COMMUNICATION II. EFFECT OF POTASSIUM AND CALCIUM IONS ON THE DEVELOPMENT OF SPINAL SHOCK

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The work of L.L. Vasil'ev [1] and his co-workers has shown that the effect of calcium ions on the nervous system is to increase the polarization, which leads to a condition similar to anelectrotonus. The calcium ions, acting as does the anode of a direct voltage, eliminate the parabiosis which has developed, and prevent it from becoming established. Under the same conditions, potassium ions cause depolarization, lead to catelectrotonus, and finally cause cathodic depression, and the development of parabiotic inhibition.

Tests by many physiologists [2-8] have confirmed the opposite effects of mono - and bivalent ions on the frog spinal reflexes.

The fact that calcium ions oppose and potassium ions assist the development of parabiosis of the spinal nervous system makes it possible to use these opposite effects in studying the development of spinal shock. If spinal shock represents a depression of a parabiotic type due to over-stimulation of the spinal nerve centers by impulses from a traumatized region, then potassium ions, by acting parabiotically, would be expected to facilitate the development of spinal shock and make it more profound, while the effect of calcium ought to oppose the development of shock or reduce it.

METHOD

In the first experiment on frogs (Rana ridibunda), the whole spinal cord was exposed. The experiment was continued one hour or more after the laminectomy, when the posture of the animal and its movements and reflexes had returned to normal. Before making the first spinal section, made between the first and second segments, and the second, made below the pelvic enlargement, a plug of cotton-wool moistened with a 1.74% solution of calcium chloride or with a mixture of equal parts of Ringer's solution and an isotonic solution (0.79%) of potassium chloride was placed for 15 minutes on the dorsal surface of the spinal cord. In some experiments, a third spinal section was made one segment below the second. Before sectioning the cord, and after, measurements were made of the threshold for the flexor reflex of the hind limb, by stimulating the skin of the foot with a current from an induction coil.

In the second experiment, the same solutions were introduced into the posterior lymph sac of Rana chensinensis. Reflex thresholds were measured from the contraction of the semitendinosus muscle in response to faradic stimulation of the peroneal nerve.

RESULTS

The results of the first experiment, in which isotonic $CaCl_2$ or KCl solutions were applied to the posterior surface of the spinal cord, are shown in Table 1.

As can be seen from the Table, after spinal section between segments 1 and 2, spinal shock occurs most frequently in experiments in which $CaCl_2$ solution is applied, while increased spinal reflexes are found chiefly

TABLE 1

Effect of High Spinal Section on Spinal Reflexes of the Posterior Limbs after Application of $CaCl_2$ and KCl to the Dorsal Surface of the Spinal Cord of the Frog

Experimental conditions / Conditions after chordotomy	$CaCl_2$	Control (Ringer's solution applied)	KCl	Total
Spinal shock	13	10	3	26
Steady level of excitation	8	24	8	40
Increased spinal reflexes	1	8	9	18
Total	22	42	20	84

after application of KCl solution. Statistical treatment of these results showed that chi squared is equal to 25 ($p=0.01$), and this shows that the relation between the substance applied to the spinal cord and the condition following chordotomy is significant.

A second spinal section below the pelvic enlargement separating the pelvic girdle and front legs from the hind legs, produced the same results as did a high spinal section (Table 2). The results shown in Table 2 are even more highly significant, and chi squared is equal to 51 ($p = 0.01$).

TABLE 2

Effect of a Second Spinal Section, Made below the Pelvic Enlargement, on Hind Limb Spinal Reflexes after Application of $CaCl_2$ and KCl to the Dorsal Surface of the Frog Spinal Cord

Experimental conditions / Conditions after chordotomy	$CaCl_2$	Control (Ringer's solution applied)	KCl	Total
Spinal shock	9	1	—	10
Steady level of excitation	13	22	11	46
Increased spinal reflexes	—	7	10	17
Total	22	30	21	73

A third spinal section, made one segment below the second in 10 frogs, produced the same condition as did the first two sections, but did not change the level of excitability of the spinal centers.

The results of the third experiment are shown in Table 3.

In this experiment, as in previous ones [9], we found that after spinal section, the following characteristic conditions could be observed: spinal shock, increased spinal reflexes, and general traumatic shock. The condition of these three conditions could be clearly diagnosed from the change in the threshold values of the reflexes, and from the kymograms obtained (see figure). In spinal shock, reflex excitability is greatly reduced,

TABLE 3

Effect of High Spinal Section on Spinal Reflexes with Parenteral Injection of $CaCl_2$ and KCl Solutions

Condition after spinal section \ Solution injected	$CaCl_2$ 0.6-2.0 ml	Control (Ringer's solution applied	KCl 1.0 ml	KCl 2.0 ml	Total
Spinal shock	18	11	7	4	40
No change	5	9	7	7	28
Increase in spinal reflexes	2	5	4	10	21
Traumatic shock		5	7	9	21
Total	25	30	25	30	110

