An electronic circuit model on cone cell pathway

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Abstract: - In this article, an electronic circuit model on cone cell pathway is presented when a light stimulus is given to at the center of receptive field. The circuit model can simulate potential change characteristics of corresponding classes of neurons in the retina when visual information is transferred through the cone cell pathway. These characteristics include photoelectric conversion and hyperpolarization characteristics of cone cell, depolarization and hyperpolarization characteristics of bipolar cell, and action potential generation characteristics of ganglion cell. The simulation results of the circuit model qualitatively accord with potential change characteristics of the real neurons.

Key-Words: - cone cell; bipolar cell; ganglion cell; potential; circuit model; simulation waveform

1 Introduction

In daylight, the cone cell pathway plays a main role in generating vision. In the primate, when a light flash shines on the center of receptive field, transfer process of visual information through cone cell pathway shows in figure1. Visual information is transmitted from one cone cell to two types of bipolar cell at the same time, which are on-center and off-center bipolar cell [1-3], and then transmitted to corresponding ganglion cell, namely on-center and off-center ganglion cell [4, 5]. At last the visual information that comes from the output of ganglion cell is sent through the optic nerve to higher centers in the brain for further processing necessary for vision [6, 7].

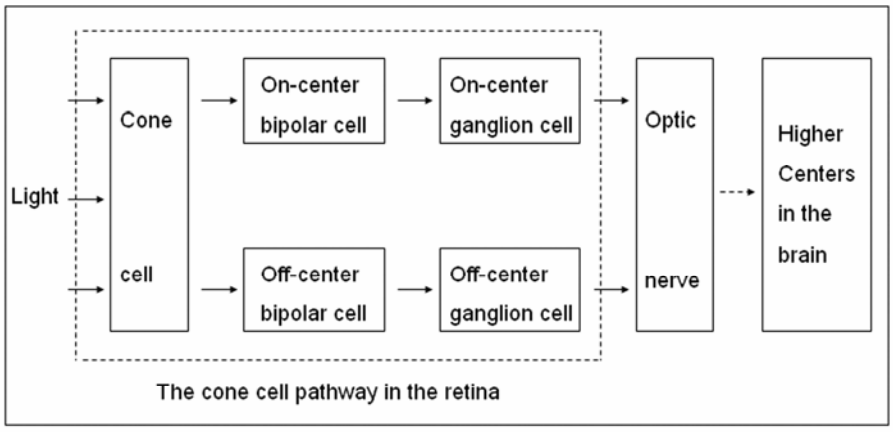

Fig. 1. Block diagram of transfer process of visual information through cone cell pathway in the primate while a light flash shines the center of receptive field.

The cone cell is one type of the photoreceptors. It can carry out absorption of light and transduction into electrical signals. When cone cells in the center of the receptive field are active because of a brief light stimulus, they hyperpolarize [8]. Hyperpolarization of cone cells make voltage-gated Ca^{2+} channels in their synaptic terminals close, reducing the Ca^{2+} influx and the amount of neurotransmitter, glutamate, which cells release [9-12]. As a result, the on-center bipolar cells

depolarize and off-center bipolar cells hyperpolarize [13, 14, 7]. The two subsets of bipolar cell make direct synaptic contact with the cone cell and the corresponding type of ganglion cell. Depolarization of the on-center bipolar cell in response to a light flash leads to depolarization of the on-center ganglion cell and hyperpolarization of the off-center bipolar cell in response to light hyperpolarize off-center ganglion cell [15, 16]. According to intracellular recordings, cone cell and bipolar cell respond to light with graded changes in membrane potential and ganglion cell produce action potential in response to light [13, 17, 18].

The knowledge from above makes it possible to construct an electronic circuit model on cone cell pathway [19], through this model, we can get a greater understanding on the activity of every neuron in the cone cell pathway and the transfer process of visual information along the pathway. The model includes three parts: First one is the circuit model about photoelectric conversion and hyperpolarization characteristics of cone cell; Second one is the circuit model about depolarization and hyperpolarization characteristics of on-center and off-center bipolar cell; Last one is the action potential generation circuit model of on-center and off-center ganglion cell. These circuits are composed of discrete components, operational amplifiers and 555 timers. They are modeled and simulated with SPICE. The validity of this model is tested by simulation waveforms that qualitatively accord with the intracellular recording curves.

