

# The Effect of Electrotonus on the Olfactory Epithelium

SHOJI HIGASHINO and SADAYUKI F. TAKAGI

From the Department of Physiology, School of Medicine, Gunma University, Maebashi, Japan

**ABSTRACT** The effect of electrotonus on the slow potential of the olfactory epithelium of the frog was studied. The "on"-slow potential induced by a general odor like amyl acetate increased its magnitude in accordance with increase of anodal current, while it decreased its magnitude with increase of cathodal current. Similar relations were also found in the case of the vapors of organic solvents like ethyl ether of low concentrations. Conversely, the on-slow potential induced by the vapors of organic solvents of high concentration decreased its magnitude in accordance with the increase of anodal current, while it increased its magnitude with the increase of cathodal current. The "off"-slow potential induced by the vapors of organic solvents of high concentration showed a potential change under the action of electrotonic currents which is similar to the change of the on-slow potential induced by general odors. It was concluded that there are two receptive processes in the olfactory cell. One is an ordinary excitatory process which produces an electronegative slow potential in response to general odors. The other is a process of a different kind which is activated only by the vapor of an organic solvent of high concentration and which shows an entirely opposite reaction from that generally found in excitable tissues when an electrotonic current is applied.

Since the pioneer work by Hosoya and Yoshida (1937) and especially since the work of Ottoson (1954, 1956, 1958, 1959 *a, b*), the slow potential of the olfactory epithelium has been known as an interesting subject for research. Some work has already been performed in our laboratory (Takagi and Shibuya, 1959, 1960 *a, b, c, d, e*, 1961; Shibuya 1960; Higashino, Takagi, and Yajima, 1961). Among the results, the one that concerns us here is that the vapors of some organic solvents such as ethers, chloroform, etc. produce slow potentials of the "on"-type at low concentrations, while they produce slow potentials of the "off"-type at high concentrations. Moreover, at these high concentrations, they often produce on-slow potentials of reversed polarity (electropositive) (Takagi, Shibuya, Higashino, and Arai, 1960; Shibuya and Takagi, 1962, 1963). Thus, three kinds of slow potentials, the electronegative "on"-, electro-

positive "on"-, and electronegative "off"-slow potentials were found in the olfactory epithelium. It has recently been proved that these three potentials originate in the olfactory cell (Takagi and Yajima, 1964 *a, b*).

This research work was intended to clarify the properties of these three slow potentials. By applying electrotonic currents to the olfactory epithelium, the changes in magnitude and polarity of these potentials have been studied. The generative mechanisms of these potentials are considered.

#### METHODS

Frogs, *Rana nigromaculata* and *Rana catesbiana*, were used. Under ether narcosis, they were decapitated. The heads were pinned onto a cork plate. The dorsal skin and bones

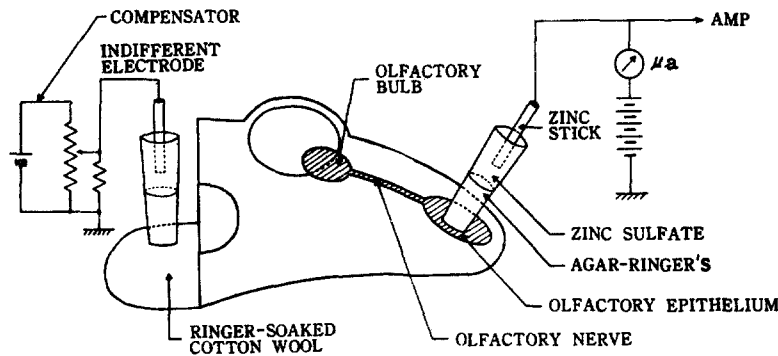


FIGURE 1. Experimental arrangement for recording from the olfactory epithelium. An exploring non-polarizable electrode was put on the olfactory eminentia. An indifferent electrode was put onto the Ringer-soaked cotton wool around the head. Electrotonic currents were applied through these electrodes. A compensator was set in series with the indifferent electrode.

were removed and the olfactory epithelium was exposed. As recording electrodes, a pair of non-polarizable ( $\text{Zn-ZnSO}_4$ -agar-Ringer's solution) glass electrodes with tip diameter of 1.2 mm was used. This sort of electrode has already been recommended as best by Kimura (1961) and Mozell (1962), since with this electrode non-biological artifactual responses were either non-existent or so small that they could not be measured. An exploring electrode was put on the olfactory eminentia to record the slow potential produced by the application of an odor. An indifferent electrode was put on Ringer-soaked cotton wool around the head (Fig. 1). The slow potential was recorded through a DC coupled amplifier with an ink-writing recorder.

