DYNAMICS OF CHANGES IN REFLEX IMPULSATION IN VASOMOTOR NERVES AND ITS SIMULATION BY A PROGRAMING DEVICE

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To detect criteria of the optimal state of transitional processes during reflex changes in the circulation it is suggested that the dynamics of the responses of the heart and blood vessels to changes in the flow of impulses in their effector nerves be compared with respect to certain arbitrary laws and to the law simulating the character of the change in the optimal state during reflex action. In response to continuous tetanic stimulation of the A + C-fibers of the tibial nerve in cats, impulses appear in the vasomotor nerves of the kidney in a sequence which resembles that used for high-speed optimal control of certain engineering objects. An electronic device which controls the pulse frequency of a stimulator in accordance with a program simulating the experimentally determined dynamics of changes in the flow of impulses in sympathetic nerves is described.

General considerations on the evolution of the control systems of the living organism suggest that they act in accordance with laws of optimal control [2]. To discover the concrete mechanisms of this control information is required on the criteria of the most suitable program of activity of the various physiological systems and, in particular, during transitional processes, i.e., during the transition from one state of the system to another. To establish the dynamic characteristics of the objects of the control, namely the heart and blood vessels, their response to a periodic change in the frequency of impulses in efferent fibers is investigated [3]. However, the problem of the criteria of efficiency of control cannot be solved by this method because it is not known how the pulse frequency should be changed in time in order that the transition of the object into the new state should take place by the best (optimal) method. The search for criteria of efficiency can be made easier if it is first established how signals at the output of the controlling system, i.e., the brain, vary in time during reflex action. In that case, by comparing the dynamic behavior of the object (the heart and vessels) during stimulation of their efferent nerves in accordance with certain arbitrarily chosen laws and with the law simulating the experimentally discovered changes in efferent impulse activity during reflex action, the quality of the transitional processes can be assessed with respect to such criteria as rapidity of action, fluctuation, precision, power-loss, and so on.

This paper gives the results obtained in an attempt to solve the first half of this problem, and a programing system designed to simulate the dynamics of changes in the flow of impulses in the sympathetic nerves of the heart in response to tetanic stimulation of spinal afferents is described.

EXPERIMENTAL METHOD AND RESULTS

Potentials from one of the postganglionic nerves of the kidney were recorded in cats anesthetized with urethane and chloralose (0.5 and 0.03 g/kg respectively, intravenously), immobilized with succinylcholine (150 μg/kg.min), and maintained on artificial respiration. These potentials were amplified and led to an electronic integrator with forced discharge at a frequency of 10 sec^{-1}. The output signal from the integra-

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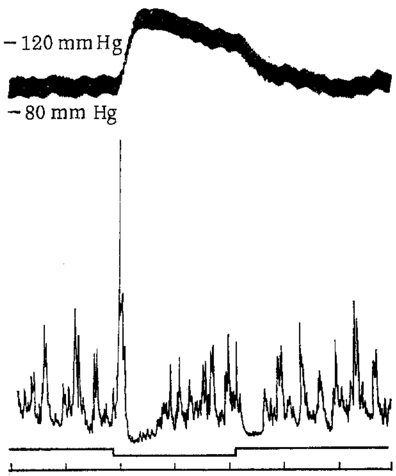

Fig. 1. Character of changes in arterial pressure and integral of electrical activity of vasoconstrictor nerves of the kidney in response to stimulation of A + C-afferents of the tibial nerve (15 V, 1 msec, 20 sec^{-1}). Periodic changes in integral of activity before and after stimulation correspond to respiratory modulation of biopotentials. Time marker 4 sec.

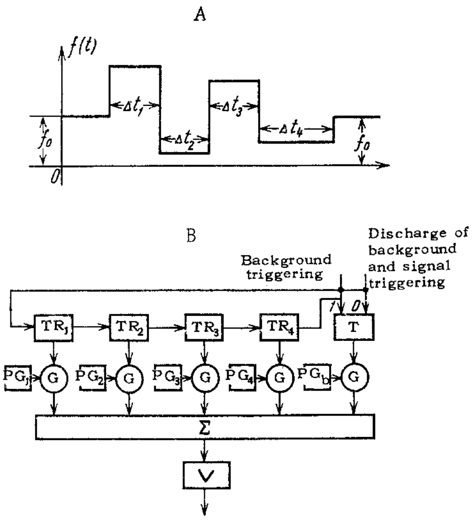

Fig. 2. Frequency f of pulse signal of programing device as a function of time (A) and functional scheme of the device (B). Explanation in text.

tor was recorded on an electronic potentiometer, the other channel of which recorded the pressure measured by an electromanometer in the carotid artery. The response of the vasoconstrictor system was evoked by electrical stimulation of the tibial nerve, the amplitude of the stimuli being sufficient to excite only the A- or the A- and C-afferents of this nerve. Activation of the fibers of each group was judged from the appearance of potentials in the corresponding groups of fibers in the electroneurogram of the stimulated nerve.

Results showing the change in arterial pressure and electrical activity in the renal nerve in response to stimulation of A + C-afferents of the tibial nerve at 20 sec^{-1} are given in Fig. 1. A transient "positive" signal, much stronger than the spontaneous electrical activity, appeared first. Its duration usually did not exceed 2-4 sec. The brain then gave a negative signal, i.e., it inhibited the flow of impulses in the constrictor fibers. The activity in the constrictor fibers then began to increase again. As Fig. 1 shows, the amplitude of the pressor reflex was entirely determined by the strength of the initial positive signal. When the stimulation ceased, the negative signal reappeared (complete inhibition of the flow of impulses), after which the strength of the tonic activity gradually returned to its initial level.

