 minutes administration of chloride free Ringer's solution, 10 mM GABA depolarized the light membrane potential by only ~18 mV and did not eliminate the light responses. Fig. 5B shows that glutamate (5 mM) depolarized the light membrane potential by ~70 mV and eliminated the light responses. Under the chloride free environment, 5 mM glutamate depolarized the light membrane potential by ~69 mV and the elimination of the light responses was delayed about a minute longer than that of normal conditions. The dark membrane potential of the horizontal cell were hyperpolarized by ~30 mV and the light responses were abolished when the Ringer's solution was exchanged for sodium-free Ringer's solution (Fig. 5C). Under the sodium-free environment, 5 mM GABA depolarized the membrane potential by ~22 mV with equilibrium potential of −59 mV (below the dark membrane potential) and 5 mM glutamate depolarized the membrane potential by ~16 mV with a depolarizing rate of 0.05 mV/sec.

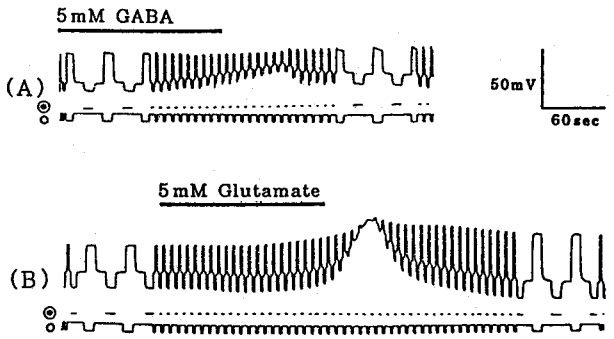

Fig. 6. An intracellular recording from horizontal cells exposed to GABA and glutamate. Each light response was evoked by a 7 sec spot stimulus (700 μm) and 3 sec turned off. During the spot stimulus, 3 sec duration of annulus flashes (1400 μm id, 2100 μm od) were superimposed. Spot stimulus hyperpolarized the dark membrane potential and superimposed annulus produced more hyperpolarization. *A* : GABA (5 mM) application was mainly associated with a reduction of the response amplitude generated by spot stimulus. *B* : Glutamate (5 mM) depolarized the membrane potential and eliminated the light responses.

Effect of GABA on the receptive fields of the horizontal cells

Fig. 6 illustrates an intracellular recording from horizontal cells exposed to GABA and glutamate under center-surround light stimuli. Each light response was evoked by red spot stimulus (700 μm) having a duration of 7 sec and an interstimulus interval of 3 sec as indicated by the square-wave pulses at the bottom of each trace. During the spot stimulus, 3 sec duration of annulus flashes (1400 μm id, 2100 μm od) were superimposed. Spot stimulus hyperpolarized the dark membrane potential and superimposed annulus produced more hyperpolarization. Fig. 6A shows GABA (5 mM) application was mainly associated with a reduction of the response amplitude generated by spot stimulus, indicating that it coupled horizontal cells. Note that the reduction of the responses from the annulus stimuli was much smaller than that from the spot stimuli. Fig. 6B illustrates glutamate (5 mM) depolarized the membrane potential and eliminated light responses. But the amplitude of the response evoked by spot stimuli was selectively enhanced in the recovery phase.

Fig. 7 shows the properties of the receptive fields of the horizontal cells. The stimulus consists of a spot and an annulus centered on the receptive field. Data

