

OPERANT BEHAVIOR DURING ANESTHESIA RECOVERY: A CONTINUOUS AND OBJECTIVE METHOD

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ANESTHESIA, from the Greek *anaisthétos* meaning insensible, describes the suppression of behavior by some agent, including chemicals, disease, and hypnosis. The anesthesiologist produces anesthesia in order to suppress certain behavioral responses that interfere with surgery. Since the majority of the anesthetics can produce death or serious physiological side-effects and after-effects if an overdose is administered, anesthesiological investigators are primarily involved in biochemical and cardiorespiratory research. Such research was conducted to provide information for use in controlling the deleterious physiological effects of the anesthetic agents administered.

The anesthesiologist's role as a *behavioral engineer* is often overlooked. In this role his primary function is the suppression of behavior with minimum behavioral side-effects and after-effects. In addition to physiological safety, the ideal anesthetic should have a rapid onset and a rapid recovery. Available general anesthetic agents act rapidly, but the ideal agent providing an immediate recovery has not been discovered. Therefore, research which compares speed of recovery from various anesthetic agents is in demand. Such research has been hampered by a lack of reliable, sensitive, and continuous measures of behavioral recovery. A new method of continuously and automatically recording the recovery of volitional behavior from anesthesia is reported in this paper, together with illustrative results on recovery from halothane and thiopental-nitrous oxide anesthesia.

METHOD

Free-operant Behavior. In the investigation of operant behavior, if the subject *operates* a

lever, switch, or similar device, he is promptly rewarded or reinforced by the presentation of a rewarding event or the withdrawal of an aversive event—hence the term “operant.” Over the past 30 years Skinner¹ has stressed the value of the free-operant, wherein the subject is *free* to respond at any time. The rate of occurrence of this response is the primary datum. Use of the free-operant dispenses with burdensome time-consuming trials and eliminates the confounding stimulation of the trials themselves. Also, subtle variations in the behavior being studied, which could occur between trials, are fully recorded in the continuous monitoring of the free-operant technique.

The free-operant has been widely used in practical applications for the investigation and measurement of behavior, including most recently the evaluation of drug effects² and behavioral deviation.³ By varying the type of response and the nature and conditions of reinforcement a wide variety of different classes of behavior can be developed, maintained, and recorded.¹ The class of free-operant behavior used in this investigation has been previously used to evaluate the depth of sleep⁴ and the depth of coma produced in electro-shock therapy.⁵ Here we present the first application of the free-operant technique to record the depth and duration of recovery from surgical anesthesia.

General Summary of Free-operant Used. An intermittent loud tone was delivered through an earphone to one ear of each patient before, during, and after anesthesia. The volitional or free-operant response was that of touching the index finger to the thumb of the preferred hand. Each response actuated an electrical apparatus which briefly reduced the intensity of the tone in the patient's ear. Rapid closing of the hand reduced the tone intensity below the auditory threshold, and the patient could avoid hearing the tone by continued responding at a high rate. Slow responding

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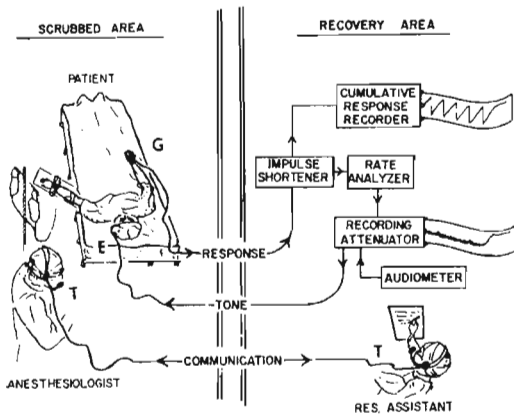


FIG. 1. Schema of apparatus used to produce, maintain, and record free-operant responding during recovery from anesthesia. Patient touches thumb to index finger of one hand (*G*) to reduce briefly the intensity of a loud tone presented to one ear (*E*). The higher the rate of responding, the lower the tone intensity. By pressing at a high rate, the patient can maintain silence. Rate of response and tone intensity are automatically and graphically recorded. Anesthesiologist reports important information to research assistant via telephone headsets (*T*).

kept the tone at a moderate intensity. If no responses were made, the tone rose to and was maintained at its maximum intensity (90 decibels above the patient's auditory threshold). Thus, the patient's rate of responding directly controlled the intensity of the tone, and he was reinforced by avoiding or escaping aversive tone intensities.

When deeply anesthetized, patients were unable to reduce the tone intensity; and as they gradually recovered, they reduced the intensity until they maintained it at the preanesthetic level. The rate of response was automatically and graphically recorded as a continuous indicator of the level of behavioral recovery.