These same electrodes were used to apply an electrotonic current. It was applied in steps of  $5 \mu\text{a}$  from 0 up to 20 or 25  $\mu\text{a}$ . When the electrode on the eminentia is electropositive, the current is called "anodal current," and when electronegative, the current is called "cathodal current." Experiments were not performed with currents beyond 25  $\mu\text{a}$ , because in those cases the base line of the ink-writing recorder became too unstable to show any reliable results.

When an electrotonic current was applied through the electrodes, the base line of the ink-writing recorder was displaced. This displacement was corrected by adjusting

the voltage of a compensator which was put in series with the indifferent electrode (Fig. 1).

As odorous substances, amyl acetate, turpentine oil, ethyl ether, propyl ether, and chloroform were used. Saturated vapors of these substances were, if necessary, diluted to the concentrations of one-fourth, one-eighth, and one-sixteenth by adding air purified by passing through active charcoal. These experiments were performed at room temperatures of 15 to 20°C. The vapors were stored in 20 ml syringes, and were blown onto the olfactory epithelium through lucite tubes of 0.7 mm inside diameter. It is known that a lucite tube has its own odor, though very faint, and besides, it adsorbs odors. Consequently, before the experiment, lucite tubes were put in boiling

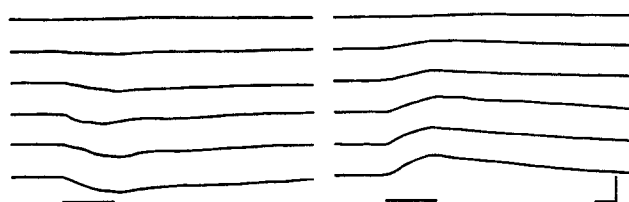


FIGURE 2. Appearance of spurious slow potentials. When purified air obtained through active charcoal is applied to the olfactory epithelium, a slow potential scarcely appears (top records on both sides). However, when the same air is applied under the action of an electrotonic current, a slow potential appears and increases in magnitude with increasing current. Records on the left show the effect of anodal currents and the ones on the right show the effect of cathodal currents. Electrotonic currents were applied in steps of  $5 \mu\text{a}$  from the second top to the bottom. Similar potentials were obtained when the same air was applied to the electrode put on the Ringer-soaked filter paper. They all are spurious potentials. The horizontal bars at the bottom indicate application of the stimulus. Calibrations of 1 mv and 1 sec. are shown at the lower right.

water for more than an hour and then were cleaned by passing distilled water through them. In order to avoid adsorption, odors of different concentrations and of different kinds were applied through their own tubes.

The tips of the tubes were kept at a distance of more than 1.5 cm from the epithelial surface in order to be free from continuous stimulation by odors diffusing out spontaneously. The odors were applied at the rate of 0.3 to 1.4 ml per sec.

In each experiment, purified air was applied as a control. With this type of electrode and with the amplification used (1 mm for  $100 \mu\text{v}$ ), purified air produced a scarcely measurable slow potential, which if present, was electronegative and of a magnitude of less than  $100 \mu\text{v}$ . Thus, the larger slow potentials, which were produced by odors, could be regarded as receptor potentials of the olfactory epithelium.

When, however, purified air was applied, a kind of slow potential appeared under the influence of an electrotonic current. It increased its electropositivity with increase of an anodal current and increased its electronegativity with increase of a cathodal current (Fig. 2). Thus, a linear relationship was found between the potential magnitude and the applied current (see Figs. 2 and 5). Similar potentials and a similar relationship can be obtained even when purified air is applied to a non-polarizable electrode put on a Ringer-soaked filter paper or on an olfactory epithelium in which

the olfactory cells had nearly completely degenerated due to the section of the olfactory nerve many days previously. Fig. 3 shows relationships obtained in such an olfactory epithelium. In this epithelium, olfactory cells had degenerated so well that they did not show any slow potential at all in response to various odors (Takagi and Yajima, 1964 *a, b*). It is noted that the relationships obtained by applying purified air, amyl acetate vapor, and ethyl ether vapor all coincide very well. The lucite tubes which were cleaned as mentioned above may still have some odor. If so, the slow potential–electrotonic current relationship should be similar to the ones obtained