The sequence of changes in the flow of efferent impulses with time as described above was reproduced consistently on repetition of the same stimuli, although during a long experiment the amplitude and duration of the "positive" and "negative" signals could vary. By comparing the responses in the renal nerve to stimulation of A- fibers alone and of A + C-fibers of the tibial nerve, it was found that the phases of the change in the signals in the constrictor fibers described above are formed by the brain only if group C afferents are included in the excitation.

The sequence of changes in polarity of the output signals of the brain controlling the blood vessels discovered in these experiments was similar to that used for the control of certain engineering objects when close to optimal rapidity of action is essential [1]. By analogy it can be considered that, during a reflex change in arterial pressure from one level to another, the vasomotor structures of the brain will produce a near-optimal signal.

PROGRAMING DEVICE FOR MODEL EXPERIMENTS

To stimulate the sympathetic fibers of the blood vessels and heart in accordance with the law governing the change in strength of impulse activity with time as shown in Fig. 1, a device was constructed which, by controlling the triggering of the stimulator, would change the frequency of stimulating pulses f (Fig. 2A).

When $t < t_1$ and $t > t_5$ the pulse sequence has the background frequency f_0. Starting from an assigned moment of time t_1 the pulse frequency changes stepwise during the interval $t_1 = t_5$ and returns at the moment t_5 to its initial value f_0.

The duration of the intervals Δt_k and the frequency at each interval can be varied up to 30 sec and between 0.1 and 100 sec^{-1}.

A functional scheme of the programing device is shown in Fig. 2B. When the voltage supply is switched on, by pressing the button marked "background adjustment," the trigger T is set in the position 1, corresponding to the open position of the gate G_5. A pulse signal from the generator, with background frequency

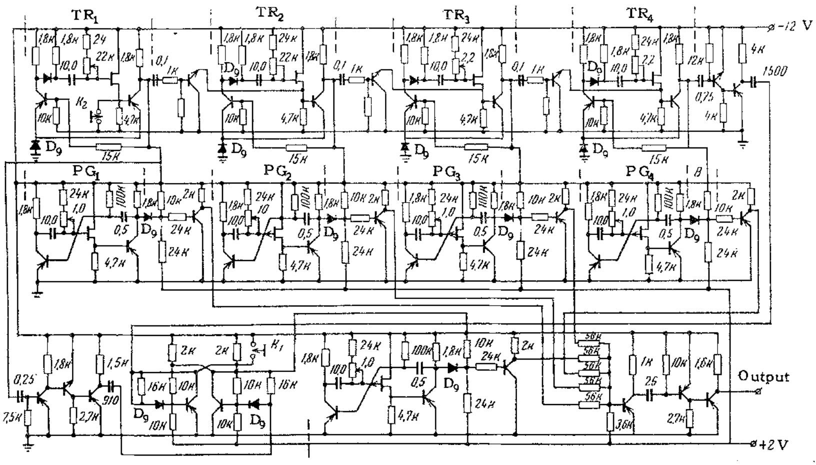

Fig. 3. Theoretical circuit of programing device. Explanation in text.

f_0, thereupon passes through the gate G_5 to the logical summation circuit Σ. The signal from the summation circuit is amplified and led to the "output."

The time intervals Δt_k are assigned by the successively activated time relays TR_k, each of which forms a gating pulse of duration Δt_k. The trailing edge of the gating pulse of the preceding time relay triggers the next relay. The first time relay TR_1 is triggered by the background discharge and signal trigger button at the moment of time t_1.

From the leading edge of the gating pulse from TR_1, a pulse is formed by means of a combined amplifier and shaper to throw the trigger T into the 0 position. The gate G_5 is thereby closed and arrival of the background pulses at the summation circuit ceases. The gating pulses of the remaining time relays in turn open the corresponding gates through which pulses from the generators PG_1 - PG_4 proceed to the summation circuit. The trailing edge of the gating pulse of the last time relay TR_4, at the moment of time t_5, forms the pulse which returns the trigger T to position 1. When this happens, pulses from the background generator begin to reach the summation circuit. To change the frequency of the output pulse signal again, the button background discharge and signal trigger must again be pressed.

The theoretical circuit of the programing device developed for this investigation is given in Fig. 3. The time relays have a transistorized monostable multivibrator circuit. The duration of the interval Δt_k is fixed by a circuit consisting of variable resistor $R = 1\ M\Omega$ and capacitor $C = 10.0\ \mu F$ in the collector of the left transistor. The time-setting circuit is connected to the base of the second transistor through a source follower on a field transistor. The high input impedance of the field transistor on the gate side enables gating pulses of sufficiently long duration to be obtained despite the relatively small capacitance.

The pulse generators PG_k are of multivibrator type working under self-oscillating conditions. The duration of the output pulse is fixed by a circuit of $R = 100\ k\Omega$ and $C = 0.5\ \mu F$ in the collector of the right transistor. The pulse repetition period is set by the variable resistor $R = 2\ M\Omega$ and capacitor $C = 10.0\ \mu F$ in the collector of the left transistor. This RC-circuit is connected with the base of the right transistor through a source follower on a field transistor with high input impedance.

Type MP41A germanium p-n-p transistors, type KY301 silicon n-p-n transistors, and KP102 silicon field transistors are used in the circuit.

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