THE ACTION OF DIRECT CURRENT ON UNSTRIATED MUSCLE

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Winton (1937) found that the stimulation of *Mytilus* unstriated muscle by direct current results in slow relaxation after contraction. He did not find any effect of polarity of the current on the mechanical response. Singh (1938 *b*) found that this tonic contraction or slow relaxation was due to the action of ions in the saline, as it was produced when stimulating ions were present in the saline and was antagonised by agencies that opposed the action of these ions. In striated muscle the mechanical response during fatigue is affected by polarity of direct current: Heilbrunn (1937). Singh (1937) showed that though *Mytilus* muscle may become inexcitable to all forms of stimulation, when the chloride of the saline is replaced with cyanide, it still responds to cessation of direct current.

In the present research, the effects of direct current, which differ in many respects from those of alternating current, were elucidated.

Experimental

The muscle used was that from the frog's stomach; circular strips were used. They were stimulated with direct current by two methods: (1) the first method was that described previously (Singh, 1938 *a*). (2) In the second method the muscle was stimulated by either the anode or the cathode varying from 1·4 to 1·5 volts, using Zn-$ZnSO_4$ non-polarisable electrodes; the indifferent electrode was on one end of the muscle which was killed by heat.

Results

When the frog's muscle is stimulated with direct current, it produces three contractions; one while the current is flowing, the other when the current stops after a latent period of about 2 to 10 seconds, and a third a few seconds (10–60), after the cessation of the current (Fig. 1).

Relation between make and break contractions.—The make and break contractions may be affected identically or oppositely. When they are affected oppositely, their magnitude bears an inverse ratio, so that the total tension may approximately remain constant (Fig. 2). Thus substances that

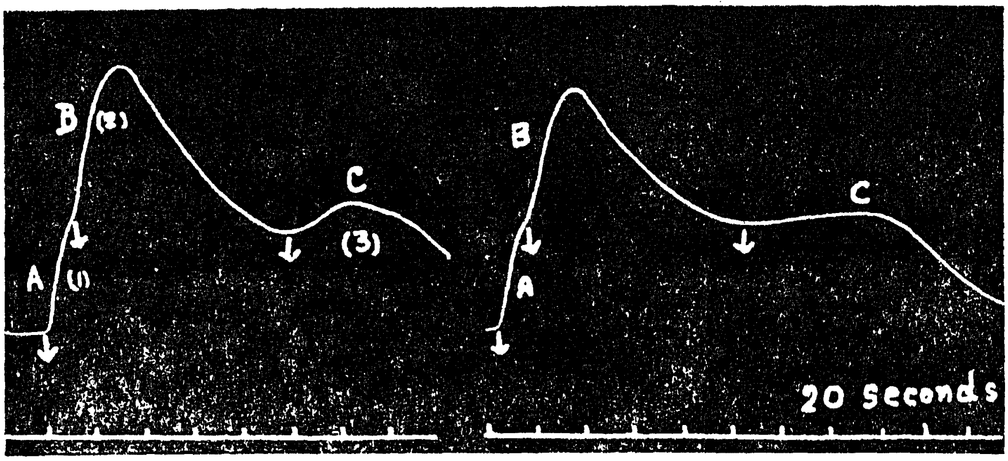

FIG. 1. Frog's stomach muscle. Contraction by 14 volts, direct current (D.C.) for 10 seconds. *A*, the make contraction between first two arrows; *B*, the break contraction; and *C*, the third contraction which is usually brought out by eserine (1 in 10^5).

