

CONCENTRATIONS OF OXYGEN, NITROUS OXIDE, NITROGEN AND ETHER AND THEIR CORRELATION WITH CERTAIN PHYSIOLOGIC VARIABLES DURING SURGICAL ANESTHESIA IN MAN

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In a previous publication (1) an apparatus was described which will measure four components found in an anesthetic mixture; namely, nitrous oxide, oxygen, nitrogen and ether. This method embodies an acoustic gas analyzer and the Beckman oxygen analyzer, and has been used to study the inspiratory concentrations of anesthetic agents during nitrous oxide, oxygen and ether anesthesia in man. Simultaneous recordings of certain physiologic variables were also obtained during this study. The physiologic variables studied were the respiratory rate and depth, the instantaneous heart rate, and the percentage oxygen saturation of arterial blood. The depth of anesthesia was recorded throughout on a basis of the Guedel classification (2). The purpose of this paper is to present the findings obtained during this study.

METHODS

Gas Analysis.—A description of the acoustic gas analyzer and its calibration has been presented in a previous publication (1) and will be omitted here.

Percentage Oxygen Saturation of Arterial Blood.—The instrument used in this study was a Wood modified Millikan oximeter. A complete discussion of the principles of the oximeter may be found in a monograph by Wood (3). This oximeter consists of three parts: an earpiece, a control panel and two Rubicon galvanometers. The calibration curve for the earpiece used was constructed from data obtained in filter tests with it and three other earpieces. Extensive calibration data had been obtained for the other earpieces by comparison with simultaneous values determined by blood gas analysis.†

The Instantaneous Recording Cardiometer.—This instrument was developed by Sturm and Wood (4). It measures the time interval

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† In the light of further calibration work done on this earpiece it appears that the calibration curve used in this study is too high. Therefore our data are about 5 to 10 percentage points higher than they should be in lower saturation ranges.

between successive heart beats and interprets that time interval in beats per minute. The instrument is activated by the R wave of the electrocardiogram. We also recorded the electrocardiogram simultaneously with the instantaneous heart rate.

The Respiration Indicator.—This device is a strain gage manometer sensitive to pressure variation of plus or minus 0.4 pound per square inch (5). The diaphragm of this manometer is connected by means of a moderately rigid rubber tube to the anesthesia mask. The output of the manometer is carried to a Heiland "A" galvanometer which marks the record as seen in figures 1 and 2.

The Mobile Recording Oscillograph.—This consists of two units: (1) a large recording unit called the wagon, which contains the electronic equipment (fig. 3); and (2) a small pickup unit called the cart (figs. 3 and 4). These two are connected by a multichannel, 25 foot

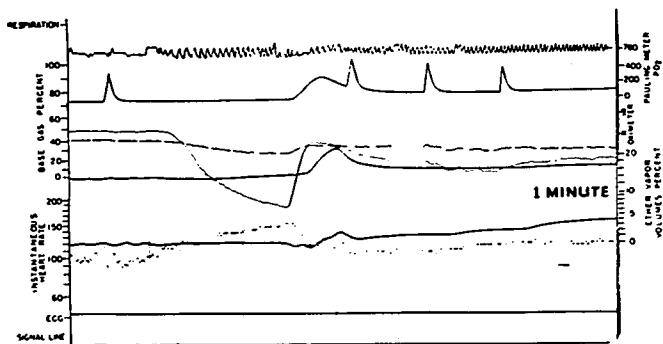


FIG. 1. Sample strip of 12 inch photographic record with one minute time lines.

cable. The large recording part may be kept outside the operating room while the smaller pickup unit is placed next to the patient (fig. 4). The following units are mounted on the wagon: A camera (a) is situated near the rear for optical recording of the deflections of various galvanometers (e) fixed on the top surface of the wagon. The camera has a cylindrical lens through which lamp filament images reflected from the galvanometer mirrors are focused on the surface of a moving strip of light-sensitive paper 12 inches wide. The speed at which the paper moves is governed by a transmission gear box in a manner allowing easy selection of any one of five film speeds from 0.2 mm. to 75 mm. per second. The exposed film is deposited in a metal box (b) which may be removed with the enclosed record for easy transport to the photographic developing room. A light control panel (c)

