difficulty in handling described in item ii can be overcome by the use of oil treatment of the glass or by improved handling techniques. A step in the direction of solving the problem of item iii has been taken by the New Jersey Dairy Laboratories, which uses mechanical rotation of dishes during preparation to improve distribution. Most laboratories employ manual rotation of petri dishes, but the colony distribution so produced is poor. Building sufficient logic into a scanning machine so that it can count "spreaders" and "pulls" properly appears, at present, to be prohibitively expensive.

Other Applications

The scanning and information processing techniques used in the automatic particle and bacterial colony counter are applicable to many problems involving the analysis of a small or large visual field. For example, any objects that can be placed in a petri dish may be counted, provided that they are sufficiently large to be resolved (0.5 millimeter in diameter). Figure 5 shows an assortment of electrical hardware components being scanned and displayed on the monitor. The bright counting dot at the top of each item shows that it was properly counted and that the instrument was not "confused" by its shape or the presence of holes. Modified versions of the instrument have also been used with equal facility to count bacterial colonies on opaque membrane filters and pinholes in opaque metal foils. Although demonstrations of these capabilities have been impressive, no single version of a flying-spot scanning device can be versatile enough to handle all of the problems requiring optical scanning. Some applications require the scanning of very large areas, and others require the scanning of microscopic areas. Furthermore, many scanning applications require logic circuitry to provide size and area, density, spectral, and other types of information. This means, of course, that different optical and electronic systems must be developed for the basic flying spot scanner-phototube combination to apply it to these problems.

A whole new field of industrial instrumentation involving the use of flying-spot scanners for automatic flaw inspection of large-area sheet products such as paper, glass, metal, and foils appears to be imminent (*8*). At the other extreme, with respect to size of area scanned, flying-spot microscopes are being developed in this country (and are commercially available in England) to perform such functions as the counting and sizing of microparticles. One of the most significant contributions to biological research, in the field of cell and tissue studies, has been the development of an ultraviolet flying-spot microscope. This instrument, developed at the University of Texas Medical School, has permitted, for the first time, the unlimited study of living cells with ultraviolet light (*9*).

It is believed by many that the flying-spot microscope, when equipped with special information-processing circuits such as those of the automatic colony counter, will provide a very powerful tool for industrial and biological research laboratories. Accordingly, it may be destined to follow a path of development, requiring evolution of techniques and accessories, analogous to the path of the development of the electron microscope. The automatic particle and bacterial colony counter should be considered, therefore, to be one step in the development of flying-spot, optical-electronic transducer instrumentation.

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2. This work was sponsored by the U.S. Army Chemical Corps. I appreciate the guidance of Nelson E. Alexander of the U.S. Army Chemical Corps. Credit is due, too, to the successful efforts of the engineering group at the Allen B. DuMont Laboratories in the development of this instrument. The evaluation of the dairy application was made possible by the cooperation of David Levowitz, director of the New Jersey Dairy Laboratories, and B. A. Larsen, director of the Sealtest Supplee Laboratory.
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Servo Control of General Anesthesia

J. Weldon Bellville and George M. Attura

The automatic control art with its associated servo machines offers a finer control of physical variables than can normally be accomplished by human operators. This holds true for complex military devices as well as for those automatic control systems that have been introduced into the field of medicine. We have developed a servo control mechanism that will control a single physiological process, depth of anesthesia.

Regardless of its application, the quantity to be controlled by a servo must fulfill certain criteria. It must be measurable by some data-sensing element which translates the quantity in test into an electric voltage, and motor means must be available to control this quantity.

In the field of anesthesia, we have a situation that will fulfill these criteria. The depth of anesthesia is the quantity that must be controlled. For our purposes, we can define depth of anesthesia in terms of the cortical potential that is recorded by an electroencephalograph. The deeper the level of anesthesia, the less the electric cortical potential. If increasing concentration of anesthetic in the blood parallels increasing depth of anesthesia, then this premise is valid, since it has been shown that there is an inverse relationship between the concentration of ether or cyclopropane in the blood and the electroencephalograph potential (*1, 2*). The depth of anesthesia is usually controlled by the amount of anesthetic agent administered to the patient per unit time, whether the agent

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is a barbiturate given intravenously or a gas which the patient is allowed to inhale. Since the depth of anesthesia can be measured as an electric quantity, a suitable servo device can be placed between the electric variable and the pump or valve that administers the anesthetic to the patient.