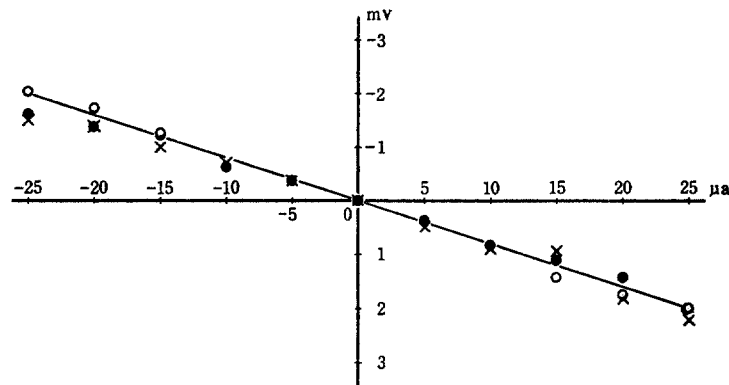


FIGURE 3. Relations between the amplitudes of the spurious slow potential and the applied currents. In the olfactory epithelium where the olfactory cells had nearly completely degenerated, spurious potentials were obtained by the application of purified air (indicated by open circles), amyl acetate vapor (indicated by filled circles), and ethyl ether vapor (indicated by x), only under the influence of the electrotonic currents. The potential amplitude–current intensity relationships in these cases coincided very well. It is clear that special odors do not add any potentials to the one produced by purified air.

by the application of general odors (see Fig. 5). In fact the former relationship is entirely opposite to the latter ones. From these observations, it can be concluded that the slow potentials which appear only under the influence of electrotonic currents (Figs. 2 and 3) are artifactual and that they are produced because a resistance between the electrode and the tissue is temporarily changed by air current. When slow potentials produced by various odors were recorded under the action of electrotonic currents, this spurious potential was also recorded as a control. After subtracting the latter potential from the former ones, real relations between the applied currents and the magnitudes of the slow potentials were sought.

These experiments were performed chiefly on the autumn frog. The experimental results obtained in the spring frog were found to be less reproducible.

## RESULTS

### A. On the Slow Potentials Induced by Amyl Acetate and Turpentine Oil Vapors

An electrotonic current was applied to the olfactory epithelium, and the slow potential induced by a saturated vapor of amyl acetate was recorded. When

an anodal current was applied, the slow potential increased its magnitude in accordance with an increase of the current from 5 to 25  $\mu a$  (Fig. 4, left). In a few cases, however, with a current beyond 20  $\mu a$ , the slow potential scarcely increased, or conversely decreased its magnitude, though slightly. When a cathodal current was applied, the slow potential decreased its magnitude in accordance with an increase of the current from 5 to 25  $\mu a$  (Fig. 4, right). The maximal magnitudes of these slow potentials were plotted on a graph against the electrotonic currents applied (Fig. 5). Similar relations were found in the case of turpentine oil vapor. The slopes of the curves were different in different

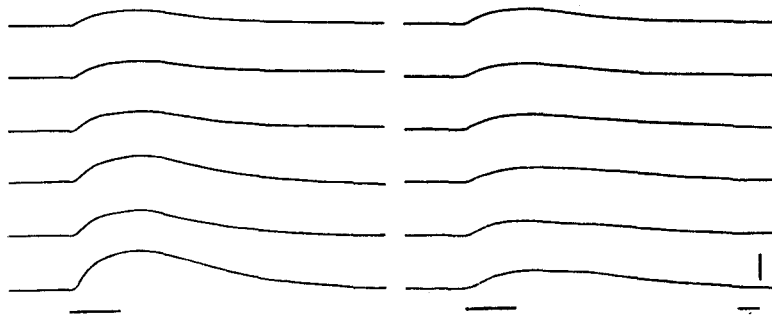


FIGURE 4. Slow potentials induced by the vapor of amyl acetate. Top records on both sides are the control slow potentials which were obtained without electrotonic currents. The slow potentials from the second record to the bottom show the effect of anodal current on the left and that of cathodal current on the right. Currents were applied in steps of 5  $\mu a$  up to 25  $\mu a$ . The horizontal bars at the bottom indicate the duration of stimulation. Calibrations of 1 mv and 1 sec. are shown at the lower right.

frogs. They were also dependent upon the kinds and concentrations of odors. In general, the slope increased when the concentration was increased. But the general tendency of the slopes was the same, from the left bottom upwards to the right top. Under the influence of an electrotonus, an off-slow potential was seldom induced by these vapors.

These relations are comparable to those found in other excitable tissues, as will be discussed later.

#### B. *On the Slow Potentials Induced by Ethers and Chloroform Vapors*

Electrotonic currents were applied to the olfactory epithelium, and the on- and the off-slow potentials induced by saturated vapor of ethyl ether were recorded. The on-slow potential decreased its magnitude with increasing anodal current, and at a certain current intensity it disappeared. With an increase of current beyond this level, the slow potential appeared with a reversed polarity and increasing magnitudes (Fig. 6). On the other hand, the on-slow potential increased its magnitude with increasing cathodal current (Fig. 6).