Apparatus. The complete apparatus is schematically diagrammed in figure 1. The only equipment that must be in the operating room is: (1) the glove manipulandum or response-switch on the patient's hand, (2) the earphone under the patient's headdress, (3) the telephone headset on the anesthesiologist, and (4) the wires that lead from these devices to the electrical apparatus in the recovery area. The electrical equipment and recorders in the recovery area fit within a closed relay

rack on wheels. The rack can be easily washed down with Zepherin for antiseptics and easily moved about the recovery area or wards.

The glove (*G* in figure 1) is made of rubber and has external metallic coating over the inner surface of the thumb and index finger. The contact of these two conductive parts closes a circuit which operates a sensitive relay requiring a current of only 0.7 microamps to avoid an explosive hazard. The closure of this relay goes through an impulse shortener which changes a continued closure into an impulse of .125 milliseconds duration. This defines a response as touching the thumb to the index finger and rules out continued contact. The output of the impulse shortener operates a cumulative response recorder which produces a graphic record of cumulative responses against time, with a paper speed of 6 inches per hour.

The output of the impulse shortener also enters the rate analyzer where each impulse is standardized in magnitude and duration, and a charge is accumulated with a constant (but adjustable) leak. The amount of charge in the rate analyzer at any given moment is a function of the rate of impulse input (or rate of thumb and index finger closure).

The output from the rate analyzer is graphically recorded on a Varian G-10 graphic recorder with paper speed of 6 inches per hour. This graphic recorder has a linear attenuator mounted above the pen slide which attenuates the output of the Beltone 9A audiometer. Therefore, the record from the recording attenuator indicates the tone intensity in decibels hearing loss, and is directly related to the rate of response for any given setting of the rate analyzer.

The tone is generated in a Beltone 9A audiometer and fed through an internal switch where it is interrupted by an external timer without any "clicks" being heard. The intermittent tone is then fed through the recording attenuator to a Telephonics type TDH-39-102 8-ohm earphone mounted in a Grason-Statler semiplastic earphone socket held in place by a rubber bathing cap with a nurse's operating room headdress over all (*E* in figure 1).*

* This apparatus is commercially available from Behavior Research Co., Box 244, Belmont 78, Massachusetts.

The physical relationship between the intensity of the tone and the rate of response which is arranged by the rate analyzer is shown in figure 2. These calibration records were taken using the rate analyzer settings employed with all cases reported in this paper. Note that at low rates of response (less than 10 per minute) the tone intensity was reduced 10 decibels immediately after each response. At high rates of responses (over 100 responses per minute) the tone was held at a constant level within a range of 1 decibel. Note also the exponential return of the tone to its pre-response intensity. This complicated arrangement in which the *intensity* of an event is some *continuous* function of the rate of a response we call *conjugate* reinforcement to distinguish it from the discrete and discontinuous reinforcement schedules used earlier by operant conditioners.¹

Records. In addition to automatic graphic records of cumulative responses and tone intensity, standard protocol sheets were filled out by a research assistant who monitored the apparatus and recorders. She was in constant two-way communication with the anesthesiologist during the time the patient was away from the recovery and preparation area. Both she and the anesthesiologist wore telephone operators' headsets (*T* in figure 1) which permitted free use of their hands and were sensitive enough to pick up whispers and other talk in the operating room. The research assistant entered relevant information on protocol sheets and made appropriate signals on the response record with a remotely controlled signal pen.

Quantification of Cumulative Response Records. The cumulative response records of the rate of responding throughout anesthesia and recovery were highly sensitive individual records. Since there was a preanesthesia and a postanesthesia control period for each patient, there was no reason to resort to comparing the behavior of a patient with the behavior of others in order to reach conclusions for that patient. However, in order to group and summarize the patterns of recovery from a number of individuals and to compare the recovery times and patterns from different anesthetic agents, some system of quantifying and summarizing these cumulative response records was necessary. An arbitrary scheme for

