AN ANALYSIS OF INHALATION ANESTHESIA BY GRAPHIC MEANS *

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INTRODUCTION

THE aim of this paper is to discuss and to explain by graphic methods certain phases of inhalation anesthesia, which although not always fully appreciated by the anesthetist are nevertheless basic to a full comprehension of the physiology of anesthesia. Before proceeding to this discussion certain essential theoretical principles will be reviewed and then some considerations of practical importance will be mentioned.

THEORETICAL CONSIDERATIONS

Anesthesia is the clinical manifestation of the partial or complete saturation of the brain and spinal cord by an anesthetic agent. The higher the saturation in the brain,† the greater is the depth of anesthesia produced. The degree of saturation in the brain by an anesthetic agent, for example ether, is directly dependent on the ether concentration of the blood.‡ Owing to the abundant blood supply of the brain and also the fact that the brain has about the same solubility for ether as blood, the concentration of ether in the brain will be equal to that of the blood at any time during anesthesia. Therefore, anesthesia, which is the clinical manifestation of the brain saturation, is likewise the clinical manifestation of the concentration of ether in the blood, i.e., the depth of anesthesia will be dependent directly on the ether concentration of the blood.

The ether concentration of the blood will depend upon the ratio of gaining ether to the loss of ether. The process by which the blood gains ether causes an increase in the blood level, whereas the process by which ether is lost decreases this level. The actual concentration is the result of these processes. The main processes involved in this gain-loss ratio are the ether gain by inspiration and the ether loss by expiration.

There is still another process, however, by which ether is lost, namely, by the activity of all body tissues. The tissues being supplied by blood containing ether will become saturated. By this process the tissues absorb (remove) ether from the blood. This absorption will continue

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† In the ensuing discussion the term "brain" should be interpreted as meaning the brain and the spinal cord.

‡ For the sake of simplicity the distinction between the role of arterial blood and venous blood is omitted.

until the tissues are saturated and equilibrium is established. The equilibrium is maintained as long as the concentration of ether in the blood is equal to that of the tissues. When the concentration of ether in the blood becomes less, elimination from the tissues occurs.

Two factors are of importance in regard to this absorption activity of the tissues. First, because of the lesser blood supply of the tissues as compared to that of the brain, together with their lower solubility coefficient for ether, a longer time is required for their saturation. Second, the weight of the brain represents only 5 per cent of the total weight of an adult. Therefore the activity of all body tissues other than the brain will be a considerable factor because of the enormous bulk involved in the process.

Keeping in mind this gain-loss ratio of ether in the blood the following will be self evident.

After ether administration is begun there follows a rapid increase in the ether concentration in the blood as well as in the brain, thus producing anesthesia. At this time, when anesthesia is well established, the saturation of other body tissues except the brain is just beginning. Therefore there results a steady removal of ether from the blood and brain by the body tissues for a certain period after anesthesia has already reached the desired depth. At this time the administered ether must replace not only that lost by expiration but also that which is lost by the removal activity of the body tissues from the blood and brain. This activity is a considerable factor. However, as the saturation point of the tissues is being approached, this activity will be decreased. When saturation is complete, equilibrium between the blood and tissues will be established. Then the ether administered must replace only the ether lost by expiration. Equilibrium between the inspired and expired ether vapor must be maintained. The dose which is necessary to maintain equilibrium is called the *maintenance dose*. When this dose is reduced, the blood-ether concentration will decrease since more ether is lost by expiration. Then ether elimination from the tissues into the blood will take place. This will add ether to the decreasing blood concentration, thus preventing a rapid disappearance of ether from the blood.

All these statements have been proved experimentally by Haggard (1, 2, 3, 4, 5).

The clear understanding of these mechanisms is essential to the discussion which is given below.

THE DIAGRAM

Figure 1 represents a graphic demonstration of the depth of anesthesia as related to the amount of the anesthetic agent administered in ideal inhalation anesthesia.

The diagram is based on a series of papers by Haggard (1, 2, 3, 4, 5) and on the principles and rules laid down by Guedel (6). Connell (7) determined the ether-vapor pressure in pulmonary tidal air and the ether tension in the body during anesthesia by use of his anesthetometer. The results which he obtained and expressed graphically by curves are similar to those given in figure 1.