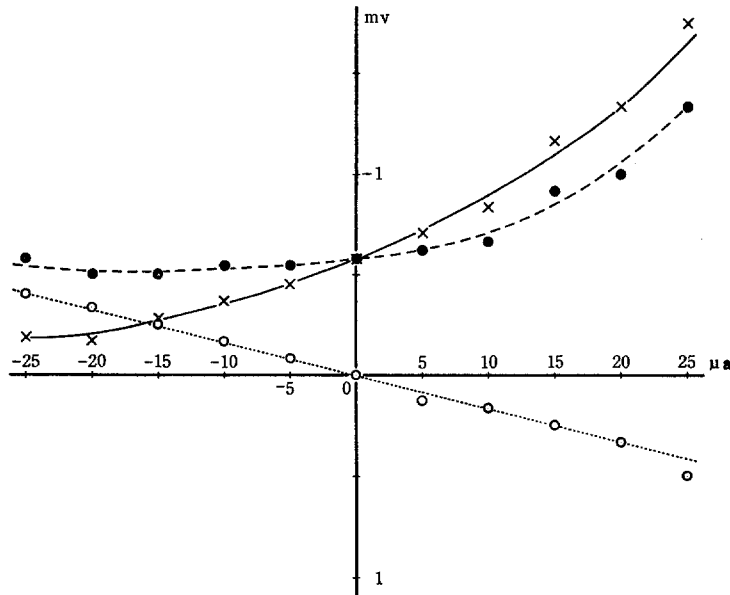


FIGURE 5. Relations between the potential amplitudes and the applied currents. Ordinate shows the amplitude of the slow potential and abscissa shows the electrotonic current applied. A dotted line indicates the change of the amplitudes of the spurious potentials, which was shown in Fig. 2. A broken line indicates the change of the slow potentials induced by amyl acetate vapor, which was shown in Fig. 4. When the artifact component is subtracted from the relation shown by the broken line, a real potential-current relation can be obtained. The continuous line indicates the real relation which should be obtained between the slow potential induced by amyl acetate vapor and the electrotonic current.

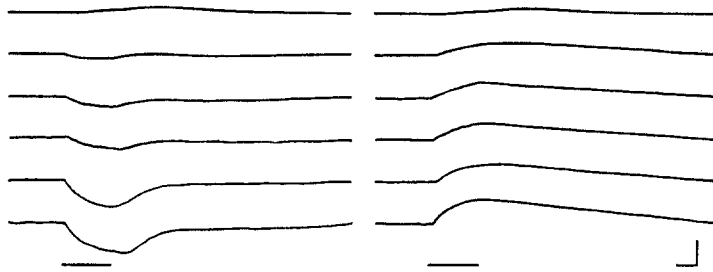


FIGURE 6. On- and off-slow potentials induced by the vapor of ethyl ether. Top records on both sides show the control potentials. When anodal currents are applied, as shown on the left side, the on-slow potential reverses its polarity and becomes increasingly electropositive, while cathodal currents increase the magnitudes on the on-slow potential, as shown on the right. The horizontal bars at the bottom indicate the application of ethyl ether. Calibrations of 1 mv and 1 sec. are shown at the lower right.

A relation between the magnitude of the slow potential and the current applied is shown in Fig. 7A. This was obtained in the same olfactory epithelium as in Fig. 4. A linear relation was often found, but a bend or a curve was sometimes found (Fig. 7A). Similar relations were found in the case of chloro-

