

## THE CLINICAL APPLICATION OF AUTOMATIC ANESTHESIA •

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Received for Publication November 24, 1950

CHANGES in the electro-encephalographic pattern of man and animals undergoing anesthesia have been the subject of investigation on the part of many research workers (1, 2, 3). In a previous publication from our laboratory a classification of these changes correlated with varying depth of ether anesthesia was submitted (4). During these studies it became apparent that there was a consistent relationship between the total electric energy output derived from the scalp leads used and the depth of anesthesia. Upon a basis of these findings, studies on animals were undertaken by one of us (Bickford) by which it was demonstrated that this relationship existed in laboratory animals for both thiopental sodium (pentothal sodium) and ether. As an outcome of these investigations a device was constructed which integrated the energy output represented in the brain waves. This device was designed in a manner that allowed the frequency of activation of a relay to be proportional to the energy output. Thus, as the energy output becomes less with deepening anesthesia, the frequency of activation of the relay becomes less. This relationship is shown in figure 1. It will be seen that the number of integrator discharges (relay activations) per minute is designated as units per minute. Further, the progressive decline in the number of discharges from light anesthesia to deep anesthesia as indicated by the brain-wave patterns is apparent. The relay was modified in a manner which resulted in the injection of a predetermined amount of thiopental into the vein of the animal with each activation. Thus in any established electro-encephalographic level of anesthesia the effect of increasing depth results in a relative decrease in the rate of administration of the anesthetic agent. If the depth of anesthesia decreases, the rate of administration increases. This relationship suggested that the automatic maintenance in animals, for long periods of time, of a state of anesthesia manifested

\* Read at the Annual Meeting of the American Society of Anesthesiologists, Inc., Houston, Texas, November 8, 1950.

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by a consistent electro-encephalographic pattern was possible. The fact has been well demonstrated in this laboratory, and the details of these studies have been published (5).

### EQUIPMENT

The facility with which a state of automatic anesthesia could be maintained in animals led naturally to similar studies in human subjects in the operating room. A portable machine suitable for use in the operating room was constructed by the Section on Engineering (fig. 2). It embodied essentially a two-channel penwriting oscillograph for recording the electro-encephalogram and electrocardiogram. Un-

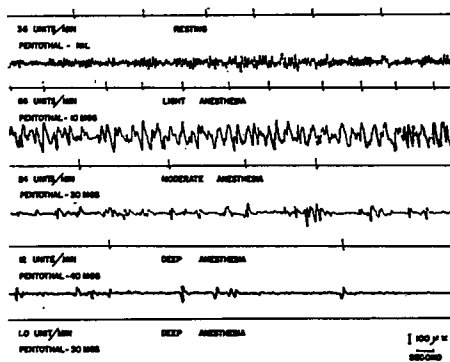


FIG. 1. Influence of pentothal anesthesia on the electro-encephalogram and the integrated potential output of the rabbit cortex. The change in the frequency of integrator discharges (units per minute) from the rapid to the very slow rate that occurs as anesthesia progresses from light to very deep, is shown.

wanted noise and 60 cycles per second interference have been greatly reduced by narrowing the frequency pass of the amplifiers to that required for automatic anesthesia (linear from 1 cycle to 10 cycles with complete cutoff at 0.5 cycle and 30 cycles). Both channels are monitored on the screen of a double-beam oscilloscope. An integrator on the electro-encephalograph channel provides the electric pulses required to activate a pump designed for the administration of ether which is carried to the vaporizer through a polythene tube. The vaporizer is made from a Krogh valve which has had its rubber membrane replaced by a circular copper screen over which there is a loose winding of heavy cotton twine. In use, the vaporizer assembly is placed on the inspiratory side of the semiclosed breathing system.