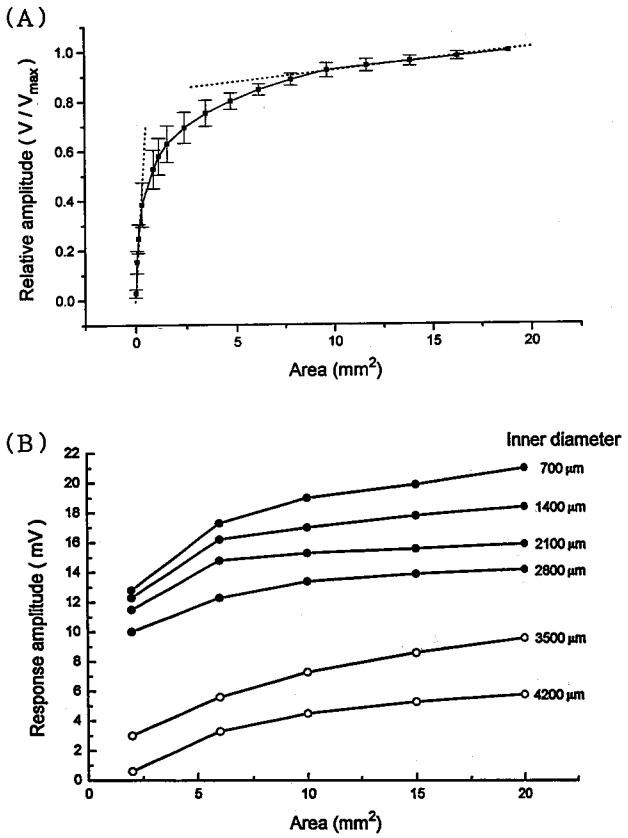

Fig. 7. Graphs show the properties of the receptive fields of the horizontal cells. *A* : data from 5 horizontal cells were normalized and plotted against the area of spot. The amplitude of the responses rapidly increased as the spot area was enlarged in the central area ($\leq$ 2.5 mm^2). And it slowly increased as the spot area was enlarged in the peripheral area ($\geq$ 2.5 mm^2). *B* : response-annulus size relations on the horizontal cell. The amplitude of the responses increased as the outer diameter of the annulus stimuli increased in size while the inner diameter remained fixed in size. The response amplitude of a series of small inner diameter ($\leq$ 2800 μm; solid circle) and that of a series of large inner diameter ($\geq$ 3500 μm; open circle) were discriminated at the small area (~2 mm^2).

from 5 horizontal cells were normalized and plotted against the area of spot in Fig. 7A. The amplitude of responses were increased by magnifying area of spot. The cell responded to the spot by increasing in size to more than 3500 μm of diameter and the curve shows a double phase. The amplitude of the responses rapidly increased as the spot area was enlarged in the central area ($\leq$ 2.5 mm^2). And it slowly increased as the spot area was enlarged in the peripheral area ($\geq$ 2.5 mm^2). Fig. 7B shows response-

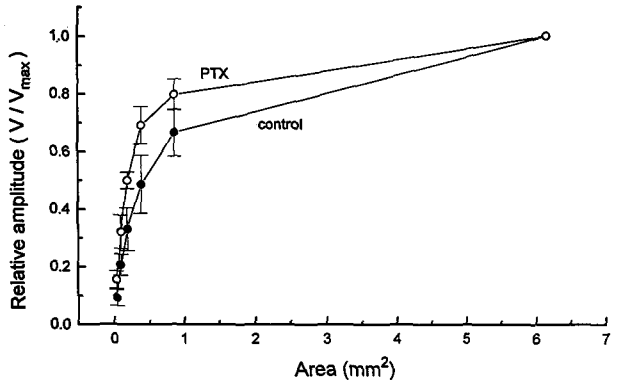

Fig. 8. The normalization of response vs spot size relations are plotted on algebraic scale in normal Ringer's solution (solid circle) and during 1 mM picrotoxin treatment (open circle). Picrotoxin induced a narrowing of the receptive field profile - i.e., an increased contribution of the central area to the response amplitude and a decreased contribution of the peripheral region of the receptive field.

annulus size relations on the horizontal cell. The amplitude of the responses increased as the outer diameter of the annulus stimuli increased in size while the inner diameter remained fixed in size. The response amplitude for the same area decreased as the inner diameter expanded. But the response amplitude of a series of small inner diameters ($\leq$ 2800 μm) and that of a series of large inner diameters ($\geq$ 3500 μm) were discriminated at a small area ($\sim$2 mm^2).

In Fig. 8, the normalization of response vs spot size relations are plotted on algebraic scale in normal Ringer's solution and also during 1mM picrotoxin treatment. Application of picrotoxin resulted in a modest increase ($\sim$100 %) of the large spot ($\geq$ 0.5 mm^2) response, a marked increase ($\sim$180 %) of the small spot ($\leq$0.5 mm^2) response. Thus, picrotoxin induced a narrowing of the receptive field profile - i.e., an increased contribution of the central area to the response amplitude and a decreased contribution of the peripheral region of the receptive field.