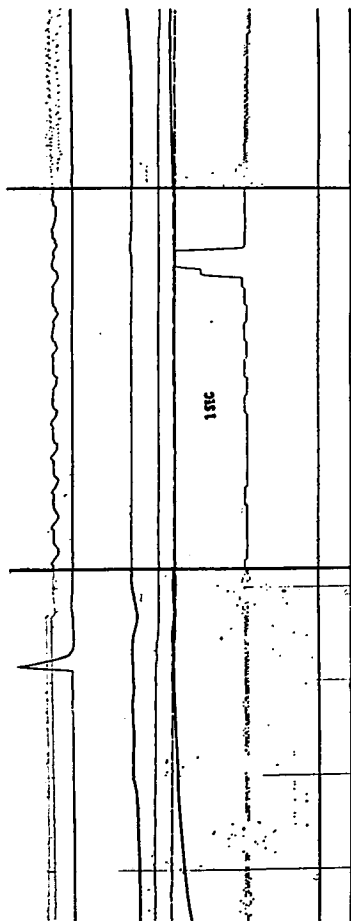


FIG. 2. Sample strip of 12 inch photographic record with one minute and one second time lines.

provides a means for adjustment of the various light sources individually or as a group.

Time lines are impressed on the record either by exposing the entire camera lens with the flash of a small filament bulb at timed intervals or by causing the bulb to be extinguished at timed intervals. The switches activating the lamp are tripped at one second or one minute intervals by motors. The selection of the appropriate time is made by throwing a switch on the light control panel. Light sources (*d*) for the galvanometers are 10 volt straight filament bulbs shielded to prevent

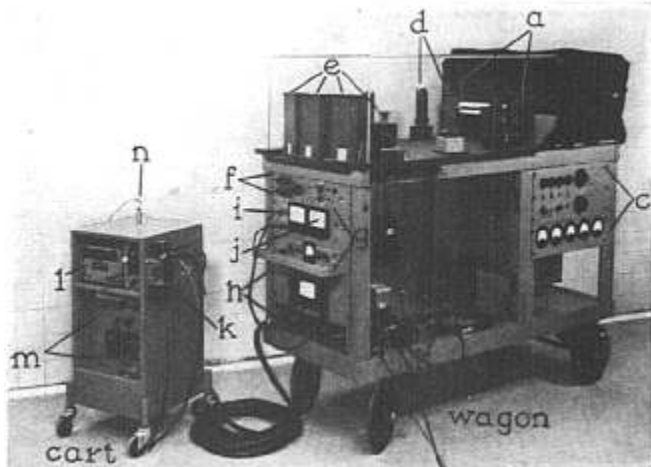


FIG. 3. Apparatus assembled for clinical study: *a*. Camera. *b*. Light-tight film box. *c*. Light control panel. *d*. Light sources. *e*. Heiland and Rubicon galvanometers. *f*. Main control panel. *g*. Acoustic gas analyzer. *h*. Cardiotachometer. *i*. Base gas meter. *j*. Ether meter. *k*. Telephones. *l*. Beckman oxygen meter. *m*. Panel with gas channel control valves, manometers and ether absorber. *n*. Oximeter earpiece.

fogging of the record. Mounted on the main control panel (*f*) of the wagon are the master switch, the camera switch, a galvanometer shunt switch and electrocardiographic galvanometer amplitude control. A signal switch causes lights on the wagon and the cart to blink and also marks the base line of the record. The controls of a Wood modified Millikan oximeter are installed on the main control panel of the wagon. The electronic unit of the acoustic gas analyzer (*g*) with its meters indicating gas percentages (*i* and *j*) is situated next below the main control panel. A Wood-Sturm cardiotachometer (*h*) is mounted below the acoustic gas analyzer. On the front of this instrument is a meter

indicating the instantaneous heart rate in terms of beats per minute. As an aid in detecting cardiac irregularities a neon glow bulb on the panel lights with each heart beat. Telephonic communication with the cart is provided (*k*).