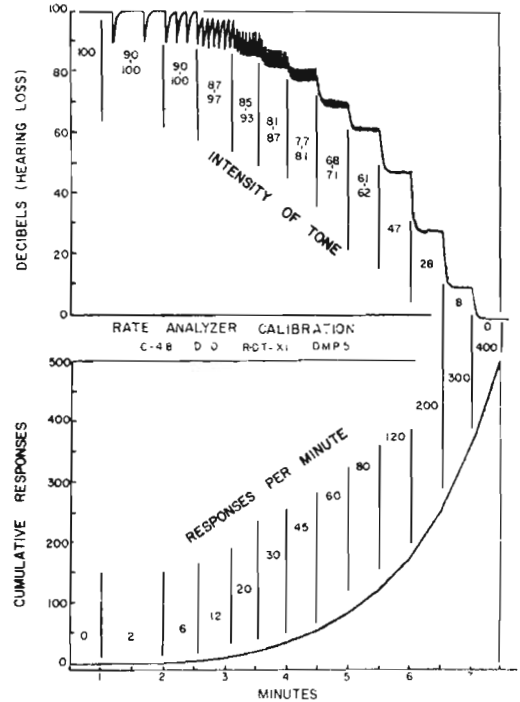


FIG. 2. Calibration records showing reductions in tone intensity for 13 different response rates from 0 to 400 responses per minute. Top record shows tone intensity in decibels (db.) hearing loss taken directly from the recording attenuator. Bottom record is taken from the cumulative response recorder. The tone intensities are not necessarily those at the patient's ear. If the patient had no hearing loss, if 100 db. was the output set on the audiometer, and if there were no line and insertion losses, the intensities shown in the figure would be accurate. However, even with 100 db. set at the audiometer, we experience approximately a 10 db. line and insertion loss, resulting in a maximum of 90 db. at the ear of a patient with no hearing loss.

quantifying the important stages of anesthesia and anesthesia recovery times is shown in figure 3.

This system of quantification of individual records not only provides numerical data for summarizing many records, but it also rules out individual differences in preanesthetic response rate which could be determined by differences in general activity level, degree of hearing loss, amount of preoperative anxiety, etc.

Control Audiograms. The audiometer in the apparatus could be moved to the wards for obtaining clinical audiograms before and after each experimental session. Audiograms were

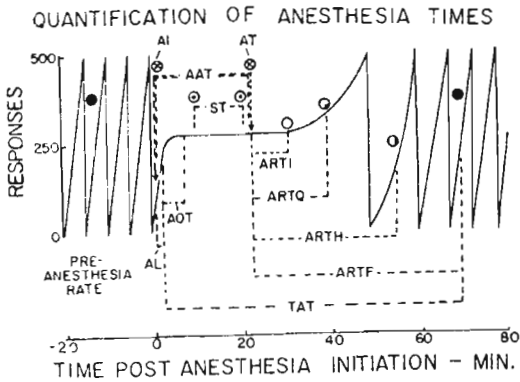


FIG. 3. Method of quantification of individual records used in summarizing recovery patterns for a number of cases. A schematic cumulative response record with a preanesthesia rate of 100 responses per minute (indicated by filled circles) is shown. Letter abbreviations stand for: AI—anesthetic initiation; AT—anesthetic termination; AAT—anesthetic administration time; ST—surgery time; AL—anesthesia latency, time from AI to first decrease in rate; AOT—anesthesia onset time, from first decrease in rate to complete suppression; ARTI—anesthesia recovery time—initial, from AT to first burst of 10 responses within one minute (open circle); ARTQ—anesthesia recovery time—quarter, from AT to one-quarter preanesthesia rate over 5 minutes (quarter-filled circle); ARTH—anesthesia recovery time—half, from AT to one-half preanesthesia rate over 10 minute period (half-filled circle); ARTF—anesthesia recovery time—full, from AT to full preanesthesia rate of response over a 15 minute period (filled circle); TAT—total anesthesia time, AAT+ARTF-AL (total period of reduced responding).

recorded the night before the operation to aid in selecting patients. Audiograms of both ears were recorded immediately before and after each session to insure that no immediate hearing losses had occurred, as well as for medico-legal reasons. A few days after each session, audiograms were recorded of both ears whenever possible to determine whether any temporary hearing losses had occurred. Obviously, hearing losses which resulted from the tone should appear only in the stimulated ear.

Patients. Patients undergoing routine operative procedures were used in these investigations. Deaf, very young, aged, or mentally deficient patients were rejected from the study. Patients with emotional disturbances, manual injuries, and injuries about the head and ears were also rejected. Anesthetics including muscle relaxants were excluded.

The 7 male and 24 female patients studied in this investigation ranged from 16 to 69

years of age and weighed from 101 to 180 pounds. Their preoperative response rates ranged from 48 to 350 responses per minute. The total anesthetic administration times ranged from 18 to 495 minutes, and the operations varied from uterine dilatation and curettage (which comprised the majority) to a radical mastectomy.

Technique of Anesthesia. Halothane and thiopental sodium- N_2O were selected as representative gas inhalant and intravenous anesthetics for use in demonstrating and validating the method. Either atropine (0.4 mg./100 pounds, intramuscularly injected) or no pre-anesthetic agent was used, since scopolamine has depressant effects on behavior which would confound the measurement of anesthesia recovery as reported below.