Human Control

At present, during the majority of operations, depth of anesthesia is determined and controlled by an anesthesiologist who observes the patient. The anesthesiologist gages the depth of anesthesia through his senses by considering the patient's respiratory rate, chest wall movements, muscle tone, blood pressure, pulse rate, pupil size, various reflex responses, and other general clinical criteria. Correlating these observations with his experience, the anesthesiologist estimates the depth of anesthesia at any given moment, and, considering the requirements of the surgeon, decides whether more or less anesthetic is necessary.

Of necessity, the process is not completely continuous. A correction is applied to the rate of administration of anesthetic agent to the patient, and, at varying intervals, the clinical observations are repeated, and the rate of administration of the anesthetic is again readjusted. There exists, thus, a cause-and-effect relationship between the anesthetic agent and the clinical signs of the patient. This relationship, together with interpretation and control by the anesthesiologist, constitutes a loop or chain of response (Fig. 1*a*).

It is important to note that the situation described is a true feedback control system in which both the patient and the anesthesiologist play important functions. It might be called a human servo, since the action of the anesthesiologist is determined by his observation of the effect of his previous actions in adjusting the rate of administration of anesthetic agent. Thus, it is in the same servo class with other automatic-control and feedback-control systems in current use in industry and elsewhere, except that the interpretation of data and the motor action to control the output physical variable are performed by the human operator, namely, the anesthesiologist.

In subsequent paragraphs, it is shown that the addition of a servo device does not change the nature of this loop, but merely improves its accuracy and speed of response. The addition of the anesthesia servo device to this feedback loop can improve it in two major respects. First, the accuracy of sensing the depth of anesthesia can be increased and, second, the time interval necessary to sense and correct the depth of anesthesia can be reduced. These two factors combined result in an accurate, uniform control of anesthesia.

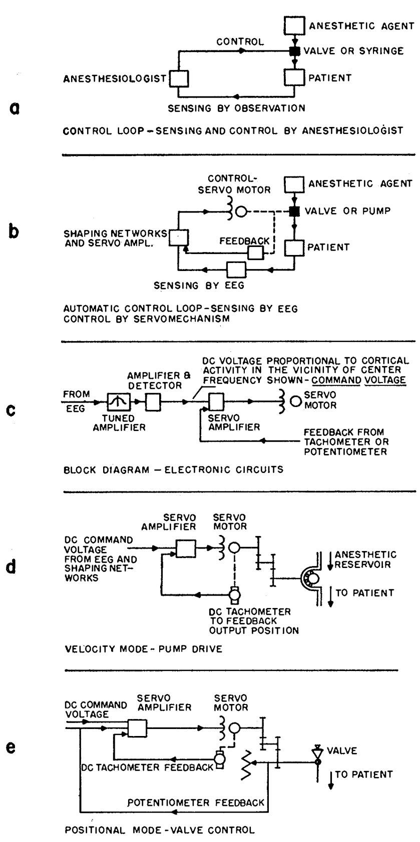

Fig. 1. Feedback loops.

Servo Control

The first system designed to control the depth of anesthesia automatically was described by Bickford in 1950 (*3, 4*). Sensing the depth of anesthesia was accomplished by noting the output of an electroencephalograph, and a fixed amount of Pentothal or diethyl ether was administered automatically in response to the integrated cortical activity. In 1952, Bickford described frequency discrimination to sense depth of anesthesia more accurately (*5*). The continuous automatic control of cyclopropane anesthesia was described in 1953 (*6*). Recently, it has been shown by electroencephalographic frequency spectrum analysis during anesthesia that the amplitude of certain frequency bands varies with the depth of anesthesia (*7*).

When the electroencephalograph is used to monitor a selected cortical frequency, its output becomes an accurate index of the depth of anesthesia. This electric voltage, properly processed and transformed, can be used to drive a servo mechanism which controls the flow of anesthetic to the patient as a direct function of the voltage. A simple block diagram of the servo-driven anesthesia system is shown in Fig. 1*b*. The electroencephalographic output is fed to a band-pass network whose output in turn contains only those frequency components from the electroencephalograph which are close to the chosen frequency. Roughly speaking, if the frequency is properly chosen, the lighter the anesthesia the greater the electric output from this band-pass circuit. This voltage, then, can be considered proportional to the level of wakefulness of the patient and inversely proportional to the depth of anesthesia. This voltage is spoken of hereafter as the "command voltage." The servo system between the command voltage and the anesthetic consists of a motor driven by a servo amplifier whose input is the output of the band-pass circuit, the command voltage (Fig. 1*c*).