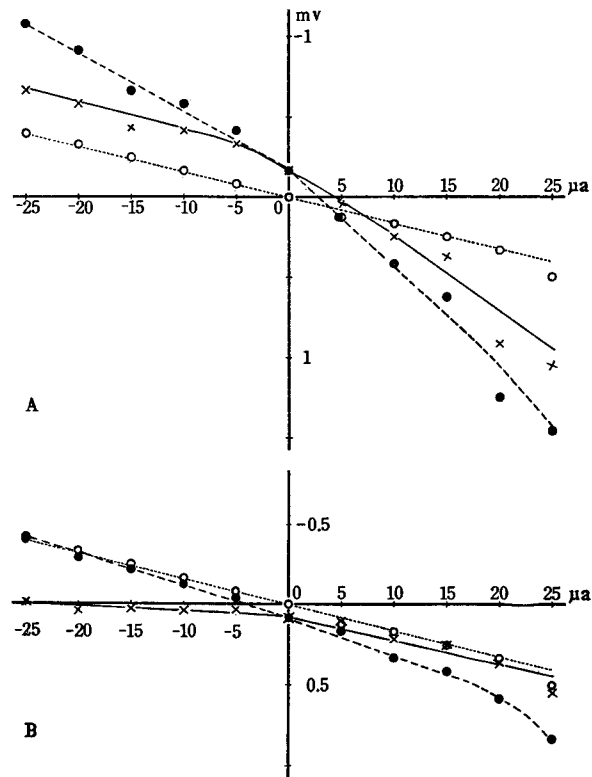


FIGURE 7. Relations between the potential amplitudes and the applied currents. A Change of the slow potential induced by ethyl ether vapor under the action of electrotonic currents. A broken line shows the relation observed in Fig. 6. When the spurious component shown by a dotted line is subtracted from this relation, a real relation between the ether potential and the current is obtained. This is shown by a continuous line. B. Change of the slow potential induced by chloroform vapor. The broken line was obtained by plotting the potential height against the applied current. When the spurious component shown by a dotted line is subtracted from it, a real relation between the chloroform potential and the electrotonic current is obtained. This is shown by a continuous line.

form (Fig. 7B) and propyl ether. These relations in the case of organic solvents are just the opposite to the ones obtained above with general odors. As will be discussed later, they are also opposite to the ones found in other excitable tissues. A comparable relation is found only in the P-III potential appearing in the retina treated with KCl (Granit and Helme, 1939).

When saturated ether vapor was repeatedly applied, the slow potential often reversed its polarity from negative to positive spontaneously. Hosoya and Yoshida (1937) found that there is a potential difference between the outer and the inner surfaces of the olfactory epithelium. This means that the olfactory cell is constantly under the action of an electrotonic current. From the above experimental results, it is presumed that the spontaneous reversal of

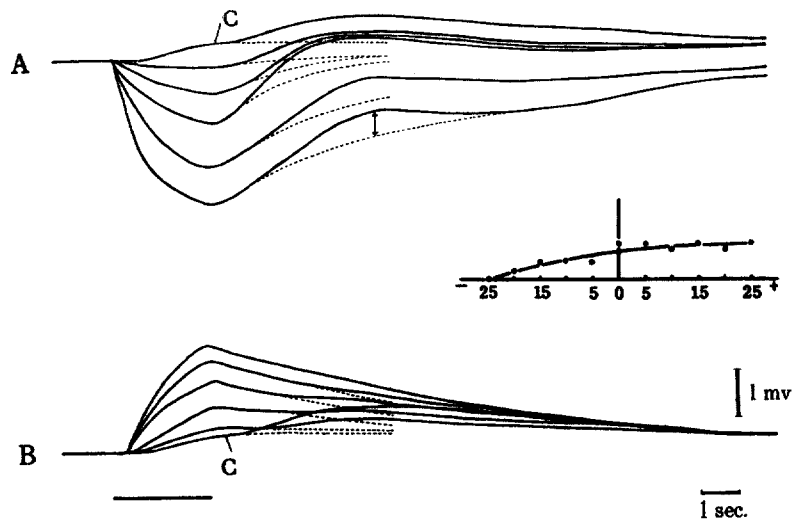


FIGURE 8. Changes of the off-slow potential under the action of electrotonus. The magnitudes of the off-slow potentials were measured against interpolated base lines (dotted lines) assumed to represent the decline of the on-slow potentials at the cessation of olfactory stimulation. A. The top record indicated by "C" is the control without electrotonus. The potentials from the second to the bottom were obtained by applying anodal current of 5 to 25  $\mu$ a. B. The effect of cathodal current. C indicates control potential. From the second from the bottom to the top are shown the changes of the slow potentials due to the cathodal currents of 5 to 25  $\mu$ a. The inset shows the relation between the off-slow potential amplitudes and the applied currents.

the slow potential may occur because of the change of this potential difference across the olfactory epithelium.

The off-slow potential is generally induced by the saturated vapor of ethyl ether. Even when it is small, it is made clear and discernible from the on-slow potential when an anodal current is applied (Fig. 8). A difficulty encountered when the relation between the magnitude of the off-slow potential and the electrotonic current was studied was in the measurement of the potential height. Since the off-slow potential follows the on-slow potential, exact measurement of the former potential height is difficult in many cases. The on-slow potential shows an exponential decline at the cessation of stimulation with general odors (Ottoson, 1956). Taking advantage of this property, a pre-



sumed exponential decay curve was drawn at the end of the on-slow potential, and the magnitude of the off-slow potential was measured (Fig. 8). Thus, a relation was obtained, as shown in Fig. 8. This relationship resembles those obtained in the case of amyl acetate and turpentine oil. The reversal of the polarity of the off-slow potential was never found.