In determining the recovery from halothane, anesthesia was induced with 3 per cent halothane in oxygen delivered from a Fluotec mixer into a nonbreathing system. When the first level of anesthesia was reached, the halothane mixture was reduced to 0.5 to 1.0 per cent in oxygen to maintain a constant level of anesthesia.

In determining the recovery from thiopental sodium- N_2O , 50 mg. of a 2.5 per cent solution of thiopental sodium was intravenously injected as an inductive test dose. Thereafter, 25 to 75 mg. dosages were injected periodically to maintain a constant level of anesthesia. A concentration of 50 per cent N_2O and 50 per cent oxygen was used along with the thiopental sodium to maintain constant anesthesia. The median dose per body weight per unit time of thiopental sodium was 0.2 mg./kg./minute.

Description of Conduct of Typical Determination. Late in the afternoon, appropriate patients from the operating room schedule for the next day were selected and audiograms recorded on the wards. The patient with the least hearing loss and the most interest in the procedure was selected. On the morning of the operation the patient came to the operating room without preoperative sedation. The pre-experimental audiogram was recorded and the earphone fitted to the most sensitive ear and secured in place. The glove manipulator was loosely secured on the patient's preferred hand.

The apparatus was turned on and the intermittent tone (.25-second duration, twice a second) was presented at 2,000 cps to the patient's ear. Tone intensity ranged between 70 to 100 decibels, depending on the patient's hearing loss. At least 15 minutes of control responding was recorded. If the anesthesiologist required it, 0.3 to 0.4 mg. atropine was then injected intramuscularly.

The patient remained in the recovery area until the operating room was available. He was then wheeled into the operating room with the apparatus continually recording. Anesthesia was induced in the usual manner and the operation performed, with full protocol recorded by the research assistant. Following operation, the patient was returned to the anesthesia recovery area while the apparatus recorded continuously. Recording was continued during recovery until at least 30 minutes of responding had occurred at the pre-anesthesia rate. At this time the apparatus was turned off and the patient returned to his ward.

DEMONSTRATIVE RESULTS

Methodological Results. With over 50 cases examined under operating conditions it is clear that the method and apparatus were easily incorporated into standard operating room procedures without disturbing patients, surgeons, or nurses, and without risk to the patients. The patients did not object to the procedure and in some cases welcomed the opportunity to participate.

Analysis of the grouped audiogram data has shown that there are no signs of even temporary experimentally produced hearing loss in over 50 patients and 12 volunteers studied over three hours each.

Analysis of the grouped data shows that there was no correlation between age, body weight, or sex and the preoperative response rate. Neither was there any relationship between age and recovery time for the few cases in which similar anesthetic administration times were available for the same anesthetic agent (halothane). No correlation was found between the preanesthesia response rate and recovery time, which suggests there is no interaction between degree of pre-experimental hearing loss and recovery time as measured by this method.

Preanesthetic Results. Early in the course of experimentation, we found that when scopolamine was used as a preanesthetic anti-secretory agent, the rate of response was markedly suppressed prior to the administration of anesthetic.⁶ Response records obtained from both patients and volunteers who were not to undergo surgery showed that scopolamine in dosages of 0.3 mg./100 pounds, intramuscularly injected, suppressed the response rate beginning between 6-31 minutes and reaching a maximum between 24-45 minutes postinjection. This suppressive effect was half gone between 112-149 minutes and recovery was not complete up to 240 minutes postinjection. No suppressing effect on the free-operant rate was observed with atropine in dosages up to 0.6 mg./100 pounds, intramuscularly, throughout the 250 minute postinjection observation periods.

In order to prevent confounding the suppressive effects of scopolamine with the anesthetics being studied, our current experimental anesthetic was administered without a preanesthetic agent, and if one had to be used, atropine was selected. Clinically, we concluded that many long recovery periods from short periods of anesthesia are probably caused by scopolamine used for premedication.

Anesthetic Agents. Since the purpose of this article is to present a new method, the results on anesthetics are presented for demonstrative rather than conclusive purposes. Records of two patients given halothane are reproduced to show in detail the sensitivity of the method, with one case representative and the other unusual. Twenty-one records of halothane anesthesia and 10 records of thiopental-nitrous oxide anesthesia are summarized using the quantification system described above. In order to demonstrate further the practical utility of the method in anesthesiological research, plots of initial recovery time (ARTI) against anesthetic administration time (AAT) and against rate of anesthetic administration (mg./kg./minute) for the 10 patients given thiopental-nitrous oxide are also presented.