The equipment mounted on the cart includes a signal switch which blinks lights on the cart and the wagon and which also marks the record in a manner similar to the signal switch on the wagon. Gas analyzing equipment on the cart includes pumps for moving a continuous sample



FIG. 4. Connections between the pickup unit and the patient: *a*. Sample tube. *b*. "Mask pressure" tube. *c*. Cardiotachometer leads. *d*. Oximeter earpiece.

through the Beckman oxygen meter (*l*) and the various channels of the acoustic gas analyzer. The Beckman oxygen meter (*l*) is mounted on the cart with a valve and manometer for adjusting the rate of gas flow through it. The sound cells of the acoustic gas analyzer are built into the cart. An ether absorption chamber may be seen on the front of the cart with gas channel control valves and manometers (*m*). The rear side of the cart provides gas sample ports and electric plug connections for leads from the patient (electrocardiographic electrodes and oximeter earpiece) (*n*), and for the cable leading to the wagon. A strain

gage manometer for measuring mask pressure is mounted on the cart where it may be easily attached by rubber tubing to the anesthesia mask.

Sample strips of the 12 inch photographic record obtained in using the foregoing equipment are shown (figs. 1 and 2). While some of the data may be read directly from the record by application of a properly calibrated scale, other data must be obtained by calculation of values recorded; for example, percentage oxygen saturation of arterial blood, percentage of nitrogen and percentage of nitrous oxide. The gas sample is taken from the inspiratory side of the anesthesia apparatus and carried by the sample tube (fig. 4) to the Beckman meter and the gas analyzer. The tubing (*b*) transmits the pressure from the anesthesia mask to the strain gage manometer. The electrocardiographic and heart rate leads (*c*) are connected to the patient's chest in the illustration. We found, however, that it was more satisfactory to attach these to the right arm and left leg of the patient. The oximeter earpiece (*d*) is attached to the subject's ear.

Data pertaining to gas analysis and heart rate were determined directly from appropriate galvanometer deflections recorded on the photographic paper. Respiration was subjected to the dual analysis of rate and amplitude. The rate was obtained by counting the number of deflections during each minute interval. The amplitude was measured arbitrarily in millimeters. The average deflection for the galvanometer activated by the strain gage manometer was 7 mm. before the start of anesthesia. It was found that 1 mm. deflection of this galvanometer line was equal to 7 mm. of water pressure. In regard to the oximeter separate measurements for each line were necessary and a calculation involving these measurements was made to obtain the absolute value of percentage oxygen saturation of the arterial blood for any particular time during the anesthesia. Certain observations which were made during anesthesia were put on a protocol and the number corresponding to that particular observation on the protocol was also signaled onto the base line of the record. Thus the time relationship of an event occurring during anesthesia could be precisely impressed on the proper place on the record.

PROCEDURE

The foregoing apparatus was used in making clinical studies on a series of 10 subjects during surgical anesthesia. Before the operation was begun, the apparatus was warmed up and a control run was performed with each of the measuring instruments. At the end of the recording each instrument was again calibrated. The patient was brought to the operating room thirty minutes early and the oximeter was attached to the ear, the electrodes for the cardiometer were applied, the strain gage manometer was connected to the anesthesia mask, and the sample tube from the gas analyzer and the Beckman oxy-

gen meter was connected to a water vapor and a carbon dioxide absorber and this in turn was connected to a T tube on the inspiratory side of the Heidbrink circle adsorption anesthesia machine.

The premedication of each patient consisted of $1\frac{1}{2}$ grains (0.1 Gm.) of pentobarbital sodium (nembutal) one to two hours before operation and a subcutaneous injection of $1/6$ grain (0.01 Gm.) of morphine and $1/150$ grain (0.00043 Gm.) of atropine approximately one hour before operation.

In these studies it was necessary for one man to operate the wagon and to make sure that this was functioning properly at all times. Another man was in the operating room observing any changes in the conduct of the anesthesia or in the patient's condition which were not measured directly by the instruments. Of particular interest was the occurrence of any effects of the anesthesia such as cyanosis, obstruction to the airway, blood pressure changes and the depth of anesthesia.

The lightproof box containing the photographic record was removed and taken to a dark room and the record was developed, fixed, washed and dried. Observations on the protocol included the settings of the flow meters and ether dial. After each record had been completely analyzed the data were placed on charts. The gas analyses were assembled into a summation graph so that all the gases present would add up to 100 per cent.

RESULTS

Ten cases were studied during anesthesia to obtain the data herein reported. Nine of the patients were undergoing intra-abdominal operations. The operations were as follows: exploration of the common bile duct, 3 cases; cholecystectomy, 3 cases; gastrectomy, 2 cases; laparotomy, 1 case; the operation in the tenth case was an extra-articular arthrodesis of the hip. The results of this study are summarized in figures 5 through 11 and in table 1.