If the anesthetic is to be administered intravenously, as is the case with Pentothal, the motor drives a positive displacement pump at a speed which is very closely proportional to the command voltage of the servo (Fig. 1*d*). In this mode of operation, we have what is called a "velocity servo," since the velocity of the output shaft is proportional to the command voltage.

If the anesthetic is a gas, a valve is used to control its rate of flow to the patient who is inhaling it. In this case, the servo must establish correspondence between the position of the valve and the command voltage. Here a type of servo commonly called a "positional servo" is employed. For a positional servo, the output voltage from the band-pass network—the command voltage—determines the instantaneous position of the valve (Fig. 1*e*).

It is important to note again that the use of a servo device does not basically alter the loop that exists when the anesthesiologist is performing the sensing and control functions. As has been explained, in that case we do have a feedback loop, with the depth of anesthesia of the patient acting as the controlled quantity and with the anesthesiologist, with his equipment, performing the dual role of sensing and controlling (Fig. 1*a*). In the new system, the servo device substitutes for the anesthesiologist; sensing the depth of anesthesia is a function of the electroencephalograph and its associated band-pass networks, and controlling the depth is a function of the servo motor and its associated mechanism. The only reason for introducing this change is to achieve a system capable of greater precision of control and greater speed of response—a system free from human error.

Description of Servo and Modes

The system described in this article has been developed by us to administer Pentothal, cyclopropane, or ether by means of servo techniques. The electroencephalogram is obtained by inserting No. 25 needle electrodes into the scalp overlying one hemisphere in a frontocentral position. Records are made on a Grass IIID electroencephalograph whose frequency response is flat from 1 to 40 cycles per second. The output from the electroencephalograph is fed into tuned band-pass electronic networks which pass only frequency components close to the tuned frequency. For this system, there are two networks: one tuned to 24 cycles per second for ether anesthesia and one tuned to 16 cycles per second for Pentothal or cyclopropane anesthesia. The proper network is selected by a switch (*S*1, Fig. 2). The band-pass circuits are shown in the accompanying schematic diagram (Fig. 2). The band-pass stage is a tuned amplifier (*V*1) with parallel-T feedback which results in a precisely known and shaped band-pass characteristic. The center of resonant frequency is determined by the values of the resistors and condensers in the tuned parallel-T feedback circuit. The output of the band-pass stage is fed to another amplifier and then rectified into a d-c voltage which varies linearly with the output of the band-pass network, and hence follows proportionately the level of wakefulness of the patient, and therefore, inversely, the depth of his anesthesia.

Whether the servo is used in the velocity mode or in the position mode, the command voltage determines how fast the motor will turn the pump to administer the intravenous agent or the position of the valve for gaseous agents. The command signal then drives a closed servo loop consisting of a motor, tachometer, and amplifier (in the velocity mode) (Fig. 1*d*) or a motor, tachometer, potentiometer, and amplifier (in the position mode) (Fig. 1*e*).

In the velocity mode, the proportionality between output velocity and command voltage is obtained by feeding back from the tachometer a d-c voltage proportional to the velocity and comparing it with the command voltage. The difference between these two, which is a very sensitive measure of the error, then drives the servo amplifier and forces the motor, tachometer, and pump to follow at a speed which is very precisely proportional to the command voltage and hence to the level of wakefulness of the patient.

In the positional mode, the command voltage is compared with a d-c voltage from the wiper of a potentiometer which is coupled to the moving part of the gas valve. Driven by the error between these two voltages, the servo system turns the motor, pump, and potentiometer until the potentiometer potential is exactly equal to the command voltage. At this point, the error between the two voltages is zero. The servo motor stops. In this way, exact proportionality between valve position and command voltage or level of wakefulness of the patient is obtained. Since the valve position bears a proportional relationship to the volume of anesthetic gas, the level of anesthesia in the patient is brought under control.

The tachometer is also retained and driven in the positional mode, although its function is different from its function in the velocity mode. In general, the positional servo is more subject to loop oscillations or "hunting" than the velocity servo. In this mode, the anesthesia servo would hunt uncontrollably around its null unless some means of damping were provided. A convenient damping technique is to feed back to the input of the servo amplifier a voltage obtained from the output shaft. The tachometer voltage is then used to damp the loop in the positional mode.