Halothane Single Cases. The cumulative response record of a 33 year old woman, 63 inches tall and weighing 116 pounds, undergoing a dilatation and curettage with halo-

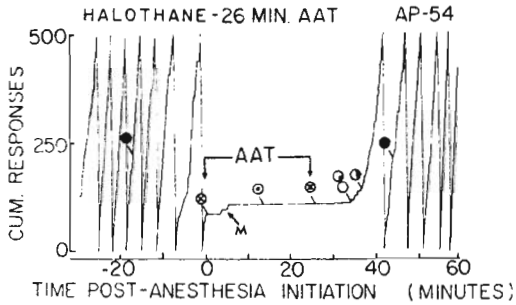


FIG. 4. Cumulative response record of a case of 26 minutes of halothane anesthesia with a rapid, non-cyclical recovery. This case is representative of the rapid recoveries following short administrations of halothane.

thane anesthesia up to 2.5 per cent (Fluotec setting) is reproduced in figure 4.† Her hearing loss at 2,000 cps was 13 decibels and her preanesthesia response rate was 150 responses per minute. Atropine (0.4 mg.) was injected intramuscularly 2 hours before anesthesia initiation. Anesthetic administration time (AAT) was 26 minutes and the time for operation was 12 minutes. The recovery in this case was rapid and representative of the majority of the shorter halothane administrations. The first responding (ARTI) occurred 9 minutes after anesthetic termination, at which time the rate almost immediately assumed one-quarter the preanesthesia value (ARTQ). Within 12 minutes the rate was at half the preanesthesia rate (ARTH), and within 19 minutes after anesthetic termination the preanesthesia rate was fully recovered (ARTF).

In figure 5 the cumulative response record of a 44 year old woman, 63 inches tall and weighing 174 pounds, undergoing a dilatation and curettage with halothane anesthesia up to 3.0 per cent (Fluotec setting) is reproduced. Her hearing loss at 2,000 cps was 25 decibels and her preanesthesia response rate was 140 responses per minute.

Atropine (0.4 mg.) was intramuscularly injected 23 minutes before anesthetic initiation. Anesthetic administration time (AAT) was 33 minutes, and the operation lasted 12 minutes. At M on the record the patient was moved from the recovery area to the operating room. During this movement the patient's

hand was moved, so that these "responses" were not initiated by the patient and should be considered movement artifacts.

The recovery of this case was cyclical and unusually long for 33 minutes of halothane administration. As can be seen in figure 6, from the 21 cases of halothane anesthesia, this is one of the two cases with cyclical recoveries. The initial burst of responding (ARTI) occurred 3 minutes after anesthetic termination. However, the rate soon fell to zero again as the patient went back to sleep. At the time the rate was at about one-quarter the preanesthesia value, the patient asked for something to relieve her pain. She was not given medication, and soon relapsed into a deeper stage of anesthesia. If she had been given a narcotic at this time, this cycle in recovery would notably have been attributed to the narcotic. Also, and perhaps more important, if she had been given a placebo at this time, this cycle in her recovery would have been called a placebo effect. It is important to mention that without continuous measurement, the cycles seen in the recovery in figure 5 could occur between the times that the patient's behavior was being tested with reflex probes or other techniques that demand the use of trials. As such, these cycles would go unrecorded and unobserved.

Possibly such cycles might be related to intermittent discharge of anesthetic stored in body tissues. Further research with more refined techniques of measuring anesthetic administration and fate used together with these sensitive behavioral recovery records on the same individuals may answer such questions.

Halothane Grouped Results. The cumulative response records from 21 cases of halothane anesthesia were quantified by the system

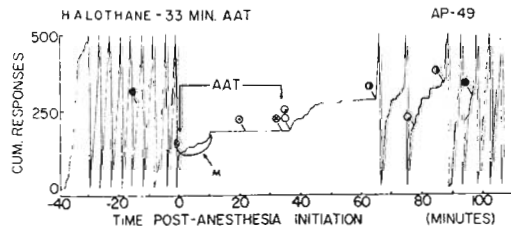


FIG. 5. Cumulative response record of a case of 33 minutes of halothane anesthesia with a rapid initial recovery but later cycles which prolonged full recovery. This case is unusual for short administrations of halothane.

† The first such record was obtained in January 1958 in the Anesthesia Laboratory, New England Center Hospital.

described above and the four recovery stages are plotted against time postanesthesia initiation in figure 6. This plot permits the direct comparison of the rates of recovery of the different cases and permits comparison with respect to the anesthetic administration time. Rapid recoveries appear in the figure as almost vertical lines, and slow recoveries are slanted to the right. Cycles in recovery (2 cases out of 21) are plotted in dashed lines. The 3 cases of over 3 hours anesthetic administration time (AAT) all required over 80 minutes for full recovery (ARTF). The plots for the 7 patients who could not be detained until full recovery do not rise to the full recovery (ARTF) line, but these data are, nevertheless, useful.