Ether Analysis.—The difference in the pattern of the gas analysis when different anesthetists are administering the anesthetic, may be noted. The anesthetic in figures 5 and 6 was administered by one anesthetist, in figures 7 and 8 by another, and in figures 9 and 10 by still another.

Table 1 gives the values of ether concentrations at frequent intervals throughout the anesthesia. Column 11 gives the average ether concentration of all 10 cases at each interval. These averages were taken at simultaneous time intervals from the beginning of the anesthesia. The first figure underlined indicates the time when the peritoneum was opened and the second figure underlined indicates the time when the peritoneum was closed. The average times for these events are also underlined in the column marked averages.

The average concentration of ether at the time the peritoneum was opened was 11.6 volumes per cent, the range being 7 to 17 volumes per

TABLE I
ETHER VAPOR CONCENTRATIONS
(VOLUMES PER CENT)

Minute of Anesthesia	Case Number										Average	
	1	2	3	4	5	6	7	8	9	10		
0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	2	1	0.3
4	4.5	2.6	0	0	1.8	0	1	0.8	5	3		1.87
6	10.8	5.7	1.2	2.2	4.7	1.8	1.8	2	8.3	6.2		4.47
8	11	5.8	2.8	9.6	9.8	6.2	4	3	10	12		7.42
10	3.8	12.3	4.6	13.8	8	11.5	8.4	4	10	13.2		8.96
12	10	15.6	8	6	11.2	17.5	11	4.8	11	11.2		10.63
14	16.6	18.8	11.6	14.6	5.8	5	11.3	7	13	11.8		11.55
16	18.5	12	12.8	19	1.4	14	11.3	9.5	17.8	11		12.73
18	7.8	12	14.5	11.6	2.8	14.4	10.2	11.7	16.2	10.4		11.16
20	12.5	13	14.5	11	4.7	15	15	11.7	11.5	10		11.89
22	15.6	14.2	2.8	9.2	10.6	13.8	10	11	8	17		11.22
24	10	14.2	6	12	8.8	13.8	13.1	4	6.2	20		10.81
26	11	11.5	7.8	15	7	10	13.3	7.5	5	20		10.81
28	10.5	25.2	11	15.8	9.6	8.5	17.2	6.5	11	21.8		13.71
30	8	10	7	12.8	11.8	14	14	7.2	12	21.5		11.83
35	8	14	6	13.5	8.5	9.6	13.8	7	14.5	18.4		11.33
40	10	12	7	9	8.5	4.8	11.2	11	6	8		8.75
45	6	11.5	7	7.8	9	3.2	9.5	9	4.5	10		7.75
50	6	11	8	13	6.2	1.8	9	7.8	3.5	7.2		7.35
55	10.5	11.5	12	10.8	3.5	1.5	8	5.8	1	4		6.86
60	6	11.8	11.8	9	3	1.7	8.5	4.5	1			6.37(9)*
65	4.5	11.8	11	6.1	2.2	1.7	7.2	4.5				6.12(8)
70	3.5	12	7.1	13	2		7	4.5				7.01(7)
75	3	11	6.2	7			12	2.5				6.95(6)
80	3	11	6.7	6.8			12	1.5				6.83(6)
85	3	11	7.3	14			10.5	1				7.80(6)
90	3	12.8	5.6	14.5			10.5	1				7.90(6)
95	3	12	6	7.4			4	1				5.56(6)
100	3	12.8	6.5	4.8			2.5					5.92(5)
105	3	12.8	5.6	3.8			2.2					5.48(5)
110	2.6	12.8	6	2.8			2					5.24(5)
115		4.8	1.8	2.7								3.10(3)
120		5.4	1	2.5								2.97(3)
125		4.8	4.8									4.80(2)
130			2.7									2.70(1)
135			1.5									
140			1									
145			1									
150			1									

* Numbers in parentheses indicate number of cases used to determine averages.

cent. The average concentration at the time the peritoneum was closed was 7.3 per cent, the range being 2.7 to 12.8 per cent. The average of the highest values for the 10 cases was 17.2 volumes per cent, the range 11.7 to 25.2. The highest figure during induction was 25.2 volumes per cent. This high value was obtained when the ether dial was left open

at 8 and the ether jar was filled with warm ether. An average was made of the lowest values found in the 9 cases when the abdomen was open. This value was 6.4 per cent, the range being 4.5 to 11 per cent. In 6 of the 9 cases the highest induction values were higher than the concentration reached at any time when the peritoneum was opened. In only 2 cases was there an increase in ether vapor concentration fol-