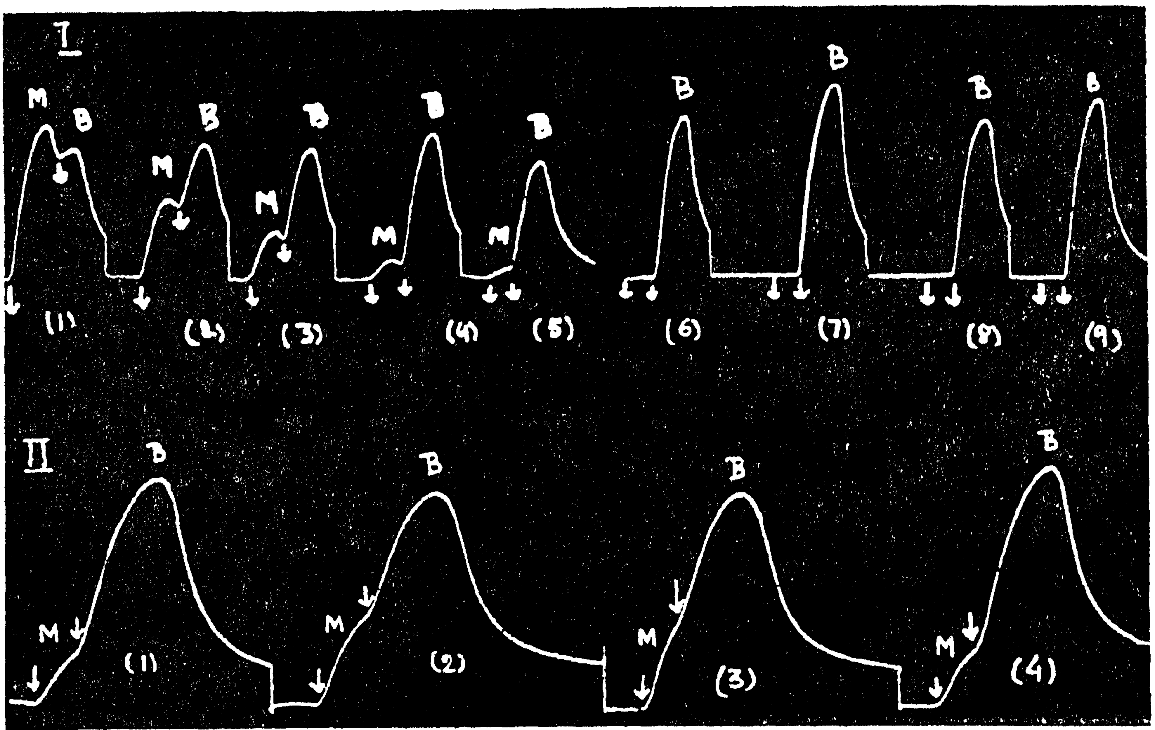

FIG. 2. Frog's stomach muscle. Stimulation by constant current 14 volts for 10 seconds every 10 minutes. Upper curves: 1st 5 contractions in saline, 80 per cent of NaCl replaced with NH_4Cl 6th and 8th contractions in 100 per cent. NH_4Cl. 7th and 9th contractions with the current reversed; note absence of make contraction (M = make and B = break contraction.) Lower curves: 1st and 4th contractions with the current in the same direction. 2nd and 3rd contractions with the current in the opposite direction; the make contraction becomes larger and the break smaller.

increase the make contraction, under such circumstances, will correspondingly decrease the break contraction. With great increase in the make contraction, the break contraction may be almost abolished (Fig. 3). The properties of the make contraction are those of the contraction produced by alternating current and those of the break contraction are similar to those

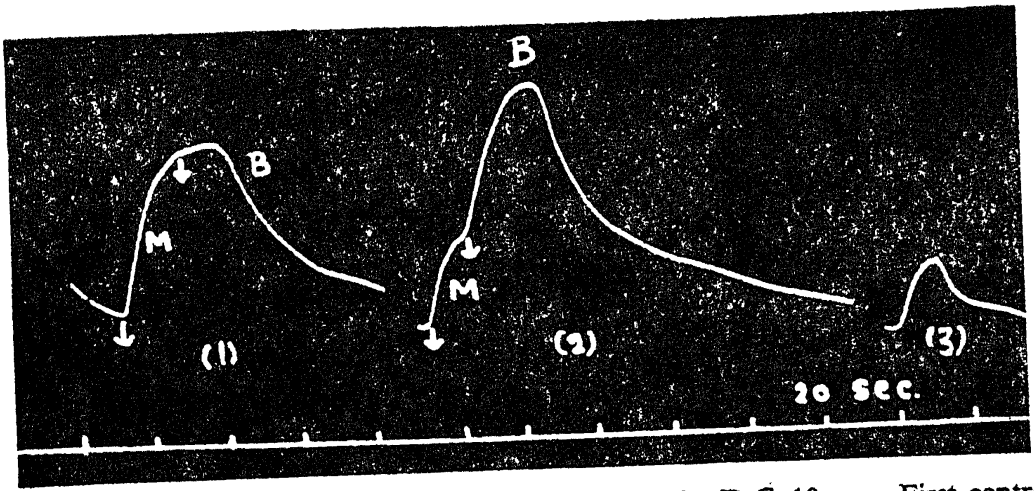

FIG. 3. Frog's stomach muscle. Contraction by 14 volts D.C.;10 sec. First contraction in acetylcholine (1 in 10^6); the break contraction is very small. The second contraction with the current reversed. The third contraction is in adrenaline (1 in 10^6).

of the potassium contraction (Singh, 1938 *a*). If the make contraction decreases, then the break contraction may increase, so that as the former vanishes, the latter alone remains. Sometimes both the contractions are absent and only the third contraction is obtained. This produces a curious phenomenon in that the muscle remains quiescent during the passage of the current, but contracts after the lapse of a few seconds or minutes. Such a contraction is best observed if spontaneous contractions are absent. The contraction is antagonistic to that produced by alternating current. It is akin to the secondary contracture (Singh, 1938 *a*), or is possibly due to nerves (Singh and Singh, 1947). This reminds one of the long latent periods of gastric or pancreatic secretion to vagus stimulation.