When the saturated vapor of ethyl ether was diluted, for instance to a concentration of one-sixteenth, the relation between the on-slow potential and the

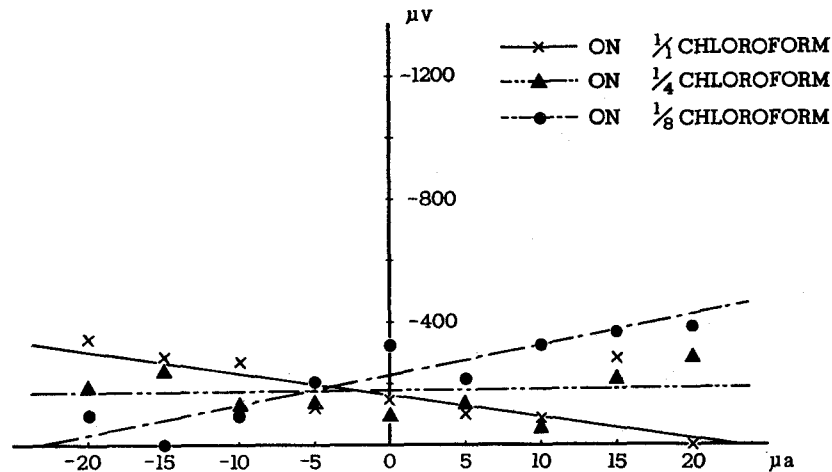


FIGURE 9. Reversal of the potential amplitude–electrotonic current relation observed between the chloroform vapors of high and low concentrations. When the concentration of chloroform vapor is low, a relation is obtained which is similar to the one found in the case of general odors as in Fig. 4. When the concentration increases, there is found a stage at which the potential amplitude does not change under the current applied. When the concentration further increases, a reversed relation as was found in Fig. 6 is obtained. The observations have been corrected for the 0 to 300  $\mu\text{v}$  spurious potentials produced by purified air in the epithelia under electrotonus.

current applied became similar to the one found with a general odor. Thus, a reversal of the relation was found between the high and low concentrations of the same ethyl ether. In the concentrations between the high and the low concentrations, an intermediate relation was found, namely the on-slow potential did not change its magnitude when electrotonic currents were applied. Entirely similar phenomena were found in the case of chloroform (Fig. 9) and propyl ether.

#### DISCUSSION

##### 1. *The Effect of Electrotonus upon Sensory Receptors and Other Excitable Tissues*

The effect of electrotonus on the vertebrate retina was studied by Granit and Helme (1939), on the stretch receptor of a crayfish by Kuffler and Eyzaguirre

(1955), and on the Pacinian corpuscle by Loewenstein and Ishiko (1960). The action potentials in the above receptors increase their magnitudes under anodal currents and decrease them under cathodal currents. Entirely similar relations were found in the end plate potential (Fatt and Katz, 1951), in the excitatory and inhibitory postsynaptic potentials of the spinal motoneuron (Coombs *et al.*, 1955 *a, b*), and in the electric organ (Bennett and Grundfest, 1961). Since the slow potentials induced by some general odors showed similar relations, the excitatory mechanism of the olfactory receptor which produces the negative slow potential is supposed to be comparable to that in other excitable tissues.

On the other hand, an exactly opposite relation was obtained with some organic solvents. They have characteristic odors, which stimulate the olfactory receptor like general odors. Besides, it is conceivable that they have another chemical action as organic solvents. It has been shown that an electronegative on-slow potential decreased its magnitude and disappeared when the concentration of ethyl ether vapor was increased, but nevertheless the induced-on-wave invariably appeared in the olfactory bulb (Takagi *et al.*, 1960). This means that the stimulating action of ether remains even when the negative on-slow potential is no longer observed. In fact, it was shown that the negative on-slow potential produced by a general odor was abolished by the vapor of ethyl ether or chloroform, but the induced "on"-wave remained (Takagi *et al.*, 1960). Therefore, it was presumed in that article that this disappearance of the on-slow potential occurred because the stimulating action was opposed by the second chemical (probably hyperpolarizing) action of ethyl ether. This presumption was strongly supported in the present experiment, because the slow potential induced by ether of low concentration showed under electrotonus a similar relation to the one produced by general odors, while the slow potential produced by ether of high concentration showed the opposite relation. Consequently, it is concluded that there are two "on"-processes in the receptive membrane of the olfactory cell. One is the ordinary excitatory process which is stimulated by odors of any kind and produces an electronegative slow potential. This may be a generator potential. The other is a process of a different kind which is activated only by the vapors of organic solvents of high concentrations and which produces an electropositive slow potential. The phenomena of inhibition found in olfactory cell activity may be due to this process (Takagi and Omura, 1963). Since ethers and chloroform have anesthetic action, this second process may be concerned with it, as already suggested (Takagi *et al.*, 1960). When the vapors of the organic solvents are applied, it follows that these two processes always compete. If it is assumed that the excitatory process is stronger at the low concentration of ethyl ether, while it is surpassed by the second process at the high concentration, the

paradoxical phenomena stated above, for instance, the disappearance of the negative slow potential at the high concentration, can be explained.