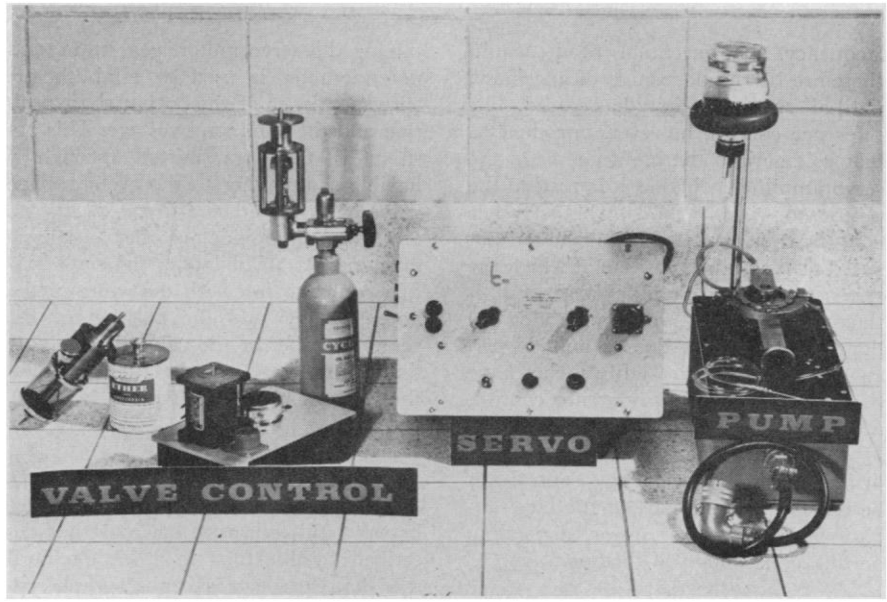

Fig. 3. Servo control unit with pump drive and valve control.

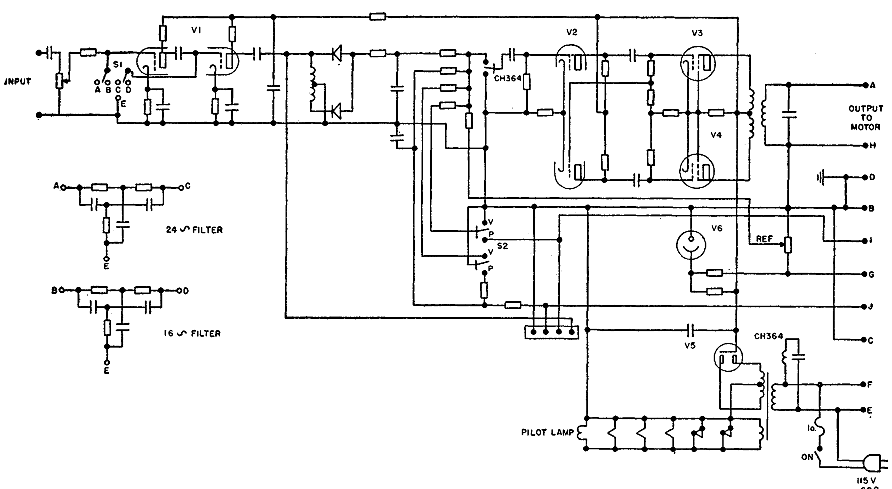

Fig. 2. Servo control unit. Connections: *A, H,* control winding of servo motor; *E, F,* reference winding of servo motor; *G, I, B,* potentiometer; *C, J,* tachometer.

Depth Control

With the circuit shown (Fig. 2) it has been possible to combine these two functions in a single apparatus using the same servo amplifier. The transition from velocity mode to position mode is made by turning a switch (*S*2, Fig. 2) on the front panel (Fig. 3) and connecting a cable to the appropriate pump or valve control.

A very important feature of this instrument is the addition of a threshold level control which sets the reference level against which the system operates (*REF,* Fig. 2). The reference level determines the steady-state depth of anesthesia of the patient. Without this control, the action of a servo system would continue the flow of anesthetic to the patient as long as there was any electroencephalographic activity at the selected frequency. The eventual result would therefore be the deepening of anesthesia until all cortical activity has ceased. The reference control, however, introduces a bias voltage into the input circuit of the servo amplifier, whether it is used in the position or velocity mode. This reference control voltage determines the output speed or the output position at which the system achieves a steady state, and it thus prevents the servo from driving the depth of anesthesia deeper and deeper. In practice, all other adjustments have been made so that this reference control, with its calibration on the front panel (Fig. 3) determines the anesthetic level of the patient. The reference control can be reset to bring the anesthetic level automatically higher or lower, depending on the requirements of the operation.