2 Methods and results

2.1 The cone cell circuit model

The cone cell circuit model includes photoelectric conversion circuit (Fig.2) and hyperpolarization circuit of cone cell in response to light (Fig.3(a)).

In figure 2, RL is a light dependent resistor (LDR), Rs is a 1Ω resistor, Vs is a 5V source. When the LDR is in the light, its resistance is set 500Ω, thus the voltage drop V_{Rs} across Rs is about 10mV.

When the LDR is in the shade, its resistance is set 1MΩ, and then the voltage drop V_{Rs} across Rs is about 5μV.

In the circuit of figure 3(a), the square wave plus V1 as stimulation source that comes from V_{Rs} in Fig.2 is given by

$$V1 = V_{Rs} \approx \begin{cases} 10mV, & 0.5ms < t \le 2.5ms \\ 0, & 0 \le t \le 0.5ms, 2.5ms < t \le 6ms \end{cases} \quad (1)$$

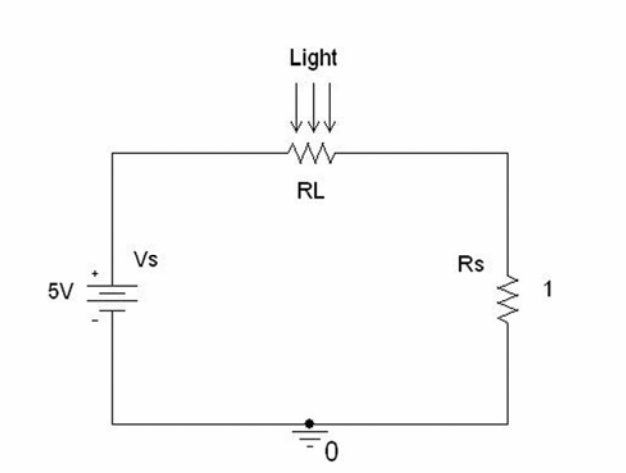

Fig. 2. The photoelectric conversion circuit of cone cell.