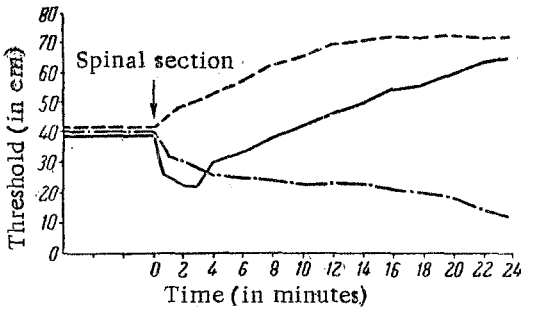

Fig. Typical changes in the reflex thresholds of the left semitendinosus muscle in a frog; faradic stimulation is applied to the left peroneal nerve. The thresholds, expressed as centimeters of separation of the two halves of the induction coil, are plotted as ordinate; time in minutes is plotted as abscissa.
———— Development of spinal shock,
– – – – – – increased reflexes,
–.–.–.–.–. traumatic shock.

but threshold stimuli sufficiently strong to elicit spinal reflexes,do not increase the state of shock but reduce it, or bring about recovery; the thresholds for reflexes gradually become reduced. Increasing the strength of the stimulus up to a certain optimum value increases the height of the muscular contraction. A condition of increased reflex activity, which may develop after spinal section, is one in which there is an increase in reflex excitability, a decrease in threshold are an increased reflex response. The condition of traumatic shock is one in which there is a progressive increase of thresholds. Here, each threshold stimulus causes a definite decrease in reflex excitability, and it becomes harder and harder to elicit a reflex contraction. Increasing the strength of the stimulus above the threshold value leads to the development of a pessimal condition. Balanced and paradoxical stages also occur. The more frequently threshold stimuli are applied (at intervals of a few seconds), the more rapidly spinal depression takes place [6, 10].

It can be seen from Table 3 that the frogs treated with $CaCl_2$ developed spinal shock more frequently, and did not develop a condition of traumatic shock, while those treated with 2 ml of isotonic potassium chloride solution usually reacted to spinal section by showing increased reflexes, or by developing traumatic shock. These reactions demonstrate clearly the contrasting effects of the calcium and potassium ions, and equally clearly distinguish the conditions of spinal and of traumatic shock as representing completely opposite states. The statistical significance of the result is shown by the value of chi squared, which had the value of 49 ($p=0.2\%$).

The results of both these experiments (see Tables 1, 2, and 3) show that the effect of calcium applied to the spinal cord is to facilitate the development of spinal shock, while potassium has the opposite action. Potassium has a parabiotic influence, which shows itself chiefly as an increase in reflex activity, or in a condition which resembles spinal shock. These facts make it necessary to draw a clear distinction between spinal shock and a condition which resembles traumatic shock, because the physicochemical and physiological changes which underline them are diametrically opposed.

The failure of any spinal shock to occur after the third spinal section, and also after the second spinal section in control frogs and in those treated with $CaCl_2$ (see Table 2), shows that impulses resulting from the wound of the spinal section cannot be the cause of spinal shock. It is more likely that these impulses prevent the development of the condition. However, a second spinal section below the pelvic enlargement in frogs treated with $CaCl_2$ caused spinal shock in 41% of the animals. From the standpoint of the conception of loss of nervous tone, we interpret the results as follows: whereas there is insufficient loss of descending intersegmental impulses from the forelimbs and pelvic girdle in the control and in the potassium-treated groups, in the calcium-treated group, the loss of impulses acts in the same way as does the removal of supraspinal impulses in frogs with an intact nervous system.

Thus, experiments have shown that changes in the spinal cord induced by potassium, which acts as an antiparabiotic agent, result in the development of spinal shock, and this constitutes evidence that the syndrome is due to an anelectrotonus. By contrast, potassium acts parabiotically on the cord, and prevents the development of spinal shock. Spinal section in frogs treated with potassium causes either an increase in activity of spinal reflexes, or else a condition resembling traumatic shock.

The second and third spinal sections in potassium-treated and in control spinal frogs cause no spinal shock. It is only in calcium-treated animals, that the second spinal section, which blocks impulses descending from the forelimb level to the lower spinal centers, can cause a second appearance of the spinal shock syndrome. The results obtained have allowed distinctions between the different concepts to be drawn, and indicate that spinal shock is to be interpreted as a condition of anelectrotonus, and that it is to be contrasted with traumatic shock, which is a parabiotic condition.

SUMMARY

In experiments on frogs, it was demonstrated that calcium ions increasing the polarization of the nerve cells, promote the development of spinal shock, following spinal section. Potassium ions prevent the development of spinal shock in the same conditions, causing increased excitation of the spinal centers or their parabiosis after chordotomy. It was established that, as distinct from the traumatic, the spinal shock results from the atony of the nerve centers of the spinal cord.

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