Motor Means

As has been mentioned, the servo motor will drive either a pump or valve through associated gearing. One successful form of a pump drive is shown in Fig. 3. The servo motor and tachometer are geared down 300 to 1 to drive the rotor of the positive-displacement pump. This pump has been adapted from a peristaltic action pump manufactured by the American Instrument Co. It consists of a constrained half-turn of flexible tubing through which the liquid intravenous anesthetic is forced by the action of rollers which press the two walls of the tubing together and hence force the anesthetic to move in one direction with a volume rate of flow proportional to the speed of the rotor of the pump. In this application it is important that a positive-displacement pump be used, for the following conditions must be met: (i) a definite correspondence must exist between the volume of fluid injected and the displacement of the pump rotor; (ii) there must be no change in the rate of fluid flow with changes in venous pressure; (iii) there must be no change in the rate of fluid flow with the change in hydrostatic pressure between the pump and reservoir. A positive-displacement pump, as its name implies, resolves all these difficulties, and this particular pump has proved to be quite successful for this application. This pump also has the distinct advantage that sterility is not a problem, since sterile intravenous tubing can be made to fit it (Fig. 3).

For gaseous anesthetics, a different system must be used. It is necessary to control the position of a valve and to keep it in tight correspondence with the rectified monitored output of the electroencephalograph—the command voltage. In our application, a gear box containing the servo motor, gear train, and potentiometer is used to establish the correspondence of the output shaft position and the command voltage. This position is then transmitted through a flexible shaft either to the cyclopropane valve or to the ether drip can stem of a circle carbon dioxide absorber anesthesia machine. At steady state, the servo system comes to rest with the wiper of the potentiometer and the position of the rotary member of the valve determining the volume rate of inhalation of anesthetic agent by the patient.

Discussion

It is important to note the difference between this servo system and that described by Bickford in 1950. Bickford saw that the electroencephalograph represented a more sensitive indicator of the depth of anesthesia than any available clinical sign. He used the rectified energy output of the cortex to charge a condenser with a d-c voltage. When this charge or voltage exceeded a certain value, it triggered a thyratron tube which in turn actuated a relay to inject a fixed volume of Pentothal. Later Bickford modified this system to include a bandpass stage to select only 12-cycle-per-second activity, since he found that the 12-cycle activity varies directly with the depth of anesthesia. The servo device employed by Bickford can be called an "on-off servo," for it lacks the proportioning feature discussed here. No Pentothal is injected into the patient until the integrated level of cortical activity exceeds a certain point. At this point the thyratron discharges, and the relay injects a slug of Pentothal into the vein. This increment of Pentothal, after a suitable delay, increases the depth of anesthesia, and the system remains dormant until the thryatron again discharges. It might be said that in this system the patient reaches a certain level of wakefulness, but that the machine senses it and injects a slug of Pentothal to increase his depth of anesthesia once more. If one were to plot the level or depth of anesthesia as a function of time for Bickford's machine, he would note an oscillation between deeper anesthesia right after the Pentothal has been injected and a lighter level of anesthesia just before the thyratron fires. It is important to note also that there is no feedback per se between the unit which administers the anesthetic agent and the electroencephalographic voltage. Hence, the calibration of the system or the time or the level at which it fires (and therefore the amount of Pentothal it injects) is a variable dependent on aging, line voltage, and several other factors.

The chief improvement of our present system has been the introduction of the feedback principle locally between the dispenser of the anesthetic agent and the output of the electroencephalograph. This local or secondary feedback loop, which is really the chief feature of the servo device we have described, serves only to set a precise calibration in the relationship between the electroencephalograph output and the amount of anesthetic agent that is introduced into the patient. A happy by-product of this type of system is that the action is continuous, and as such it can continuously readjust itself so that it maintains a constant depth of anesthesia within the patient instead of oscillating as an "on-off servo" does.

Present Application

The servo described in this article can be a valuable aid in pharmacologic evaluation of drugs. Some physiological responses such as pulmonary and vascular reflexes are dependent on the depth of anesthesia. Maintenance of a constant level of anesthesia eliminates this variable. If depth of anesthesia is controlled automatically, and if additional anesthetic is introduced as a disturbance factor, the response of the servo system will represent a measure of drug action. Thus, the relative potency of agents which affect the electroencephalogram can easily be determined. Other servo systems will undoubtedly be used in the future by the pharmacologist since they can be used to study drug action at or near equilibrium conditions.

Even though this servo device responds more quickly and controls depth of anesthesia more accurately than the human operator, it may be many years before these control instruments are widely used clinically. The anesthesiologist senses many variables and correlates his observations with past experience and the requirements of the surgeon in order to determine the anesthetic requirements. This servo is limited in that it senses only one variable, the electroencephalogram. Certainly more complex devices that sense several variables and have memories and fail-safe features are possible.

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