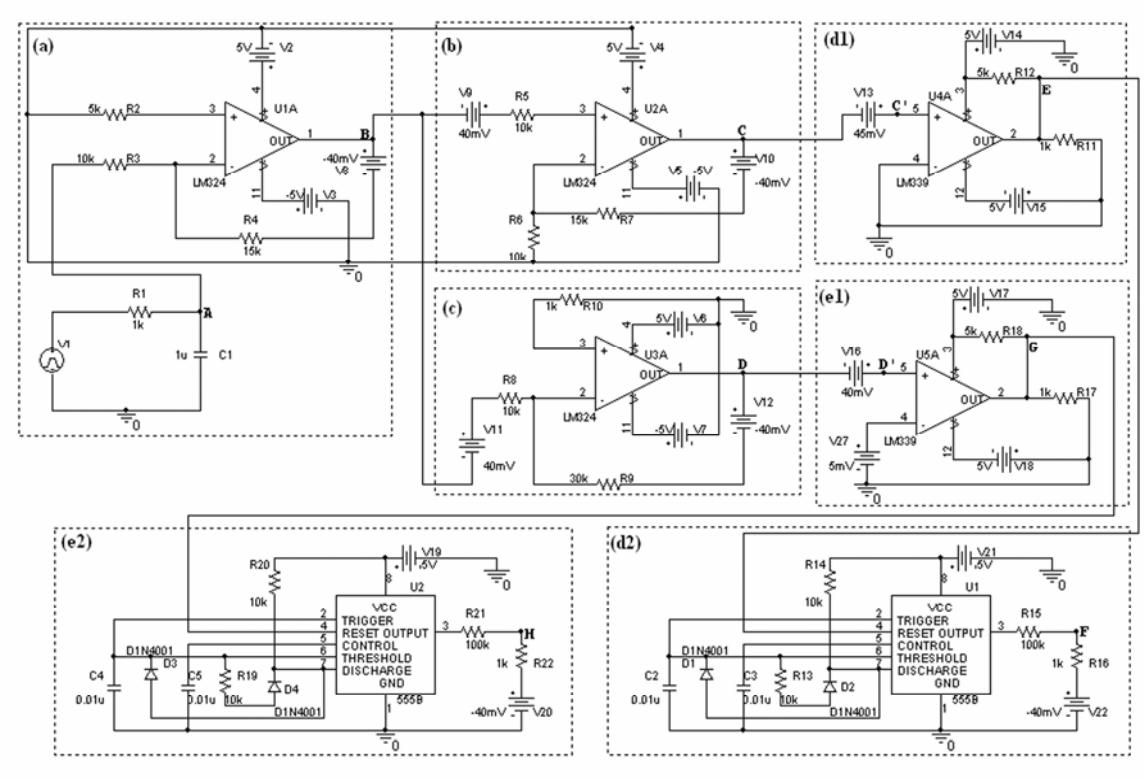

Fig. 3. The electronic circuit model of cone cell pathway in the primate while a light flash shines the center of receptive field. (a) Hyperpolarization circuit of cone cell. (b) Potential transmission circuit of off-center bipolar cell. (c) Potential transmission circuit of on-center bipolar cell. (d1) and (d2) Action potential generation circuit of off-center ganglion cell. (e1) and (e2) Action potential generation circuit of on-center ganglion cell.

For the series R1C1 circuit, the capacitor C1 voltage is V_A. An expression for V_A is illustrated in equation (2):

$$V_A = \begin{cases} 0 & 0 \le t \le 0.5ms \\ V1[1-\exp(-\dfrac{t-0.5\times10^{-3}}{R1C1})], & 0.5 \le t \le 2.5ms \\ V1[1-\exp(-\dfrac{2.5\times10^{-3}}{R1C1})]\exp(-\dfrac{t-2.5\times10^{-3}}{R1C1}), & 2.5ms < t \le 6ms \end{cases} \quad (2)$$

V_A can simulate the shape of the potential change curve of cone cell.

The resistors R2, R3, R4 and operational amplifier U1A constitute inverting amplifier that gets hyperpolarized curve matching the real curve qualitatively. The output voltage of inverting amplifier is V_B. The expression for V_B is given by:

$$V_B = -\frac{R4}{R3} V_A - 4\times10^{-2} \quad (3)$$

The waveform of V1, V_A, V_B are shown in fig.4. The waveform of V_B functionally conform to hyperpolarized potential change of cone cell by light.

The cone cell has amplification characteristic that can be simulated by changing the ratio of R4 to R3 in equation (3).