The median anesthetic administration time (AAT) was 46 minutes with a range of 18 to 495 minutes. The median anesthesia recovery time-initial (ARTI) was 6 minutes with a range of 1 to 66 minutes. The median anesthesia recovery time-half (ARTH) was 19 minutes with a range of 4 to 132 minutes. The median anesthesia recovery time-full (ARTF) was 35 minutes with a range of 14 to 141 minutes. The distribution of the times for these four recovery stages were all skewed to the right. Also, the variability increased from the initial to full recovery stages. This means that the sources of variability between individual cases serve to lengthen rather than reduce recovery time. Among such sources of individual variability

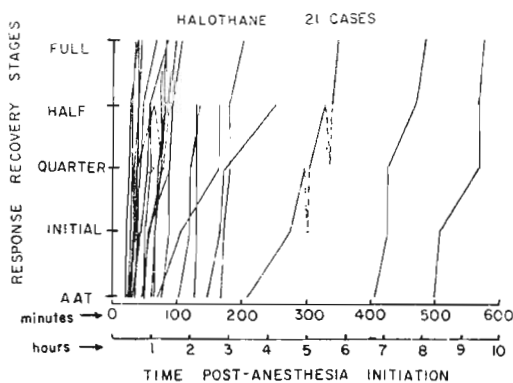


FIG. 6. Patterns of behavioral recovery for 21 cases of halothane anesthesia plotted against time. The recovery stages and quantification system are diagrammed in figure 3 and described in the text.

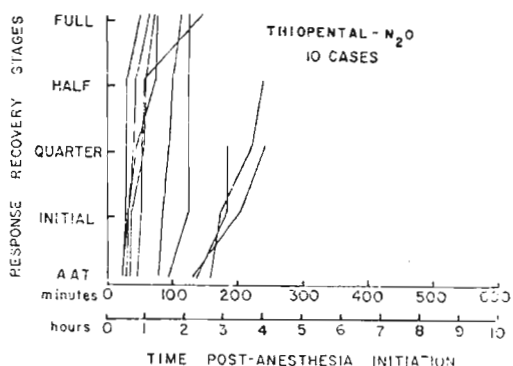


FIG. 7. Patterns of behavioral recovery for 10 cases of thiopental sodium-N₂O anesthesia plotted against time. The recovery stages and quantification system are diagrammed in figure 3 and described in the text.

are: (1) response competition from postoperative pain, (2) over-anesthetization, (3) storage of anesthetic in body tissues, and (4) response fatigue.

Thiopental-Nitrous Oxide Grouped Results. The cumulative response records from 10 cases of thiopental-nitrous oxide anesthesia were quantified by the system described above and the recovery stages are plotted against time postanesthetic initiation in figure 7. In comparing these thiopental-nitrous oxide recovery patterns with those for halothane displayed in figure 6, it is clear that for this limited number of cases the thiopental-nitrous oxide recoveries are just as rapid as those after halothane when they are equated for anesthetic administration time. If this observation is borne out by further research, it would embarrass the commonly held notion that halothane recoveries are more rapid.

The median anesthetic administration time (AAT) for these 10 thiopental-nitrous oxide cases was 62 minutes with a range of 22 to 159 minutes. The median anesthesia recovery time-initial (ARTI) was 8 minutes with a range of 2 to 47 minutes. The median anesthesia recovery time-quarter (ARTQ) was 21.5 minutes with a range of 6 to 115 minutes. The median anesthesia recovery time-half (ARTH) was 22 minutes with a range of 7 to 115 minutes, and the median anesthesia recovery time-full (ARTF) was 34 minutes with a range of 18 to 115 minutes.