The use of conventional solder type electro-encephalographic electrodes was found to be inconvenient in operating-room practice. In their place are used small piano wires which have been sharpened in the manner of a hypodermic needle and bent to form a hook. The hub ends of these electrodes are provided with threads which allow easy attachment to the leads. The latter consist of fine wire shielded to reduce static artefacts. To assure that the patient's head does not rest on needles, and because satisfactory potentials could be obtained, the placement of bipolar electrodes is made on one side of the scalp, 1 inch

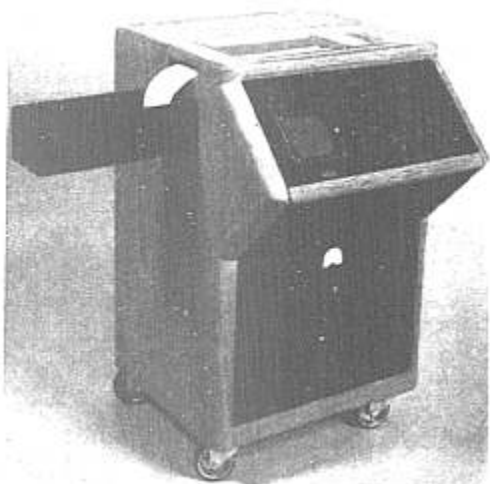


FIG. 2. Automatic anesthetizer designed for use in the operating room.

from the midline as follows: The distance from the glabella to the inion is divided into three equal segments and the electrodes are inserted into the scalp at the anterior and posterior ends of the middle segment thus determined. A similar electrode is placed in the mastoid region and connected to a ground lead. Difficulties arising from electrical interference which led to troublesome artefacts have been minimized by the use of a second grounded contact consisting of a Crooke's metal plate of large surface area (approximately 15 square inches). The plate coated with electrode jelly is placed on the back of the patient at the junction of the neck and the thorax.

## PROCEDURE

The procedure used in these clinical studies was as follows: The electro-encephalographic leads were attached to the subject in the manner described and conventional electrocardiographic electrodes were placed to record one of the three standard limb leads. A short record of the resting rhythm was made after premedication but prior to the administration of the anesthetic agent. The induction of anesthesia was begun in the usual manner using, in most cases, nitrous oxide, oxygen, and ether sequence with a semiclosed carbon dioxide absorption system. In a few cases the inhalation anesthetic agent was administered by the same method following induction with thiopental. In no case did the thiopental used for induction have any effect on the subsequent course of automatic ether anesthesia. The course of induction proceeded in the conventional manner until an electro-encephalographic level was reached which was adequate for the insertion of an endotracheal tube. This was done in every case, and then the mask replaced on the face and secured with elastic head straps. Soon after intubation, the course of the anesthesia was turned over to the automatic anesthetizer and suitable adjustments in the device were made on an empiric basis to maintain the desired level of anesthesia.

While it is possible to make these adjustments at a variety of points in the electromechanical system, such as by varying the gain of the amplifier, by changing the attenuation of the integrator input, or by altering the output of the pump, it was deemed advisable to limit the variable to a single control. In practice it has been found expedient to adjust the desired depth of anesthesia with the attenuator control. The net result of this adjustment is to change the amount of ether delivered per unit of brain-wave energy. The ability to anticipate the depth of anesthesia that would be maintained following adjustment of the integrator control became more certain with increasing experience. Following proper adjustment, the anesthesia was maintained automatically for the duration of the operative procedure.

## MODE OF OPERATION

It has been stated that there exists a consistent relationship between the clinical depth of anesthesia and the electrical output of the cortex. This relationship, which is demonstrated in figure 3, is such that after an analgesic state is produced the cortical output decreases with increasing depths of anesthesia. The quantitations of the brain potentials represented by discharges of the integrator are recorded simultaneously with brain-wave patterns which have been found to occur at various clinical depths of anesthesia. It should be noted that in the case shown the rate of discharge of the integrator decreases from 65.4 per minute in analgesia to 60 per minute in light anesthesia and to 43.6 per minute in moderate anesthesia. It continues to decrease

with deeper anesthesia so that at an extremely deep level the discharge rate is only 1.3 per minute. The integrator discharges activate a pump which has been adjusted to administer 0.1 cc. of ether with each stroke. Consequently the rate at which the ether would be administered depends upon the frequency of integrator discharges and ultimately upon the depth of anesthesia.