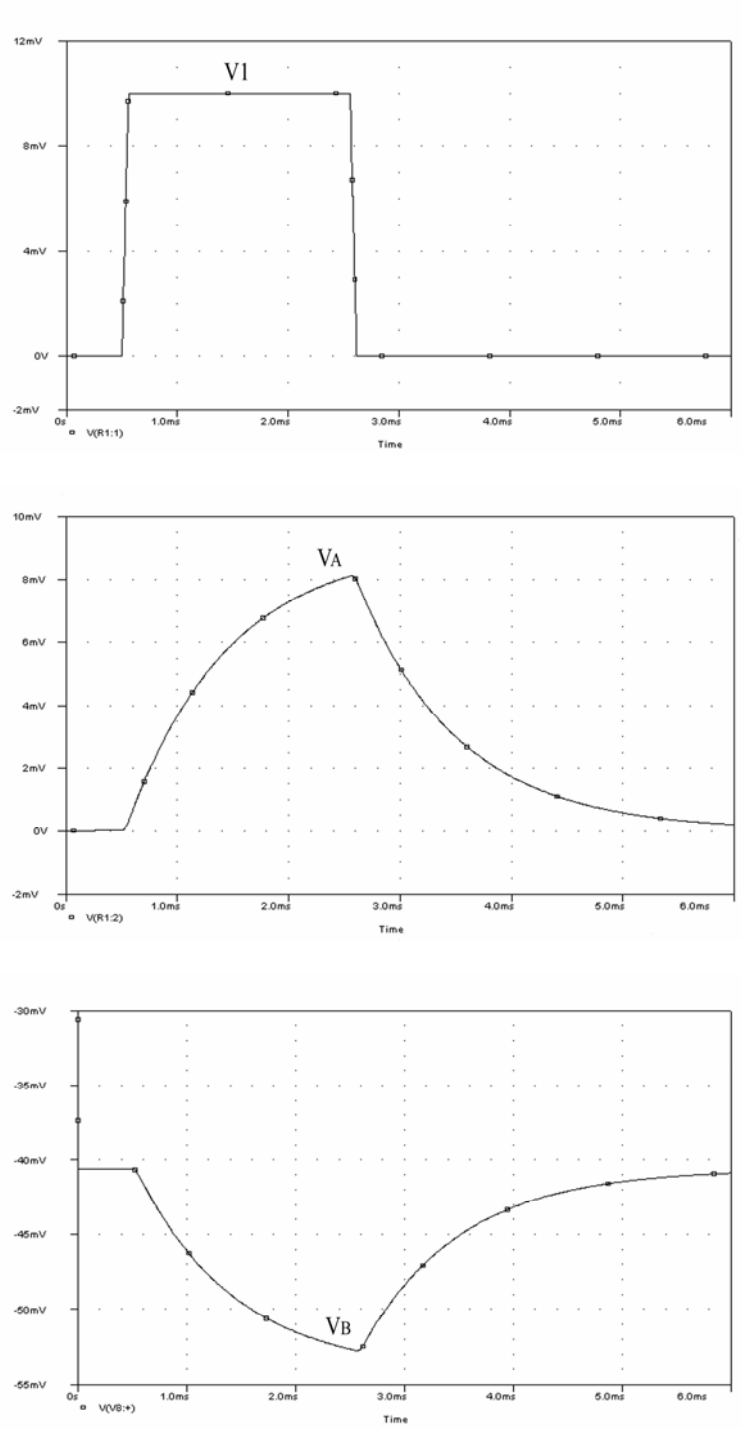

Fig. 4. The waveforms of V1, V_A, and V_B. V1, the square wave plus as stimulation source; V_A, the capacitor C1 voltage; V_B, the cone cell potential.

2.2 The potential transmission circuit model of bipolar cell

For bipolar cells, on-center bipolar cell and off-center bipolar cell are referred in this article. In response to light, they are depolarized and hyperpolarized, respectively.

As shown in fig.3(b), the potential transmission circuit of off-center bipolar cell is composed of resistors R5,R6,R7 and amplifier U2A. It is a noninverting amplifier. The output voltage V_C is the potential of off-center bipolar cell. The

expression of V_C is given by equation (4):

$$V_C = V_B \ (1+\frac{R7}{R6}) - 4\times10^{-2} \qquad (4)$$

As shown in fig.3(c), resistors R8,R9,R10 and amplifier U3A constitute the potential transmission circuit of on-center bipolar cell. It is an inverting amplifier. The output voltage V_D is the potential of on-center bipolar cell. The expression of V_D is given by equation (5):

$$V_D = -\frac{R9}{R8} \ V_B - 4\times10^{-2} \qquad (5)$$

Off-center bipolar cell and on-center bipolar cell can amplify signals [20, 21]. This function can be carried out through changing the ratio of R7 to R6 in equation (4) and the ratio of R9 to R8 in equation (5).

The waveforms of V_C and V_D are shown in fig.5. They all functionally accord with potential change characteristics of the real neurons.