In relating the dosage of thiopental to the pattern of behavioral recovery there are too

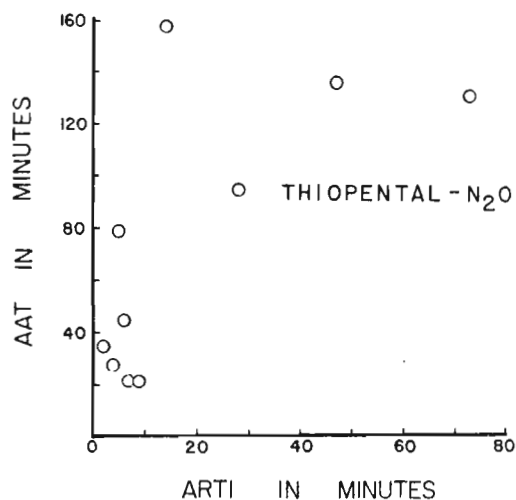


FIG. 8. Anesthetic administration time (AAT) plotted against time from the termination of anesthetic to the initial burst of responding (ARTI) for 10 cases of thiopental-sodium- N_2O anesthesia.

few cases to determine the details with accuracy. However, with only these 10 cases, some relationships emerge that so well support other data on thiopental-nitrous oxide anesthesia, that reporting these relationships adds validity to this new method and suggests areas of research in which it might be applied practically. The initial recovery time (ARTI) is plotted against anesthetic administration time (AAT) for the 10 thiopental-nitrous oxide cases in figure 8. All cases with AAT's less than 80 minutes in duration had ARTI's of less than 10 minutes. Anesthetic administration lasting over 80 minutes produced initial recovery times of much longer than 10 minutes duration.

In figure 9, the rate of thiopental administration in mg./kg./minute is plotted against the initial recovery time (ARTI) for the same 10 cases of thiopental-nitrous oxide anesthesia. The 5 cases with the slowest rate of anesthetic administration produced the 4 longest initial recovery times. However, these 4 long initial recovery cases, even though they had the lowest rate of thiopental administration, were the cases with the longest anesthetic administration times. This implies that a high rate of thiopental administration over a short period of time does not produce as prolonged a recovery as a low rate of administration over a long period of time.

DISCUSSION

Relation to Previous Methods. The previously used methods of measuring depth and duration of anesthesia fall into two general classes: (1) crude probing of the patient's behavioral response thresholds with a variety of alerting stimuli at selected times during recovery, and (2) objective recording of physiological indicants which undergo changes during anesthesia.

Though valid, behavioral probing methods are poorly controlled and unreliable. Also, the state of the patient between probes can only be inferred (see figure 5 for sources of error in such inferences). Furthermore, probes alert the patient and interact with the level of anesthesia being measured much more than do continuous methods. The Bender face-hand test⁷ and motor responses to vocal commands^{8,9} fall in this class.

Other probing techniques in which reflexes are periodically tested (*e.g.*, the pupillary response to light) suffer from the above disadvantages and, in addition, have further disadvantages of their own. Reflex probes have limited validity because they sample only a small segment of the behavior of the total organism. More important, reflex probes are differentially sensitive to anesthetic agents and therefore cannot be used to compare the recovery from different anesthetics without extreme caution.

Objective, continuous records of physiological indicants (*e.g.*, respiration, EEG) are reliable and useful in controlling deleterious physiological side-effects, but they are invalid because they do not directly measure behavioral recovery. The EEG is sensitive to the deep stages of surgical anesthesia¹⁰ where complete motor arrest prevents the use of the free-operant method. The free-operant method is sensitive to the light stages of anesthesia in which EEG records are normal and which comprise the major portion of the behavioral recovery period. With caution concerning the alteration of EEG patterns by hypoxia and hypercarbia, the EEG and free-operant methods used together may provide objective, continuous measures of the depth of anesthesia, from onset, through deep surgical, to and including full behavioral recovery.

Implications for Behavioral Sciences. Psychologists and psychiatrists from Helmholtz through Freud, up to the current research interest in learning during sleep, brainwashing, and soulwashing, have been interested in subconscious behavior. The method reported here provides a way of producing and recording behavior during subconscious states and opens the way for an actual experimental analysis of dreams, subconscious learning, and levels of consciousness. Although slightly different modifications and adaptations will have to be made for each application, the basic method is here.

In this and preceding articles^{4,5} it was shown that differential free-operant motor responses can be produced and maintained in individuals in states in which they cannot verbally describe the responding either at the time it occurs or after it has occurred. Also, such responding occurs in states in which verbal response to questions and motor response to commands are absent. Suggestions as to why this particular free-operant technique succeeds in the production and maintenance of subconscious behavior follow:

First, a response of relatively wide topography, which can be emitted at a high rate in subconscious states, is used. A highly differentiated response is not as useful for this purpose because it would be present only in relatively light subconscious states.

Second, the reinforcing stimulus is presented via a sense modality which does not become inoperative in subconscious states (as would be the case with the eyes closing if vision were used).