DISCUSSION

We found that TACA, kainate, quisqualate and NMDA depolarized the catfish horizontal cells, but muscimol and baclofen did not evoke any change in the membrane potential under the cobalt environment. As chloride equilibrium potential was identified to be

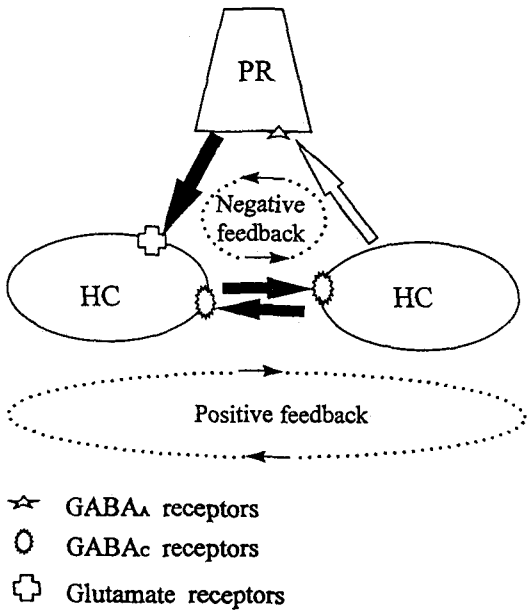

Fig. 9. A simplified schematic illustration of the receptive field formation by chemical coupling. And the horizontal cell forms the positive feedback loop with neighboring horizontal cells via the GABA$_C$ receptors and the negative feedback loop with photoreceptors via the GABA$_A$ receptors. Glutamatergic feedforward signal from the photoreceptors to the horizontal cells links the negative and the positive feedback loops. The symbols of the receptors are indicated on the bottom.

approximately $-$30 mV (Miller & Dacheux, 1983; Dong et al, 1994; Takahashi et al, 1995) and the light evoked potential was $-$70 mV, if muscimol acted on the horizontal cell directly, it should depolarize the cell even under cobalt administration. But muscimol didn't depolarize the horizontal cells under the cobalt environment. Also, muscimol hyperpolarized the dark membrane potential of horizontal cell and bicuculline, the GABA$_A$ receptor antagonist, depolarized the dark membrane potential of horizontal cell (not shown). So, muscimol may suppress synaptic transmission via photoreceptor and bicuculline may block feedback from horizontal cell to photoreceptor. It is presumed that the photoreceptor is suppressed by means of the GABA$_A$ receptor acting on the GABA which is released from a horizontal cell. This causes horizontal cells to be hyperpolarized, thus producing a negative feedback loop. The result is consistent with the results from a turtle and a mudpuppy (Miller et al, 1981; Kaneko & Tachibana, 1986).

In contrast to the above, horizontal cells can produce a positive feedback mechanism. In the cat-

fish retina, intracellular chloride concentration of horizontal cell was about 48 mM estimated by Nernst equation, and chloride equilibrium potential was −27 mV. When the chloride channel is opened by GABA, the membrane potential will be driven close to the chloride equilibrium potential, which causes the cell to depolarize. And GABA released from a horizontal cell can depolarize the neighboring horizontal cells. The depolarization of the horizontal cells leads to more GABA release. Thus a chemical coupling between horizontal cells is formed. It is known that horizontal cells are linked by gap junction (McMahon et al, 1989), but Stockton and Slaughter (1991) observed depolarizing actions by GABA on horizontal cells in the mudpuppy retina. And Kamermans and Werblin (1992) suggested the chemical couplings exist between horizontal cells. Dong et al (1994) reported that there are GABA mediated chemical couplings between horizontal cells in the catfish retina. Takahashi et al (1995) presented the possibility of receptive field formation by chemical coupling. But there has been no anatomical study to indicate that horizontal cells make chemical synaptic connections with neighbouring horizontal cells. However, Sakai and Naka (1986) reported that much of the release of GABA from horizontal cells in fish and toads is Ca^{2+}-independent, suggesting a substantial nonvesicular release of transmitters from horizontal cell processes. So, some of the transmitter released from catfish horizontal cells may be nonvesicular and may not be readily visualized under the electron microscope. Our results suggest that the depolarizing actions by GABA on horizontal cells take place via $GABA_C$ receptors, and it is consistent with results from the other studies on $GABA_C$ receptors (Bai et al, 1993; Dong et al, 1994; Dong & Werblin, 1995). Therefore, it is presumed that there is a positive feedback system via $GABA_C$ receptors between horizontal cells in the catfish retina.