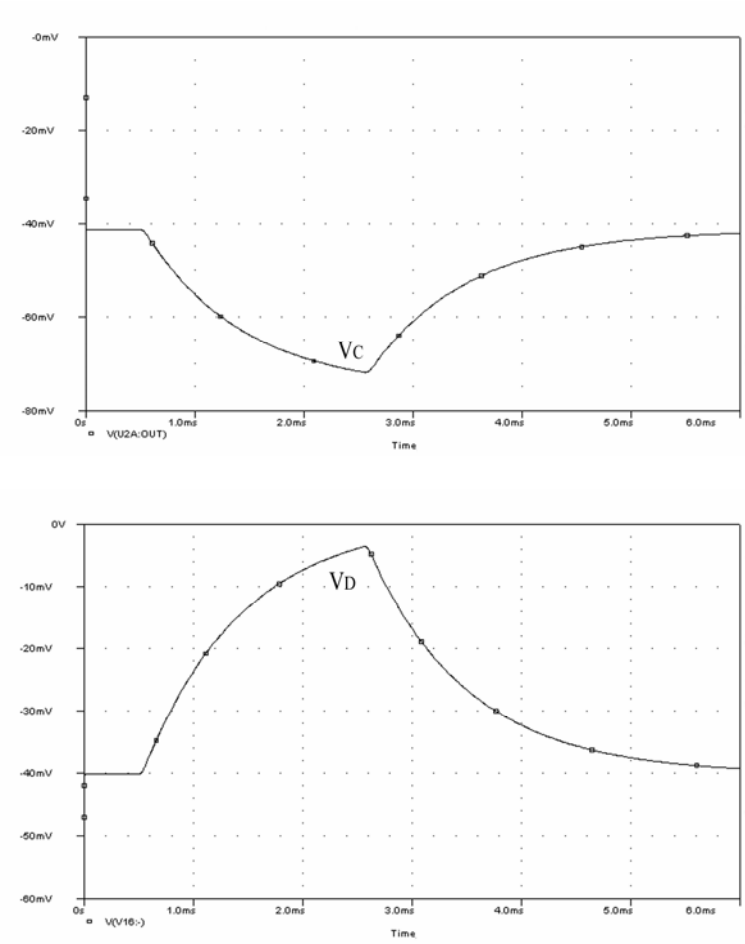

Fig. 5. waveforms of V_C and V_D. V_C, the potential of off-center bipolar cell; V_D, the potential of off-center bipolar cell.

2.3 Action potential generation circuit model of ganglion cell

In fig.3, the circuit (d1) and (d2) form action potential generation circuit of off-center ganglion cell. The circuit fig.3(d1) is a voltage comparator circuit that is made up of resistors R11, R12 and voltage comparator U4A. It can convert graded local potential V_C that is produced by off-center bipolar cell into digital signal V_E. When the input voltage $V_{C'}$ of the comparator U4A is above zero voltage, the output V_E of the comparator is HIGH level. When the input voltage $V_{C'}$ is below zero voltage,

the output V_E is LOW level. The waveforms of $V_{C'}$ and V_E are shown as fig.6. The circuit fig.3(d2) is a multivibrator that consists of 555 timer U1 and some of resistors, capacitors and diodes. The output V_F of 555 timer U1 is the action potential of off-center ganglion cell. The action potential of ganglion cell is a digital signal with constant amplitude and adjustable frequency. When V_E is LOW level, V_F is also LOW level. When V_E is HIGH level, V_F is a pulse sequence and the period T_{V_F} of V_F can be calculated with the formula:

$$T_{V_F} = T_{FH} + T_{FL} = 0.7 \times R14 \times C2 + 0.7 \times R13 \times C2 \quad (6)$$

Where the high time T_{FH} from each pulse is given by

$$T_{FH} = 0.7 \times R14 \times C2$$

and the low time T_{FL} from each pulse is given by

$$T_{FL} = 0.7 \times R13 \times C2$$

The frequency of action potential V_F of off-center ganglion cell can be adjusted by changing the values of R13 and R14 in formula (6). The waveform of V_F is shown as figure 7.

In fig.3, the action potential generation circuit of on-center ganglion cell includes circuit (e1) and (e2).