Effect of stimulation.—During the beneficial effect of contraction, the make contraction increases, and the break contraction decreases. To begin with, the muscle may be inexcitable to make but may give a large response to break of the current. During fatigue the make contraction decreases, and the break contraction increases. During both these phases, these contractions may be affected indentically. This shows that during fatigue and the beneficial effect of contraction, factors arise which affect the two excitabilities in the same and in the opposite direction respectively.

Effect of strength of stimulus.—With some increase in voltage, at first, both the contractions increase, but thereafter the make contraction increases at the expense of the break, so that with high voltages (40–50 volts D.C.), the break contraction may be abolished (Fig. 4). The latter contraction may, however, reappear, if the response now begins to decline with increase in voltage. The above observations suggest that some common factor which is probably ionic, is responsible for both the contractions, so that if it is

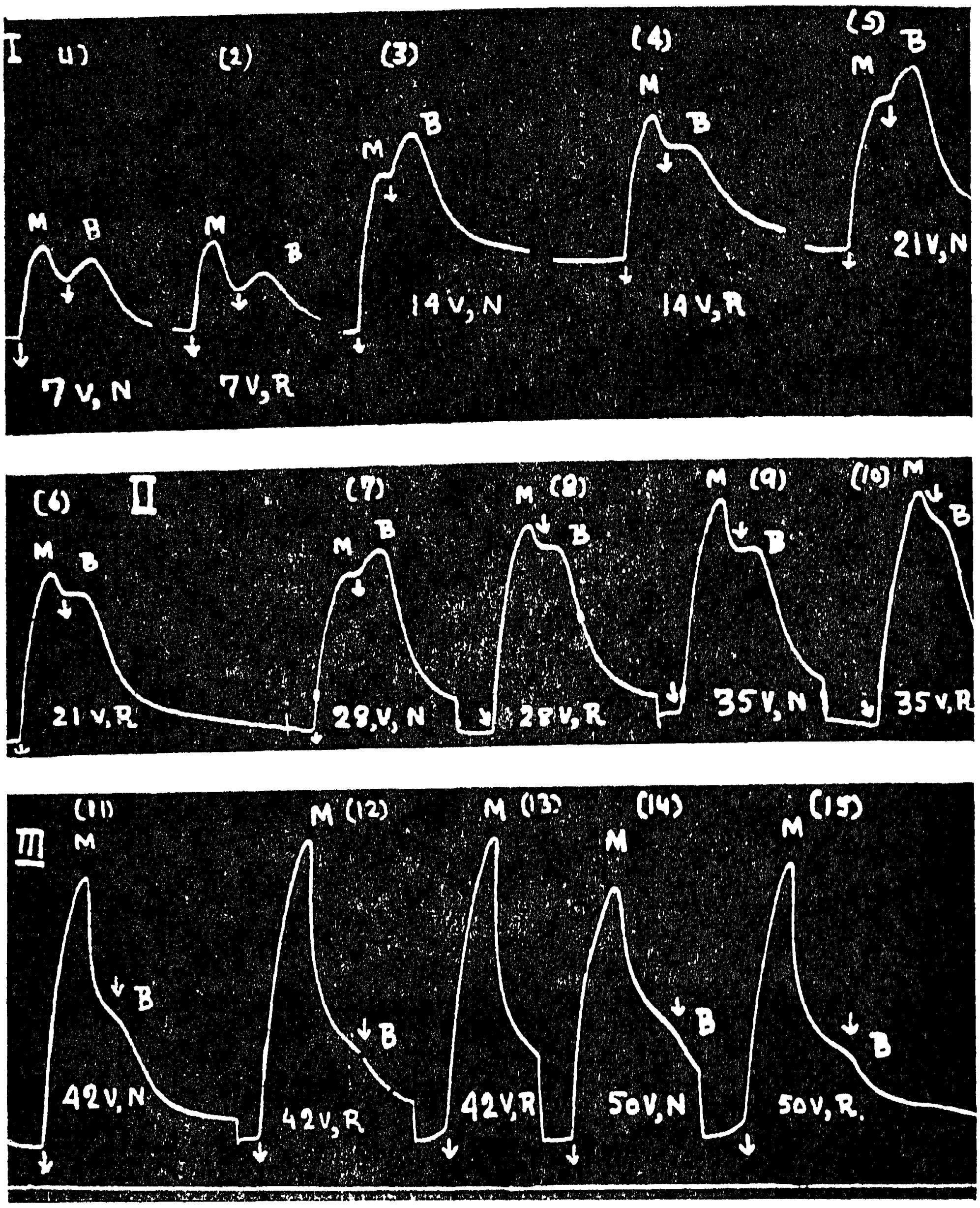

FIG. 4. Frog's stomach muscle. Contraction by D.C. M = make contraction, B = break contraction, N = normal direction, R = reversed direction. Note that in the lowest figure, in the thirteenth contraction with 42 volts, the break contraction has been abolished.

used more for the make contraction, less of it remains for the break contraction.

