Delayed Rectification and Anomalous Rectification in Skeletal Muscle Membrane

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Katz (1948) made an analysis of the electrical properties of the muscle fibre membrane and observed that delayed rectification was not elicited by a subthreshold cathodal current. Further, he (1949) observed that muscles in 50 mM K2SO4 solution revealed a property of anomalous rectification: i.e., they had a low membrane resistance for inward current but a high resistance for outward current. Recently Hodgkin and Horowicz (1959) studied the influence of K and Cl on the resting potential of single muscle fibre of the frog and observed that the potassium permeability of the muscle membrane showed the rectification in the opposite direction to the delayed rectification of the squid axon. This was further confirmed by Adrian (1960) and by Freygang and Adrian (1960).

On the other hand, Jenerick (1953) reported that the muscle fibre exhibited the resistance change in the same direction to delayed rectification, and Narahashi, Deguchi, Urakawa, and Ohkubo (1960) showed that delayed rectification became apparent in the fibre which was made inexcitable by tetrodotoxin.

The aim of the present experiment was to determine the conditions in which muscle membrane exhibited delayed rectification or anomalous rectification. It will be shown that delayed rectification is shifted into anomalous rectification after depolarizing the membrane for a few seconds.

Two micropipettes were inserted into one muscle fibre of the frog's sartorius within 200 μ of each other. The one (filled with 2 M-Na citrate, Boistel and Fatt, 1958) was used to apply the polarizing current, the other (filled with 3 M-KCl) was used to record potential changes. Polarizing current was monitored with a series resistor of 1–2 KΩ and a high gain D-C amplifier. Tetrodotoxin (1×10⁻⁷) was applied when it was necessary to make the muscle inexcitable. The potassium permeability did not seem to be appreciably altered by this drug. Contraction was abolished by placing the muscle in a solution made hypertonic with sucrose (2½ times the normal tonicity, Hodgkin and Horowicz, 1957).

First, the V-I curve was plotted in a Cl-free solution containing 39 mM Na2SO4, 1.25 mM K2SO4 and 8 mM CaSO4 with phosphate buffer.
Tetrodotoxin was applied. Even after equilibrating the preparation in the solution for more than 30 minutes, a current pulse often induced a long-lasting variation in the membrane potential. But it was found that this difficulty was removed by applying hyperpolarizing or depolarizing current in advance. Curve A of Fig. 1 shows an experiment in which the membrane was first hyperpolarized by 43 mV with a direct current; then rectangular current pulses of different intensity and direction were superposed on it, and the voltage-current curve was plotted from measurements of the membrane potential at the end of the current pulse of 100 msec duration. It shows that the rectification over the range of membrane potential between $-100$ mV and $-30$ mV is in the direction of anomalous. But at about $-20$ mV the curve shows an inflexion, indicating the exist-

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**Fig. 1. Voltage-current relation of muscle membrane in 39 mM Na$_2$SO$_4$, 1.25 mM K$_2$SO$_4$ and 8 mM CaSO$_4$ solution. Sucrose was added to make the tonicity 2.5 times the normal. Tetrodotoxin (1× 10$^{-10}$) was applied. Ordinates: membrane potential at the end of the rectangular current pulse of 100 msec duration. Hyperpolarization downwards. The dotted line represents the resting membrane potential. Abscissae: intensity of the applied current pulse. The current which made the membrane hyper- or depolarized in advance is not shown in the figure. Curve A: the membrane has been hyperpolarized by 43 mV. Curve B: the membrane has been depolarized by 30 mV.**

**Fig. 2. Voltage-current relation of muscle membrane in 40 mM K$_2$SO$_4$ and 8 mM CaSO$_4$ solution. Sucrose was added to make the tonicity 2.5 times the normal. Tetrodotoxin was not added. Ordinates: membrane potential at the end of the rectangular current pulse of 100 msec duration. Hyperpolarization downwards. The potential of the bath was taken to be zero. The dotted line represents the resting membrane potential. Abscissae: intensity of the applied current pulse. The current which made the membrane hyper- or de-polarized in advance is not shown in the figure. Curve A: the membrane has been hyperpolarized by 63 mV. Curve B: no direct current was applied.**
ence of delayed rectification.

The hyperpolarizing direct current was then terminated; instead, an outward direct current was applied depolarizing the membrane by 30 mV. After several minutes for equilibration square pulses were superposed on it as before. The result is given in curve B of Fig. 1. It will be seen that in this curve the slope resistance near -20 mV is much greater than that at the corresponding potential in curve A. This fact indicates that the lowered membrane resistance due to delayed rectification is eliminated by a long-lasting depolarization.

Fig. 2 shows an example of similar experiment in Cl-free solution containing 40 mM K₂SO₄ and 8 mM CaSO₄ with phosphate buffer. In this solution a current pulse did not induce long-lasting variation in membrane potential. Curve A of Fig. 2 indicates that the fibre whose membrane potential has been hyperpolarized by 63 mV with a direct current, reveals delayed rectification when the membrane potential is made above -10 mV by cathodal current pulses. Several minutes after cessation of the hyperpolarizing current, the V-I relation (curve B) reveals that anomalous rectification becomes apparent near the membrane potential of -10 mV instead of delayed rectification. When the cathodal current pulse is further increased making the membrane potential +70 mV or more, the resistance is reduced again. However, this lowering of the resistance is different from delayed rectification, since the former was not eliminated by a long-

![Graph](image-url)

Fig. 3. Time course of the change in the effective membrane resistance after cessation of the hyperpolarizing current pulses in 40 mM K₂SO₄ and 8 mM CaSO₄ solution. Ordinates: effective resistance of the membrane which was measured 2.1 times a second with small pulses of 210 msec duration. Abscissae: time after the cessation of the inward direct current which has hyperpolarized the membrane by 62 mV.
lasting cathodal current. Hence, this decrease of resistance is supposed to represent the reversible break-down of membrane rather than delayed rectification.

Fig. 3 shows an example of the experiment in which the time course of the change in the effective membrane resistance was followed after cessation of a hyperpolarizing direct current in a muscle treated in a solution of 40 mM K₂SO₄. The effective resistance was measured 2.1 times per second with small square pulse of 210 msec duration. From the figure it is apparent that the resistance is first decreased by cessation of the hyperpolarizing current (delayed rectification), and then it gradually increased (anomalous rectification). The half time of the increase in the resistance varied from fibre to fibre and ranged from about half a second to 3 sec or so.

These results may well indicate that inactivation exists also in K conductance in muscle fibre, that its time course is rapid compared with that of nerve fibre (Lüttgau, 1960), and that the anomalous rectification becomes apparent due to inactivation of K-conductance.

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References