The circuit figure (e1) is a voltage comparator circuit that is composed of resistors R17, R18 and voltage comparator U5A. It can convert graded local potential V_D that is produced by on-center bipolar cell into

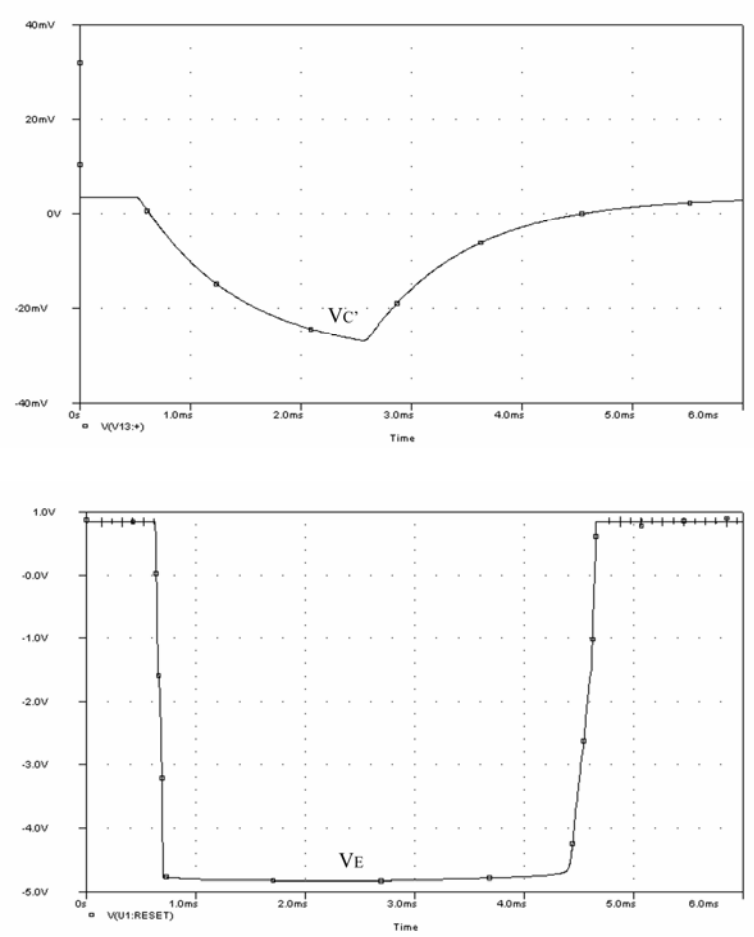

Fig. 6. The waveforms of $V_{C'}$ and V_E. $V_{C'}$, the input of the voltage comparator U4A; V_E, the output of the voltage comparator U4A.

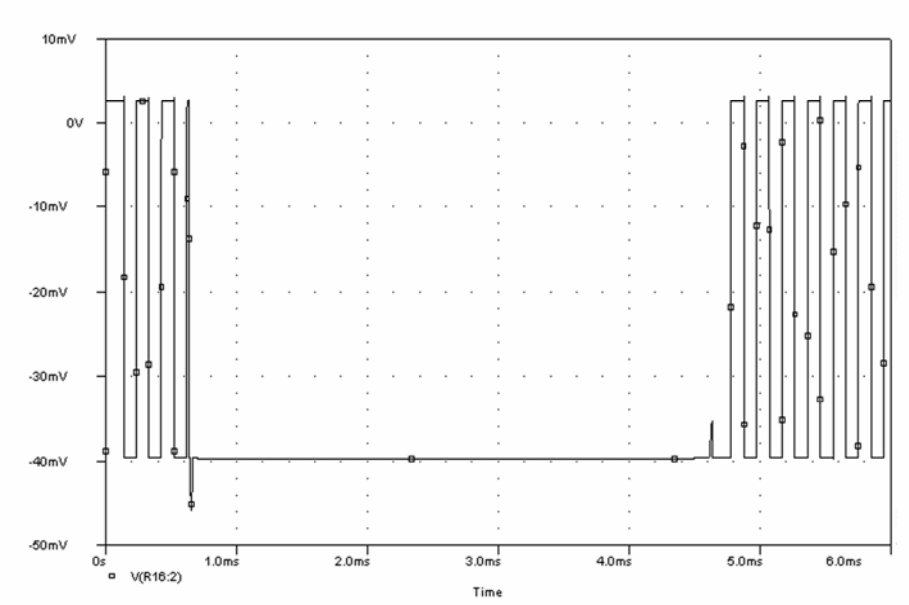

Fig. 7. The waveform of V_F . V_F , the action potential of off-center ganglion cell.