To demonstrate how the system functions, suppose it were desired to maintain a moderate depth of anesthesia (represented by electroencephalographic level 4). If the anesthesia were to become deeper, the energy output of the cortex would decrease, and the decreased discharge rate of the integrator would result in the patient's receiving

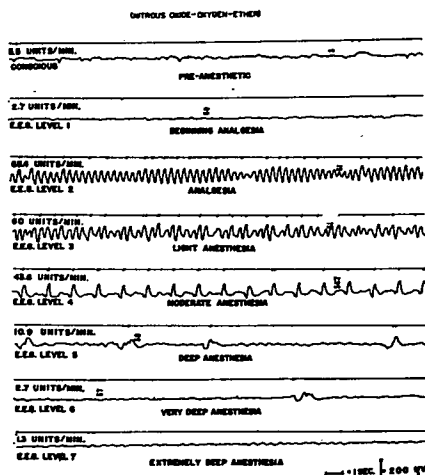


FIG. 3. The relationship between integrator discharges (units per minute) and depth of anesthesia as indicated by the electro-encephalographic pattern, is demonstrated. As anesthesia progresses from light to extremely deep, the rate of integrator discharges decreases.

proportionately less ether. This would result in his returning to the desired lighter level of anesthesia. Conversely, if for any reason the anesthesia were to get lighter than the depth for which the system had been adjusted, the cortical output would increase resulting in a more rapid rate of discharge of the integrator. Relatively more ether would be administered to the patient, and anesthesia would return to the desired depth. In actual practice the system tends to hold a given level for which it has been adjusted.

Figure 4 demonstrates the response of the automatic anesthetizer to an external disturbance which affects the depth of anesthesia that is being maintained. In this case the subject had been maintained automatically in a moderate depth of anesthesia. To put the subject momentarily deeper and to demonstrate the response of the anesthetizer, 3 cc. of ether were injected into the vaporizer during the thirty-first minute of anesthesia. The expected compensatory drop in the integrator discharge rate (and therefore a decrease in the rate of ether administration) can be observed. Within three minutes the depth of anesthesia had returned to its previous level. At about the forty-sixth

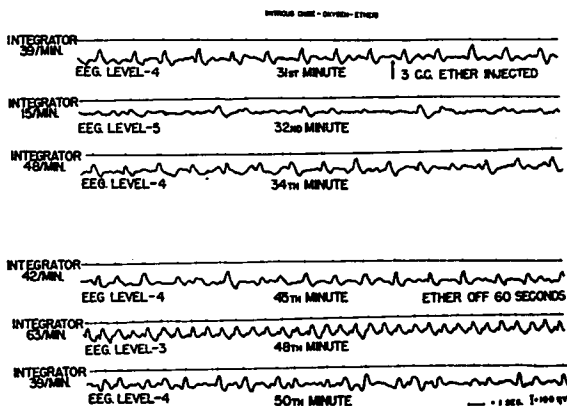


FIG. 4. The ability of the servo-anesthetizer to compensate for external interference is illustrated. In one example extra ether was added to the anesthesia system manually. In the other example the normal ether supply from the automatic anesthetizer was interrupted for one minute. Compensation for both these emergencies is indicated in the integrator rate and electro-encephalographic patterns shown.

minute of anesthesia a compensating response in the opposite direction is demonstrated. The administration of the ether was manually interrupted for sixty seconds and in the forty-eighth minute the integrator discharge rate had increased markedly. After the interruption was discontinued, the resulting increased amount of ether which the subject received caused return to the original level of moderate anesthesia in two minutes. The homeostatic properties of the system are thus seen in human anesthesia, as had been noted in studies on animals. This self-compensation is probably the most important factor in enabling the system to maintain an even level of anesthesia.

## RESULTS

This report concerns 50 cases in which the automatic control of anesthesia has been maintained (table 1). Thirty-one patients were males and 19 were females, and the ages ranged between 24 and 78 years. An analysis of records of these cases revealed a total anesthesia time of ninety-three hours of which the total duration of automatic maintenance of anesthesia was sixty-nine hours (approximately 74 per cent of the total anesthesia time). A more detailed analysis of the records of the 50 cases revealed that the electro-encephalographic patterns observed were confined, in more than 95 per cent of the total duration of automatic maintenance to those patterns that have been appraised as indicative of safe surgical levels of anesthesia.