In addition, sodium-free Ringer's solution slightly suppressed the depolarizing actions by glutamate or GABA in the catfish retinal horizontal cell. It is natural that the depolarizing action by glutamate was suppressed in sodium free medium since glutamate opens cation channels, but it is interesting that the depolarization by GABA was suppressed in that medium. It suggested that there is a synergy in the depolarizing actions by GABA and glutamate in the catfish retinal horizontal cells.

Since the horizontal cell forms the positive feedback loop with neighboring horizontal cells via the $GABA_C$ receptors and the negative feedback loop with photoreceptors via the $GABA_A$ receptors in the catfish retina, both of feedback mechanisms and receptive fields by chemical coupling in the outer retina could be summarized as a simplified schematic illustration (Fig. 9).

It is well known that the signal from photoreceptors is transmitted to horizontal cells via glutamate receptors, the signal from the horizontal cells is transmitted to photoreceptors and neighboring horizontal cells via GABA receptors (Bloomfield & Dowling, 1985; Zhou et al, 1993; Witkovsky et al, 1995). And GABAergic horizontal cells provide a sign conserving neurotransmitter input to autoreceptors and to neighboring horizontal cells. So, the chemical coupling may contribute to the formation of a broad antagonistic surrounding in photoreceptors and bipolar cells, in addition to an electrical coupling between horizontal cells (Takahashi et al, 1995).

Meanwhile, many studies on the receptive field formation by electrical synapses have been carried out. Hidaka et al (1989) found electrical junctions between cultured horizontal cells, and DeVries and Schwartz (1992) studied gap junctions between horizontal cells of the catfish by electrophysiological methods. Wolburg and Kurz-Isler (1985) investigated the modulation of the receptive field of horizontal cells by gap junction in goldfish retina. And Piccolino et al (1982) reported that picrotoxin, the $GABA_C$ receptor antagonist, reduced the receptive field of horizontal cells.

It is assumed that the horizontal cells of the catfish retina might use GABA as their transmitters and that the GABAergic system contributes to form receptive fields of the horizontal cells. $GABA_C$ receptors may be involved in a chemical coupling between horizontal cells and concerned with the depolarizing actions by GABA on horizontal cells in the catfish retina. $GABA_A$ receptors may be involved in negative feedback mechanism between photoreceptor and horizontal cell. Moreover, glutamate may be involved in connecting positive and negative feedback systems since it potentiated the GABA's actions. It may cause nonlinearity to modulate information in the outer retina. Therefore, it is presumed that large receptive fields in the catfish retina may be formed not only by electrical coupling but also chemical coupling between horizontal cells. And information may travel laterally by pathways involving both electrical coupling com-

posed of gap junctions and chemical coupling in the outer retina.

ACKNOWLEDGEMENTS

This work was supported by the Research Grant from Korea Science and Engineering Foundation in 1995~97 (F-025529-1). The authors thank Byung-Soo Yoon, the president of Choong-book Fish Farmers Association and Joong-ang fisheries Co. for providing the fresh catfish.

REFERENCES

Bai SH, Jung CS, Lee SJ. Electrophysiological analysis of GABA and glycine action on neurons of the catfish retina. *Kor J Physiol* 27: 163−174, 1993

Barnstable CJ. Glutamate and GABA in retinal circuitry. *Current Opinion in Neurobiol* 3: 520−525, 1993

Bloomfield SA, Dowling JE. Roles of aspartate and glutamate in synaptic transmission in rabbit retina. I. Outer plexiform layer. *J Neurophysiol* 53: 699−713, 1985

Cammack JN, Schwartz EA. Ions required for the electrogenic transport of GABA by horizontal cells of the catfish retina. *J Physiol (Lond)* 472: 81−102, 1993

Cook JE, Becker DL. Gap junctions in the vertebrate retina. *Microscopy Res Tech* 31: 408−419, 1995

DeVries SH, Schwartz EA. Hemi-gap-junction channels in solitary horizontal cells of the catfish retina. *J Physiol (Lond)* 445: 201−230, 1992

Djamgoz MBA. Diversity of GABA receptors in the vertebrate outer retina. *TINS* 18: 118−120, 1995

Dong CJ, Picaud SA, Werblin FS. GABA transporters and $GABA_C$-like receptors on catfish cone- but not rod-driven horizontal cells. *J Neurosci* 14: 2648−2658, 1994