digital signal V_G . When the input voltage $V_{D'}$ of the comparator U5A is above 5 mV, the output V_G of the comparator is HIGH level. When the input voltage $V_{D'}$ is below 5 mV, the output V_G is LOW level. The waveforms of $V_{D'}$ and V_G are shown as fig.8. The circuit fig.3(e2) has the same structure and function with the circuit fig.3(d2). The output V_H of 555 timer U2 is the action potential of on-center ganglion cell. When V_G is LOW level, V_H is also LOW level. When V_G is HIGH level, V_H is a pulse sequence and the period T_{V_H} of V_H can be calculated with the formula:

$$T_{V_H} = T_{HH} + T_{HL} = 0.7 \times R20 \times C4 + 0.7 \times R19 \times C4 \quad (7)$$

Where the high time T_{FH} from each pulse is given by

$$T_{HH} = 0.7 \times R20 \times C4$$

and the low time T_{FL} from each pulse is given by

$$T_{HL} = 0.7 \times R19 \times C4$$

The frequency of action potential V_H of on-center ganglion cell can be adjusted by changing the values of R19 and R20 in formula (7). The waveform of V_H is shown as fig.9.

3 Discussion

In this article, based on the retinal anatomic structure and electrophysiology characteristics, an electronic circuit model on cone cell pathway is designed by 555 timers, operational amplifiers and discrete components. Because of the non-linearity and complexity of biological system, it is difficult to establish a model for accurately and quantificationally imitate potential changing of every neuron in the cone cell pathway. The model proposed in this paper can functionally simulate electrophysiology characteristics of cone cell, bipolar cell and ganglion cell when visual information is transmitted through the cone cell pathway. But in the qualitative study, some quantitative considerations are given. First, the potential change of every neuron starts from the resting potential. In the circuit of fig.3, all the output sides of circuit of every neuron are added a voltage source. These voltage sources are V8, V10, V12, V20 and V22 whose values are corresponding resting potential of cone cell, off-center bipolar cell, on-center bipolar cell, on-center ganglion cell and off-center ganglion cell, respectively. All these values are set -40mV because the resting potentials of these neurons are about -40mV. The input sides of the circuits of bipolar cell and ganglion cell also add voltage sources V9, V11, V13, and V16. The values of V9, V11, and V16 are 40mV that offset the resting potential attached the output side of the front stage cell circuit. This practice makes the input