Third, a schedule of reinforcement is used which does not require relatively high order discriminations that only occur in light subconscious states. The conjugate schedule of reinforcement,^{4,5} in which the intensity of the reinforcing stimulus varies directly and immediately with the rate of response, answers this purpose. Another important aspect of the conjugate schedule is that since the reinforcing stimulus intensity is directly controlled by the rate of responding, the patient's absolute, avoidance, and escape thresholds are free to vary with the different stages of anesthesia. In fact, there is doubt that such thresholds exist,

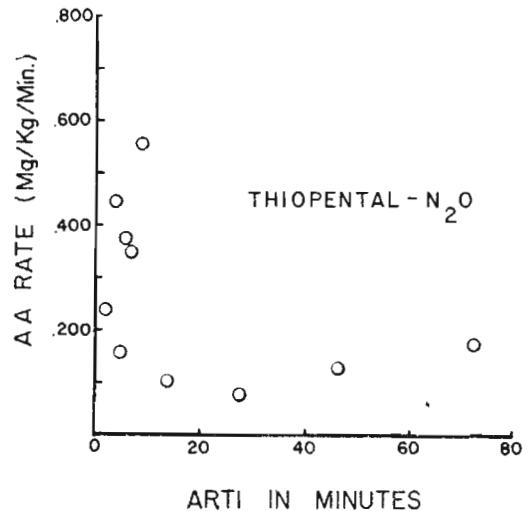


FIG. 9. Rate of administration in milligrams per kilogram body-weight per minutes of anesthetic administration (mg./kg./min.) plotted against anesthesia recovery time to the initial burst of responses (ARTI) for 10 cases of thiopental sodium-N₂O anesthesia.

since it appears they were a function of the different methods used to investigate aversive behavior, rather than behavior classes found in organisms. This doubt is supported by our observation that recoveries from anesthesia are gradual, continuous, and cyclical rather than a series of discrete stages.

One of the biggest problems with the earlier behavioral probing methods described above is that the intensity of the probing stimulus must be determined by the investigator. Often the investigator may inadvertently stimulate the patient at too high an intensity for his stage of anesthesia and alert or awaken the patient. The subconscious state then no longer exists for further analysis. This is one of the major disadvantages of the anesthesiologist's common clinical method of slapping the patient's face, shaking him, or yelling questions in his ear to determine the depth of anesthesia.

Fourth, the intensity continuum of the reinforcing stimulus must range from below the absolute threshold through discriminative and conditioned aversive values, up to and including unconditioned aversive values. This range is necessary so the stimulus will be minimally alerting at all times and can assume the full range of absolute intensity values

necessary to produce responding at all levels of subconsciousness without awakening the patient.

Implications for Anesthesiological Science. The method of continuously monitoring behavioral recovery from anesthesia reported in this article has wide application in anesthesiological research, not only in comparing the durations and patterns of recovery from different anesthetic agents, but also in investigating the effects of operative trauma, hypoxia, and hypercarbia on recovery pattern. Anesthetization of volunteers who will not undergo surgery would be useful as controls in determining the effects of operative trauma on recovery time.

Since the method can be easily adapted for use with lower animals, the way is opened for the direct comparison of animal and human behavioral recoveries without variables being confounded by different methods of measurement. Such animal investigations would be useful in screening new anesthetic agents as well as in monitoring recovery from physiological experiments which are out of the question with human material.

The method might well have immediate practical clinical uses in: (1) monitoring the depth of general anesthesia in difficult operations demanding very light general anesthesia with deep local anesthesia (*e.g.*, cardiac surgery), (2) guiding the nursing care during the postoperative recovery period, and (3) determining the end-point of recovery which would permit the safe return of the patient to his own room or to his home.

SUMMARY AND CONCLUSIONS

The recording of free-operant behavior throughout anesthesia and recovery provided a sensitive, continuous, objective, and valid record of the duration and pattern of behavioral recovery from surgical anesthesia. The method is practical, since the apparatus was easily operated by a technician and readily adapted into operating room procedures and applied to the majority of routine surgical cases. Patients, surgeons, and nurses did not object to its use.

Full behavioral recovery from anesthesia, as measured by this method, takes a much

longer time than was previously determined by clinical signs and physiological indicators. Recoveries after long administration of both halothane and thiopental-nitrous oxide were more gradual than those after short durations of anesthetic administration.

Recovery records were sensitive to differential individual reactions to anesthesia and revealed cycles in recovery often overlooked by other methods of observing behavioral recovery.

The investigation was supported by research grant M-3167 from the National Institute of Mental Health, Public Health Service. The assistance of Robert E. Heckman, M.D., Norman Grace, A.B., and Elizabeth Maxwell, A.B., is gratefully acknowledged.

This study was presented at the Annual Meeting of the American Society of Anesthesiologists, New York, New York, October 5, 1960.

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