Dong CJ, Werblin FS. Zinc downmodulates the $GABA_C$ receptor current in cone horizontal cells acutely isolated from the catfish retina. *J Neurophysiol* 73: 916−919, 1995

Grant GB, Dowling JE. A glutamate-activated chloride current in cone-driven on bipolar cells of the white perch retina. *J Neurosci* 15: 3852−3862, 1995

Hals G, Christensen BN, O'Dell T. Voltage-clamp analysis of currents produced by glutamate and some glutamate analogues on horizontal cells isolated from the catfish retina. *J Neurophysiol* 56: 19−31, 1986

Hidaka S, Shingai R, Dowling JE, Naka KI. Junctions form between catfish horizontal cells in culture. *Brain Res* 498: 53−63, 1989

Kamermans M, Werblin F. GABA-mediated positive auto feedback loop controls horizontal cell kinetics in tiger salamander retina. *J Neurosci* 12: 2451−2463, 1992

Kaneko A, Tachibana M. Effects of γ-aminobutyric acid on isolated cone photoreceptors of the turtle retina. *J Physiol (Lond)* 373: 443−461, 1986

Lam DM, Lasater EM, Naka KI. γ-Aminobutyric acid: A neurotransmitter candidate for cone horizontal cells of the catfish retina. *Proc Natl Acad Sci USA* 75: 6310−6313, 1978

McMahon DG, Knapp AG, Dowling JE. Horizontal cell gap junctions: Single-channel conductance and modulation by dopamine. *Proc Natl Acad Sci USA* 86: 7639−7643, 1989

Miller RF, Dacheux RF. Intracellular chloride in retinal neurons: measurement and meaning. *Vision Res* 23: 399−411, 1983

Miller RF, Frumkes TE, Slaughter M, Dacheux RF. Physiological and pharmacological basis of GABA and glycine action on neurons of mudpuppy retina. I. Receptors, horizontal cells, bipolars and G-cells. *J Neurophysiol* 45: 743−763, 1981

Murakami M, Ohtsu K, Ohtsuka T. Effects of chemicals on receptors and horizontal cells in the retina. *J Physiol (Lond)* 227: 899−913, 1972

Naka KI, Garraway NRG. Morphological and functional identifications of catfish retinal neurons. I. Classical Morphology. *J Neurophysiol* 38: 53−71, 1975

Naka KI, Nye PW. Receptive-field organization of the catfish retina: Are at least two lateral mechanisms involved? *J Neurophysiol* 33: 625−642, 1970

Naka KI, Ohtsuka T. Morphological and functional identifications of catfish retinal neurons. II. Morphological identification. *J Neurophysiol* 38: 72−91, 1975

O'Dell TJ, Christensen BN. Horizontal cells isolated from catfish retina contain two types of excitatory amino acid receptors. *J Neurophysiol* 61: 1097−1109, 1989

Piccolino M, Neyton J, Witkovsky P, Gerschenfeld HM. γ-Aminobutyric acid antagonists decrease junctional communication between L-horizontal cells of the retina. *Neurobiol* 79: 3671−3675, 1982

Sakai HM, Naka KI. Synaptic organization of the cone horizontal cells in the catfish retina. *J Comp Neurol* 245: 107−115, 1986

Stockton RA, Slaughter MM. Depolarizing actions of GABA and glycine on amphibian retinal horizontal cells. *J Neurophysiol* 65: 680−692, 1991

Takahashi KI, Miyoshi SI, Kaneko A. GABA-Induced Chloride Current in Catfish Horizontal Cells Mediated by Non-$GABA_A$ Receptor Channels. *Jpn J Physiol* 45: 437−456, 1995

Vaughan DK, Lasater EM. Renewal of electrotonic synapses in teleost retinal horizontal cells. *J Comp Neurol*

299: 364−374, 1990

Witkovsky P, Gabriel R, Krizaj D, Akopian A. Feedback from luminosity horizontal cells mediates depolarizing responses of chromaticity horizontal cells in the Xenopus retina. *Proc Natl Acad Sci USA* 92: 3556−3560, 1995

Wolburg H, Kurz-Isler G. Dynamics of gap junctions between horizontal cells in the goldfish retina. *Exp Brain Res* 60: 397−401, 1985

Zhou ZJ, Fain GL, Dowling JE. The excitatory and inhibitory amino acid receptors on horizontal cells isolated from the white perch retina. *J Neurophysiol* 70: 8−19, 1993