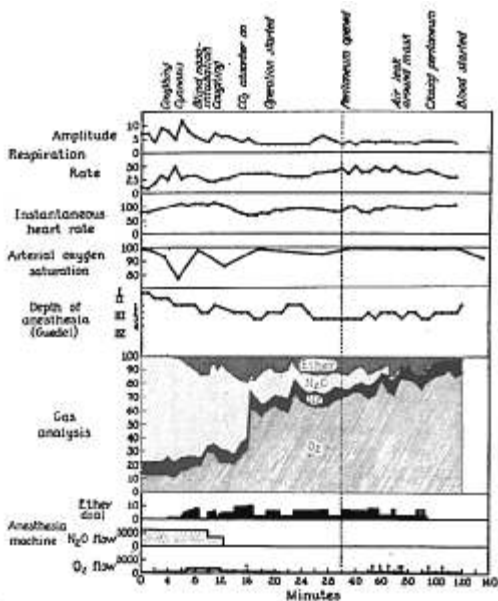


FIG. 5. Graphic summary of data of clinical case: White male, gastric resection. Time units are two minute intervals to dotted line and ten minute intervals following dotted line. Oxygen and nitrous oxide flows are in cubic centimeters per minute, ether dial is setting on the Heidbrink apparatus, gas analysis is in volumes per cent, depth of anesthesia is according to the Guedel classification, arterial oxygen saturation is percentage oxygen saturation of arterial blood, heart rate is in beats per minute, respiratory amplitude is in arbitrary units.

lowing the opening of the peritoneum because the patient was not well relaxed. Many factors influence concentration of ether vapor delivered to the patient. The most important is the ether dial setting. From this group of cases it is apparent that changes in the ether dial are quickly and substantially reflected by changes in the ether concentration delivered to the patient. However, no accurate estimation of the ether concentration can be made from the ether dial setting.

Oxygen and Nitrous Oxide Analysis.—In general, oxygen and nitrous oxide bore a reciprocal relationship to each other in all cases. Nitrous oxide was used as an induction agent in all 10 of the cases reported. A modified McKesson technic was used in 2 cases (figs. 9 and 10). In these 2 cases pure nitrous oxide was administered to the patient for a short period at the beginning of the induction.

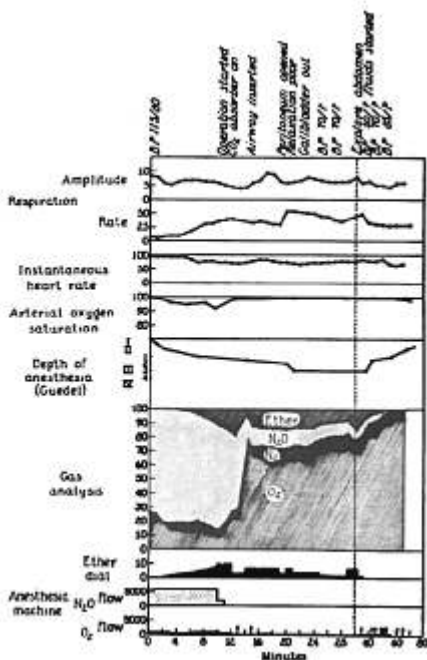


FIG. 6. Graphic summary of data of clinical case: Female, cholecystectomy.

The effect of low oxygen and high nitrous oxide concentrations on the percentage oxygen saturation of arterial blood, heart rate and respiration will be discussed under appropriate sections.

Nitrogen Analysis.—Figures 5 and 6 illustrate a closed technic in which there is considerable inboard leak of air; hence the nitrogen concentration is relatively high. Figures 9 and 10 illustrate 2 cases in which the anesthetist maintained a secure fit between the mask and the face and very little nitrogen was encountered during anesthesia. As

might be expected the nitrogen content is most important during induction when oxygen concentration is already low because of the high concentration of nitrous oxide present.