Though in the foregoing discussion odors were simply divided into the two categories, general odors and odors of organic solvents, this division seems tentative. In fact, it is conceivable that many general odors may induce more or less of the second process. With some odors, the excitatory action may be predominant, while with others the second action may prevail. On the other hand, there may be differences in the receptive processes of different olfactory cells. In some cells, one of the two processes may prevail, while in others the other may. In the light of these considerations, it is not surprising that the results obtained with the same odor are not always the same in different preparations.

### 2. *On the Generative Mechanism of the On-Slow Potential*

In section 1 of the Discussion, it was concluded that there are two receptive on-processes, namely the ordinary excitatory process and a second process which opposes the former one. Takeuchi and Takeuchi (1960) found that the sodium and potassium conductances of the end-plate membrane increase, with the ratio  $\Delta G_{\text{Na}}/\Delta G_{\text{K}}$  remaining constant, when a transmitter substance reaches the receptor, and they devised an equivalent circuit for the end-plate membrane. The ordinary excitatory process of the olfactory receptor cell which is stimulated by odors may be explained by an increase of the conductances in the equivalent circuit. The increase in magnitude of the slow potential by anodal current and the decrease by cathodal current are also explained by the circuit. On the other hand, the second process activated by the vapors of organic solvents at high concentrations and the changes of the potentials produced by this process under electrotonic currents cannot be explained by the increase of the conductances. Since the electropositive slow potential shows an entirely opposite effect of electrotonic current from that shown by inhibitory postsynaptic potentials, the generative mechanism must be different from the one for IPSP. What the true generative mechanism is will be answered when the underlying ionic mechanism is made clear. However, if a decrease, instead of an increase, is assumed to occur in the conductances, the appearance of the electropositive slow potential may be explained, and the paradoxical phenomena found in Figs. 6 and 7 may thus be explained as the competition between the increase and the decrease of the conductances.

### 3. *On the Generative Mechanism of the Off-Slow Potential*

It has been concluded that the off-slow potential originates in an independent "off"-element in the olfactory epithelium (Takagi *et al.*, 1960). However, the off-slow potential very often appeared accompanying the electropositive on-slow potential (Takagi *et al.*, 1960). This phenomenon was made more mani-

fest when an anodal current was applied (Fig. 8). Besides, it seemed that the appearance and disappearance of both the positive on- and negative off-slow potential coincided well, after the newt was transferred onto the land (Shibuya and Takagi, 1962, 1963). From these observations, it seems possible that the off-slow potential is generated by a mechanism similar to that of anodal break excitation.

If an excitation process like anodal break excitation should exist, and if an electropositive potential should always be accompanied by a negative potential, the presence of two component potentials would be enough to explain the paradoxical phenomena so far observed.

The authors are indebted to Miss Yajima, Miss Sakamoto, and Mr. Koyama for the preparation of figures. This work was carried out with the aid of a grant for scientific research from the Ministry of Education of Japan.

Received for publication, May 28, 1964.

#### REFERENCES

- BENNETT, M. V. L., and GRUNDFEST, H., 1961, The electrophysiology of electric organs of marine electric fishes. II. The electroplaques of the main and accessory organ of *Narcine brasiliensis*, *J. Gen. Physiol.*, **44**, 805.
- COOMBS, J. S., ECCLES, J. C., and FATT, P., 1955 *a*, The specific ionic conductances and the ionic movements across the motoneuronal membrane that produce the inhibitory post-synaptic potential, *J. Physiol.*, **130**, 326.
- COOMBS, J. S., ECCLES, J. C., and FATT, P., 1955 *b*, Excitatory synaptic action in motoneurons, *J. Physiol.*, **130**, 374.
- FATT, P., and KATZ, B., 1951, An analysis of the end-plate potential recorded with an intra-cellular electrode, *J. Physiol.*, **115**, 320.
- GRANIT, R., and HELME, T., 1939, Changes in retinal excitability due to polarization and some observations on the relation between the processes in retina and nerve, *J. Neurophysiol.*, **2**, 556.
- HIGASHINO, S., TAKAGI, S. F., and YAJIMA, M., 1961, The olfactory stimulating effectiveness of homologous series of substances studied in the frog, *Japan J. Physiol.*, **11**, 530.
- HOSOYA, Y., and YOSHIDA, H., 1937, Ueber die bioelektrische Erscheinungen an der Riechschleimhaut, *Japan. J. Med. Sc.* III. Biophysics, **5**, 22.
- KIMURA, K., 1961, Olfactory nerve response of frog, *Kumamoto Med. J.*, **14**, 37.
- KUFFLER, S. W., and EYZAGUIRRE, C., 1955, Synaptic inhibition in an isolated nerve cell, *J. Gen. Physiol.*, **39**, 155.
- LOEWENSTEIN, W. R., and ISHIKO, N., 1960, Effects of polarization of the receptor membrane and of the first Ranvier node in a sense organ, *J. Gen. Physiol.*, **43**, 981.
- MOZELL, M. M., 1962, Olfactory mucosal and neural responses in the frog, *Am. J. Physiol.*, **203**, 353.
- OTTOSON, D., 1954, Sustained potentials evoked by olfactory stimulation, *Acta Physiol. Scand.*, **32**, 384.
- OTTOSON, D., 1956, Analysis of the electrical activity of the olfactory epithelium, *Acta Physiol. Scand.*, **35**, suppl. 122, 1.