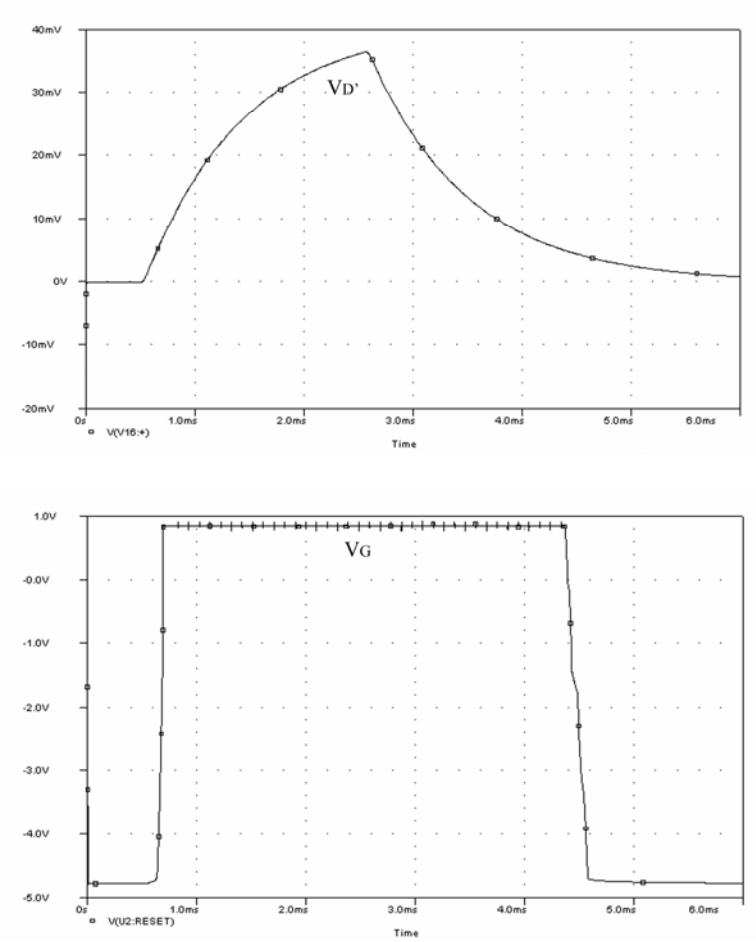

Fig. 8. The waveforms of $V_{D'}$ and V_G . $V_{D'}$, the input of the voltage comparator U5A ; V_G, the output of the voltage comparator U5A.

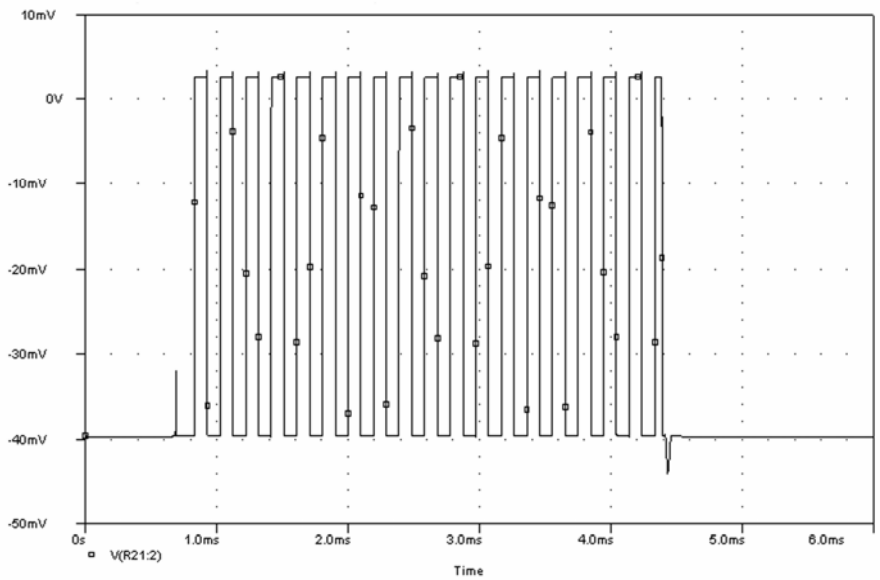

Fig. 9. The waveform of V_H . V_H, the action potential of on-center ganglion cell.

signal of the present stage circuit change from 0V and therefore, it is easy to control output of the circuit. V13 is set 45mV. There are two reasons for setting this value. First, it offset the resting potential

of the output side of the front stage cell circuit. Second, the zero potential of input signal is improved 5mV in order to compare with zero voltage of MINUS input of voltage comparator U4A, and a reasonable output signal can be got through this setting. Next, the potential of neurons that are mentioned in this article ranges from several millivolt to several hundred millivolt [22, 23], it can be carried out by changing values of the resistors to vary voltage gain or using resistor voltage divider.

The circuit model on cone cell pathway presented in this article is mainly a function model of neurons. The purpose of establishing model is to research the relationship between input voltage and output voltage of every neuron in the cone cell pathway, so as to explain information processing capacity of all classes of neurons in the cone cell pathway when a brief light shines the center of receptive field.

In the research of circuit modeling of retina, the researchers pay only attention to circuit modeling of a single neuron in the retina or considering retina as a whole. In this article, an electronic circuit model that reflects the relationship of all neurons in the cone cell pathway of retina is presented. This model can effectively combine the characteristics of a single neuron with the retinal whole function. It can more truly clarify the biological mechanism of the retina and provides a new way for the research of retinal modeling.

Acknowledgements

I thank Professor Yoshihiro Mano and Dr. Fang Liu for their help in developing the research project and Professor Hidetoshi Wakamatsu for his encouragement. I am also grateful to Professor Yukichi Hara, Professor Kenji Sato, and Professor Masato Matsuura for critically reading the manuscript. This work was supported by a research scholarship from Japanese Ministry of Education, Culture, Sports, Science, and Technology.

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