Heart Rate.—The record obtained of this physiologic variable is based on a measure of the time interval between successive heart beats. These data were recorded continuously during anesthesia. Thus we obtain information about the heart rate which is not ordinarily avail-

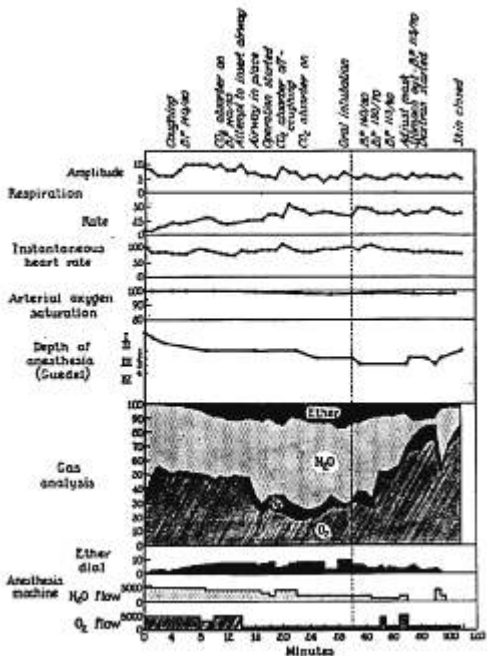


FIG. 7. Graphic summary of data of clinical case: Female, gastric resection.

able. Illustrated in the first minute of figure 1 is the fact that in the normal person in the waking state the interval between heart beats varies significantly from beat to beat. Actually when this time interval is interpreted as rate per minute there is often as much variation as 50 per cent within a minute. Shortly after the induction of anesthesia this normal variation of the heart rate is greatly reduced and in many cases is almost entirely obliterated as seen in figure 2. This observa-

tion was made in all 10 cases studied within twenty minutes after the beginning of anesthesia. The exact significance of this change in the normal variation of the heart rate and its mechanism are not known.

Figures 5 and 10 illustrate a change in the heart rate with a concomitant reduction in percentage oxygen saturation of arterial blood. Two other cases in this series illustrated the same finding. Figure 10 illustrates a marked and abrupt rise in the heart rate, probably caused by anoxia, both at the beginning and at the end of anesthesia. The changes

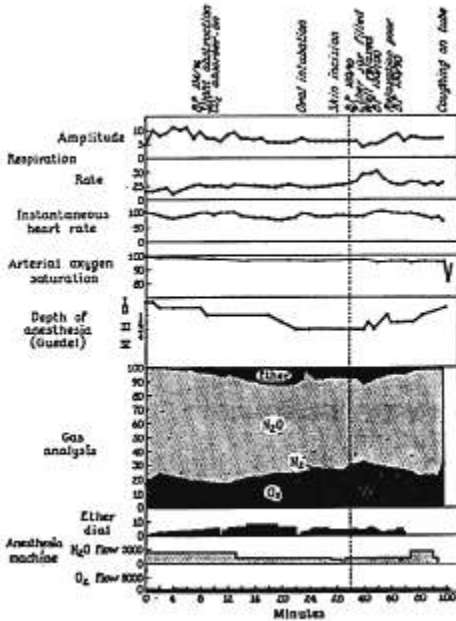


FIG. 8. Graphic summary of data of clinical case: Female, exploration of common duct.

in the heart rate in this case almost parallel the changes in the percentage oxygen saturation of arterial blood. This phenomenon is more apparent on some occasions than on others, for in figure 9 one sees a marked reduction in the percentage oxygen saturation of arterial blood with a small change in the heart rate. The reverse of the foregoing is seen in figure 6, in which the heart rate decreased from 95 at the beginning of anesthesia to 75 during the period of the greatest oxygen deprivation when the percentage oxygen saturation of arterial blood

decreased from 100 to 94. Figure 6 further illustrates an interesting point in that the heart rate varied only 20 beats per minute from the beginning to the end of anesthesia. Of the 10 cases in this series this was the only one to show a serious fall in blood pressure. The patient had a systolic pressure of 70 mm. of mercury for more than twenty-five minutes of the anesthesia and at one point the pressure fell to 50 mm. of mercury systolic. The heart rate, however, remained steady between

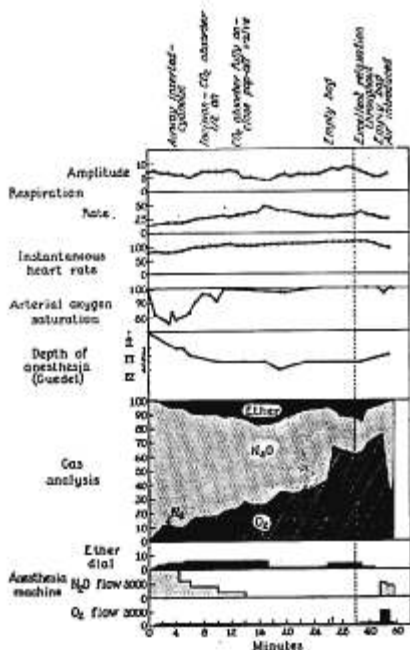


FIG. 9. Graphic summary of data of clinical case: Male, exploratory laparotomy.