Effect of temperature.—The optimum temperature for the make contraction is 25 to 30° C. and that for the break contraction 15 to 20° C. Thus the break contraction belongs to the potassium group like the alternating current off-contracture.

Effect of ions and drugs.—The effect of following substances was tested: (1) Monovalent cations, Li, Na, NH_4, K, H. (2) Divalent cations, Ca, Sr, Ba, Mg. (3) Monovalent anions, Br, NO_3, I, SCN, CN. (4) Drugs, adrenaline, acetylcholine and eserine. The effect of these substances on the make contraction resembles that on the contraction produced by alternating current, and the effect on the break contraction, that on the potassium contraction. The effects of ammonium and potassium are interesting. If all the sodium of the saline is replaced with ammonium or if 20–40 per cent. is replaced with potassium, then the make contraction disappears and only the break contraction remains, suggesting that the latter is dependent upon ions in the saline. All of the sodium may be replaced with potassium, and the muscle still responds to the break of the current (Fig. 5). This suggests

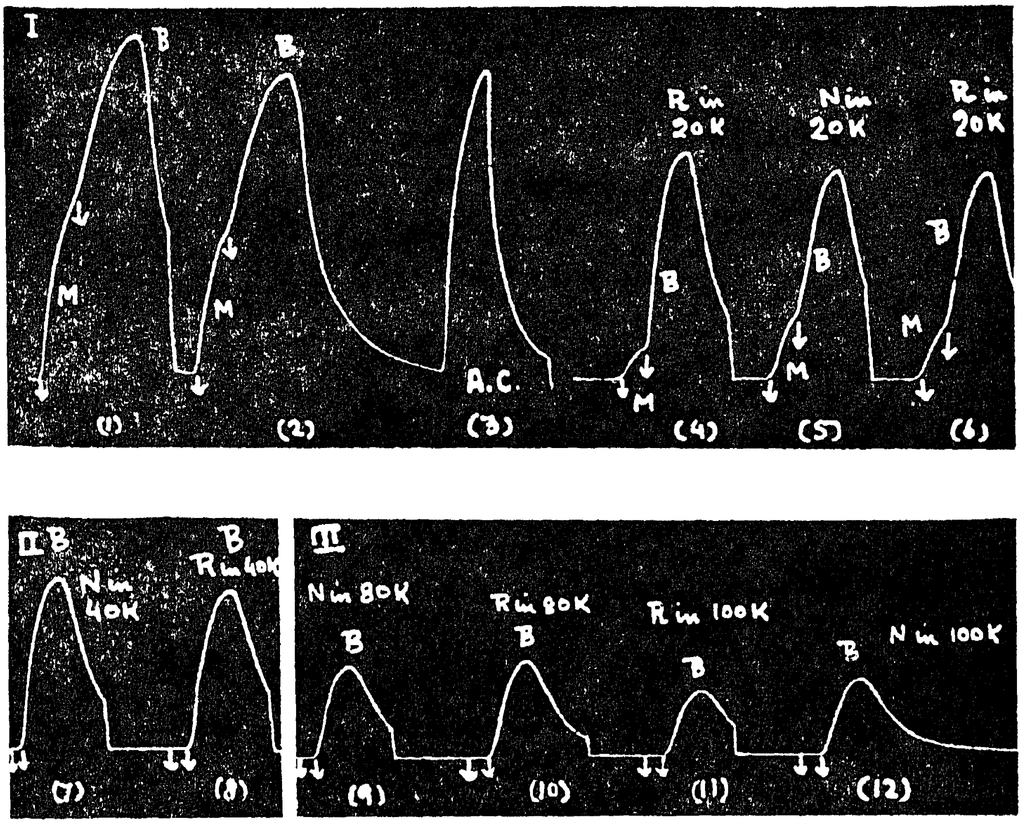

FIG. 5. Frog's stomach muscle. Stimulation by D.C. 14 V/10 sec. I. First two contractions with curves in normal and reversed direction; 3rd contraction by alternating current 8 V/10 sec. for comparison. 4th, 5th and 6th contractions in saline with 20 per cent. of sodium replaced by potassium (R in reversed direction, and N in normal direction). II and III are self-explanatory. K = percentage of potassium replacing sodium of the saline. In curves 7 to 12 the make contraction is absent.