TABLE 1  
OPERATIONS PERFORMED UNDER AUTOMATIC ETHER ANESTHESIA

Operation	Cases
Exploratory laparotomy	2
Herniorrhaphy	4
Cholecystectomy	7
Choledochoduodenostomy	1
Choledochostomy	1
Removal of carcinoma of ampulla of Vater	1
Gastrectomy	18
Hysterectomy	1
Abdominal perineal resection of rectum	2
Anterior resection of sigmoid colon	11
Hemicolectomy	2
Total	50

In one of these cases a complication which might be attributed to the method has occurred. The patient had temporary respiratory arrest while the electro-encephalogram revealed a pattern usually consistent with safe surgical anesthesia. For reasons of safety, use of the method was discontinued in this case at once. The reason for this occurrence is still obscure and is deemed of sufficient interest to warrant further investigation into possible causes and preventive measures. A device has been designed and demonstrated in the laboratory which is capable of interrupting the automatic administration of an anesthetic agent when the respiratory rate falls below a certain selected minimum. Envisioning the possibility of similar complications which might arise from a sudden circulatory failure, efforts are now being directed toward the development of a similar automatic cutoff which will be activated by undue fall in blood pressure.

## COMMENT

It is not our purpose in presenting these studies to propose the substitution of a complex electromechanical machine for a competent

anesthetist, any more than one would seriously propose flight in a commercial airliner equipped with an automatic pilot without the presence of the crew. However, we do feel that certain applications of this method offer sufficient promise of practical value to warrant serious consideration. These applications can be considered according to four major categories:

1. The device may find a field of usefulness in clinical anesthesia when applied under circumstances in which the prolonged maintenance of an even level of anesthesia is desirable. The fact that it is capable of accomplishing this end has been demonstrated in these studies. A potential field of usefulness, though as yet untested, might be found in the maintenance of an even level of anesthesia in patients to whom curare has been administered. There is now sufficient evidence to indicate that for practical purposes curare will have little or no influence on the functioning of the method.

2. If therapeutic value should be indicated in the prolonged maintenance of narcosis, it is reasonable to assume that this method might be adapted to that purpose. We are unaware of any recognized therapeutic procedures involving prolonged deep narcosis with the agents used to the present time.

3. Perhaps the greatest immediate value to be derived from the use of this method lies in the field of its research application. There has long been a need for definite objective control of anesthesia in many of the problems encountered in pharmacologic and physiologic investigations. Often the uncertainty introduced by the necessity of maintaining animals under anesthesia of uncalculated depths has an important bearing on the conclusions derived from the experiment. Up to the present time this variable has been controlled by the interpretation of certain isolated reflex phenomena which in themselves are notably inconstant. In addition to those research applications it is our belief that this method may constitute a valuable tool in the elucidation of the fundamental nature of anesthesia in the higher species of animal life.

4. In a more general way it is felt that the development of automatic control of anesthesia, which is an example of the application of servo-mechanism theory, opens wide and interesting possibilities of automatic control in the entire field of medicine.

Finally we propose that the name "servo-anesthesia" be applied whenever reference is made to a system for the administration of an anesthetic agent on a basis of feed-back principles.

#### SUMMARY

The steps leading up to the development of a device for the automatic electro-encephalographic control of depth of anesthesia in surgical patients are reviewed.

The servo-anesthetizer is based upon the principle that the output of cortical electric energy falls off consistently in relation to increasing depth of surgical anesthesia.

The servo-anesthetizer functions on the principle of a feed-back mechanism with a certain degree of self-compensation for errors introduced. It embodies an amplifier and integrating circuit for converting cortical electrical energy into electric pulses which are utilized in activating a mechanism for administering ether to a patient.

The method has been applied to 50 patients undergoing surgical anesthesia with mixtures of nitrous oxide, oxygen and ether.

An analysis of the records revealed (a) that in 50 cases 74 per cent of the total anesthesia time was controlled by the servo-anesthetizer, and (b) that safe surgical electro-encephalographic levels of anesthesia were maintained 95 per cent of the time during which servo-anesthesia was continued.

The values of servo-anesthesia, actual and potential, are discussed.

#### ACKNOWLEDGMENT

The authors wish to express their gratitude to Drs. C. W. Mayo, H. K. Gray, Waltman Walters, J. M. Waugh, and J. H. Pratt who co-operated in allowing these studies to be made on their surgical patients, and to Miss Rosemarie Haefliger for her valuable technical assistance.

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