75 and 85. The skin was warm and dry and the patient's color was good.

Percentage Oxygen Saturation of Arterial Blood.—During induction in 8 of the 10 cases there was a moderate to severe fall in the percentage oxygen saturation of arterial blood. In 4 cases this was below a value of 80 per cent. During maintenance anesthesia, in only 3 cases was there any significant drop in the oximeter reading. In Case 1 it was the result of deep anesthesia with inadequate respiratory exchange. In Case 3 it was owing to obstruction of the airway plus the adminis-

tration of a low concentration of oxygen, and in another case the fall was small with no obvious cause. At the end of anesthesia immediately after the mask had been removed there was a fall in percentage oxygen saturation of arterial blood in 7 cases. In 3 of these the value was below 90 per cent.

Respiratory Rate.—The respiratory rate was slowest at the beginning of anesthesia, varying from 8 to 16 per minute. It showed a grad-

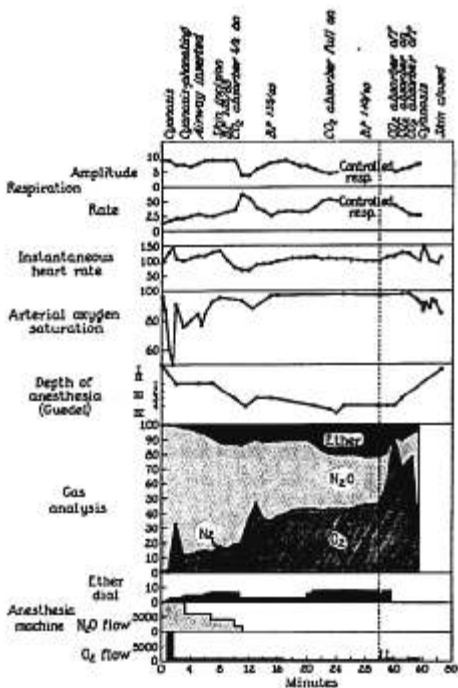


FIG. 10. Graphic summary of data of clinical case: Female, cholecystectomy.

ual increase during induction in the cases studied. The maximal rates varied from 48 to 86. In 9 of the cases the rate was 50 or above at one time or another during anesthesia, and in 4 cases the rate rose above 60. We wish to point out that with this type of recording one detects very fast rates which may be present for only a short time and which the anesthetist may miss entirely. During maintenance anesthesia the rate remained rapid between 30 and 50. In only 2 cases did the rates

fall below 30 and these did not fall below 25. The respiratory rate showed considerable variation during anesthesia and there were many changes which could not be correlated with any single factor. Two consistent observations were the increase in rate during induction and the marked increase in respiratory rate as the depth of anesthesia progressed. The maximal respiratory rates were observed during planes 3 and 4 or just before entering or after emerging from stage 4 anesthesia.

Respiratory Amplitude.—This variable was studied and recorded by the arbitrary means of measuring the response of the strain gage to inspiratory and expiratory pressures. This must be a function of tidal volume; however, no effort was made to correlate this response to an exact volume. Changes in respiratory amplitude were frequently

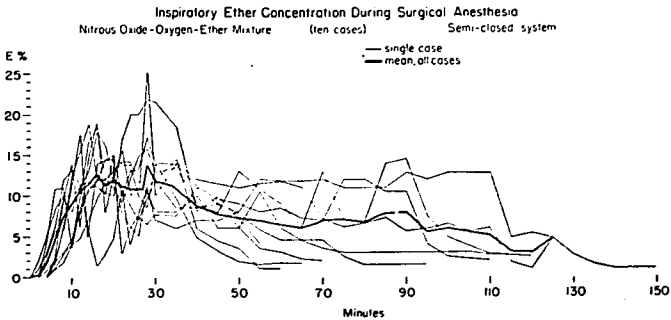


FIG. 11. Inspiratory ether concentration during surgical anesthesia.

observed during anesthesia, and the causes of these changes were not always clear. During induction the amplitude usually became less. During maintenance the amplitude was usually less than at the beginning of anesthesia. There was no definite correlation of the respiratory amplitude with the respiratory rate, and one was observed to change without alteration in the other. The most constant factor correlated with low amplitude was deep anesthesia.