that the inexcitability in excess of ammonium and potassium is not due to damage but to some redistribution of ions in the muscle. Hydrogen ions too (pH 5) produce a similar action. Similarly all the sodium chloride of the saline can be replaced with calcium and strontium chlorides; barium produces similar effect if 20 per cent. of sodium is replaced. Magnesium, on replacing all the sodium chloride, and adrenaline (1 in 10^{7}–10^{6}) have opposite action; the make contraction remains but the break contraction disappears.

Effect of polarity of current.—The magnitude of the total response and that of the individual make and break contractions, varies with the directions of the current. The effect on the make and the break contraction is reciprocal. If there is no appreciable difference between the responses when the current is reversed, it can be produced by altering the ionic content of the saline either by replacing the sodium or the chloride ion with some other ion, or altering the total concentration of ions by altering the sodium chloride content of the saline. Polarity may affect the response in the electrolyte-free medium.

Effects of polar stimulation.—On make and break of the current, contractions occur both at the anode and the cathode, the anodal contraction at the make being smaller than the cathodal. The properties of the make contractions are similar to those of the contraction produced by alternating current, and those of the break contraction are similar to those of the potassium contraction. In excess of potassium, as the make contractions disappears, the break contraction becomes powerful, the anodal contraction being the biggest. If contracture is first induced in frog's muscle, or in the guinea pig's uterus, then inhibition is produced instead of contraction, the anodal inhibition at the make being greater than the cathodal. Thus either inhibition or contraction may occur at the cathode or the anode on make or break of the current; this is in agreement with recent work on nerve (see Wiggers, 1944).

Discussion

The contraction produced on break of the direct current depends upon two factors: (1) Changes in the saline. (2) The make response. The make and the break contractions are affected reciprocally, so that if any substance is added to the saline the break contraction will be affected by change in the saline as well as by change in the make contraction. Hence the response is rather irregular.

The break contraction is similar to the alternating current off-contracture. It can be produced in the electrolyte-free medium, so the assumption that it is due to the leakage of ions from the fibres is justified. It is also increased by ions outside the muscle fibres, so that it is produced by leakage of ions into an outer zone (Singh, 1944).

The muscle may be inexcitable to all forms of stimulation except that due to break of a constant current; this suggests that one of the factors that causes diminution in excitability is some rearrangement of ions. This cannot be explained on the assumption that the interior of the muscle fibres is uniform, and that they are surrounded by only one membrane.

The fact that the contraction on make of the constant current, is antagonistic to that on break, is not explained by the current theories of excitation by constant current. The fact that the response varies with polarity, suggests that the membranes of the muscle are not equally permeable in both directions. This would produce rectification, and so account for the stimulating action of alternating current.

Summary

(1) The properties of the contraction produced by break of a constant current are similar to those of the alternating current off-contracture; the make contraction resembles that produced by alternating current.

(2) The muscle responds to break of a constant current when it may be inexcitable to all other forms of stimulation; it may respond when all the sodium chloride of the saline is replaced with chlorides of lithium, ammonium, potassium, calcium, magnesium and strontium or in acid solutions (pH 5).

(3) Magnesium and adrenaline abolish the break contraction.

(4) The response differs with polarity of the direct current; this suggests that the permeability of the membranes is different in the two directions. Stimulation by alternating current is probably due, therefore, to rectification.

(5) The make and the break contractions bear a reciprocal relation to each other.

(6) With polar stimulation, the results are very complicated; contraction or inhibition may occur at the anode or the cathode on make or break of the current.

References

Heilbrunn, L. V. .. *Outline of General Physiology*, London, 1937.

Singh, I. .. *J. Physiol.*, 1937, **89**, 8; 1938 *a*, **92**, 62; 1938 *b*, **94**, 1; *Proc. Ind. Acad. Sci.*, 1944, **20**, 195.

——— and Singh, I. .. *Proc. Ind. Acad. Sci.*, 1947. (In the press).

Wiggers, C. J. .. *Physiology in Health and Disease*, London, 1944, p. 122.