- OTTOSON, D., 1958, Studies on the relationship between olfactory stimulating effectiveness and physico-chemical properties of odorous compounds, *Acta Physiol. Scand.*, **43**, 167.
- OTTOSON, D., 1959 *a*, Studies on slow potentials in the rabbit's olfactory bulb and nasal mucosa, *Acta Physiol. Scand.*, **47**, 136.
- OTTOSON, D., 1959 *b*, Comparison of slow potentials evoked in the frog's nasal mucosa and olfactory bulb by natural stimulation, *Acta Physiol. Scand.*, **47**, 149.
- SHIBUYA, T., 1960, The electrical responses of the olfactory epithelium of some fishes, *Japan. J. Physiol.*, **10**, 317.
- SHIBUYA, T., and TAKAGI, S. F., 1962, A note on the on- and off-responses observed in the olfactory epithelium of a newt, *Gunma J. Med. Sc.*, **11**, 63.
- SHIBUYA, T., and TAKAGA, S. F., 1963, Electrical responses and growth of olfactory cilia of the olfactory epithelium of the newt in water and on land, *J. Gen. Physiol.*, **47**, 71.
- TAKAGI, S. F., and OMURA, K., 1963, Responses of the olfactory receptor cells to odours, *Proc. Japan Acad.*, **39**, 253.
- TAKAGI, S. F., and SHIBUYA, T., 1959, "On"- and "off"-responses of the olfactory epithelium, *Nature*, **186**, 60.
- TAKAGI, S. F., and SHIBUYA, T., 1960 *a*, The "on" and "off" responses observed in the lower olfactory pathway, *Japan. J. Physiol.*, **10**, 99.
- TAKAGI, S. F., and SHIBUYA, T., 1960 *b*, Potential oscillations in the lower olfactory pathway of the toad, *Nature*, **186**, 724.
- TAKAGI, S. F., and SHIBUYA, T., 1960 *c*, The electrical activity of the olfactory epithelium studied with micro- and macro-electrodes, *Japan. J. Physiol.*, **10**, 385.
- TAKAGI, S. F., and SHIBUYA, T., 1960 *d*, The potential oscillations observed in the olfactory epithelium, nerve and bulb of the toad and frog, *Japan. J. Physiol.* **10**, 499.
- TAKAGI, S. F., and SHIBUYA, T., 1960 *e*, Electrical activity of lower olfactory nervous system of toad, in *Electrical Activity of Single Cells*, (Y. Katsuki, editor), Igaku-Shoin Press, Bunkyo-ku, Tokyo.
- TAKAGI, S. F., and SHIBUYA, T., 1961, Studies on the potential oscillation appearing in the olfactory epithelium of the toad, *Japan. J. Physiol.*, **11**, 23.
- TAKAGI, S. F., SHIBUYA, T., HIGASHINO, S., and ARAI, T., 1960, The stimulative and anaesthetic actions of ether on the olfactory epithelium of the frog and the toad, *Japan. J. Physiol.*, **10**, 571.
- TAKAGI, S. F., and YAJIMA, T., 1964 *a*, Electrical responses to odours of degenerating olfactory epithelium, *Nature*, **202**, 1220.
- TAKAGI, S. F., and YAJIMA, T., 1964 *b*, Electrical activity and histological change of the degenerating olfactory epithelium, data to be published.
- TAKEUCHI, A., and TAKEUCHI, N., 1960, On the permeability of end-plate membrane during the action of transmitter, *J. Physiol.*, **154**, 52.