COMMENT

Ether Concentration.—Since the work of Haggard (6) there has been debate regarding the concentration of ether necessary to produce surgical anesthesia. The important contributions by Waller (7), Connell (8), Boothby (9), and others may be divided into two groups. On one hand is the group who observed rather low ether concentrations during anesthesia, and on the other hand the group who found high ether concentrations during anesthesia. The figures offered in the

work of each individual are: Waller (7), 3 to 4 volumes per cent; Ronzoni (10), 4.35 to 5.4 volumes per cent (causes respiratory arrest); Haggard (6), 3.7 to 4.0 volumes per cent; Robbins (11), 3 to 3.5 per cent following high induction values, and 4 to 5 per cent after low induction concentrations; Mann (12), 5 to 6 per cent; Falconer and Latterell (13), induction values of 4.7 to 10.1 volumes per cent; and on the other hand Connell, induction values of 14 to 20 per cent and a maintenance value of 6.5 per cent; Boothby (9), induction values of 8 to 14 per cent and maintenance value of 6.7 per cent; Tyler (14), 6.5 per cent. The results of our ether analyses are in fair agreement with those of Connell (8) and Boothby (9). They are in sharp disagreement with the figures obtained by Ronzoni (10) and Haggard (6). The induction values in all of our cases were above 11.2 per cent and were frequently much higher. Our average value from the thirtieth to the sixtieth minute of anesthesia ranged from 6.37 volumes per cent to 11.83 volumes per cent.

This is the first attempt of which we have knowledge to measure the nitrous oxide and oxygen concentration quantitatively and continuously during clinical anesthesia. The value of this type of analysis is that one has a second-to-second picture of what happens to the gas concentrations during anesthesia. Sudden changes are quickly and accurately reflected on the record by this means of analysis. Furthermore, this method gives the anesthesiologist an opportunity to study the relationship of variations in the inspired mixture to certain physiologic changes in his patients. An example of this relationship is seen in the fact that the percentage oxygen saturation of arterial blood was frequently lowered during induction. Two cases (figs. 9 and 10) are presented which illustrate a marked fall in the arterial oxygen saturation when a modified McKesson technic was utilized.

Another critical period in so far as the patient's oxygenation is concerned was the immediate postanesthetic period when the high concentration of oxygen that the patient had been breathing was replaced by room air and the percentage oxygen saturation of arterial blood frequently was seen to fall. Seven of our 10 cases had a fall during this period and 3 of these to a value below 90 per cent.

In regard to the heart rate, during ether anesthesia the heart becomes regular so far as the interval between successive heart beats is concerned. It might be said that the heart is cut off from its extrinsic innervation and beats in a more automatic fashion. We do not know the exact mechanism of this change in the rhythm of the heart and it awaits further study for elucidation.

SUMMARY AND CONCLUSIONS

The application of the acoustic gas analyzer and certain other instruments for the measurement and recording of certain physiologic variables to a study of clinical anesthesia is presented.

In a series of 10 cases our results indicate:

1. Inspiratory ether concentrations necessary for anesthesia for abdominal surgical procedures are higher than generally believed. Average concentrations for working in the peritoneal cavity range from 6.1 to 13.7 volumes per cent.

2. Six illustrations are presented to show the various types of gas analysis patterns which one may obtain during nitrous oxide-oxygen-ether anesthesia. The effect of low oxygen concentrations on the percentage oxygen saturation of arterial blood is seen in some cases presented.

3. The normal rhythmic change in the heart rate is almost obliterated under anesthesia and the time intervals between heart beats are almost equal.

4. An increase in heart rate often occurs in the presence of anoxia as indicated by a fall in the percentage oxygen saturation of arterial blood.

5. Respiratory rate increases and respiratory amplitude decreases as anesthesia progresses to a lower stage and plane. Respiratory rate during maintenance anesthesia is consistently more rapid than when the patient is awake.

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