For the sake of convenience, the representative case chosen is that of an anesthesia given during an abdominal operation performed upon a patient having all average conditions (i.e., average sedation, respiratory threshold, reflex irritability, anatomical and physiologic functions, etc.). Complete abdominal relaxation (lower second plane) is required for a period of thirty minutes. For demonstrative purposes, the anesthetic agent is ether and it is administered by the open drop method, which best suits the purposes of description. The curves, therefore, represent the conditions

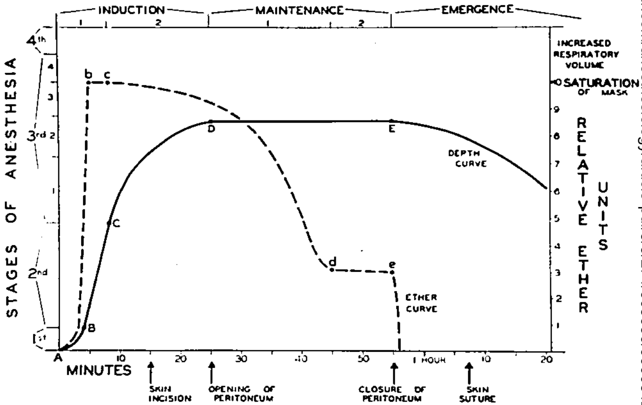

FIG. 1. Relation of depth of anesthesia to amount of anesthetic agent administered.

present during ether anesthesia. However, they are also applicable with certain modifications to any gas or vapor which, as in the case of ether, is absorbed and eliminated unchanged.

It is emphasized that the purpose of this diagram is not to give exact data but merely to demonstrate certain relationships between the depth of anesthesia and the amount of ether given.

The *abscissa* indicates the time in minutes. The arrows under the line show the approximate time when certain steps of the operation take place.

The *left ordinate* shows the depth of anesthesia in stages.*

* The primary consideration in assigning distances as shown on the left ordinate is that they should be suitable for graphic demonstration. However, the relative distances of the stages and levels correspond approximately to the respective ether concentrations of the brain and blood except for the first stage, which is represented by a shorter distance.

The *right ordinate* shows the amount of ether administered in relative units, i.e., one unit may be 5 drops or 50 drops per minute, depending on different factors (such as the type of patient, mask or cone and size of vaporizing surface, etc.). The highest dose is equal to the point at which the entire vaporizing surface of the mask or cone is saturated. Above this highest dose are those doses accompanied by increased respiratory volume. By this is meant that in the case of increased respiration, the area of alveolar membrane exposed becomes larger than usual and therefore more ether is absorbed from the same concentration.

The solid line (*depth curve*) represents the depth of anesthesia. Its starting point is *point A*, the beginning of anesthesia. Four minutes later it reaches *point B*, the beginning of the second stage (where consciousness is lost). Another four minutes is required to reach *point C*, which represents both the end of the second stage and the beginning of the first plane of the third stage. In about fifteen minutes after the start of anesthesia, when the patient's eyes become fixed (first plane passed), the skin incision is made. About ten minutes later, when the desired depth is reached (*point D*), the peritoneum is opened. For the next half hour the depth of anesthesia remains the same. Then the peritoneum is closed (*point E*). From here the depth gradually decreases and at the end of the operation (skin suture), about thirteen minutes later, the depth will have come down to about the lower first plane and will continue thereafter (not shown completely on the diagram).

The broken line (*ether curve*) represents the relative amounts of ether given. Its starting point is the same as the starting point of the depth curve (*point A*). After the administration is begun, the amount of ether given is increased until it reaches the highest dose (saturation of mask at *point b*) about five minutes after the start. This highest dose is continued for the next three or four minutes until the third stage is reached (*point c*, which corresponds to *point C* of the depth curve). From here there follows a decrease in the amount of ether given until equilibrium is reached (*point d*), about forty-five minutes after the beginning. Then only the maintenance dose is given until maintenance of the desired depth is no longer necessary (*point e*, which corresponds to *point E* of the depth curve). After this all ether administration is discontinued. This latter curve is purposely called the ether curve. When another anesthetic agent is used (for example cyclopropane) the curve will have some modifications and might be named after the respective anesthetic agent (for example cyclopropane curve).

Discussion

When viewing the *depth curve* as a whole it can be seen that it consists of three parts, the first of which represents an increase in depth (*A* to *D*), the second represents an unchanged depth (*D* to *E*) and the third part represents a decrease in depth (from *E* onward). The first part of anesthesia, which is characterized by an increasing depth and which begins at the start of anesthesia and lasts until the desired depth is reached, is called *induction*. The second part, which is characterized by no change in depth and which lasts from the arrival at the desired depth until this depth is left, is called *maintenance*. The third and final part of anesthesia, which is characterized by a decrease in depth and which lasts from when the desired depth is left until the end of the anesthetic action, is called *emergence*.

Viewing the *ether curve* as a whole, it can be seen that the first part of it (*a* to *d*) represents an increase and decrease in the amount of ether administered. The second part of it (*d* to *e*) represents a constant amount of ether given. The final part (from *e* onward) represents a decrease in the amount of ether given. The first part of ether administration, which lasts from the start until equilibrium is reached, induces the desired concentration of ether in the blood and brain, and also keeps this level constant while the other body tissues are becoming saturated (i.e., the removal of ether from the blood). This part normally takes longer than the induction. It can be assumed that it requires about forty-five minutes. It actually lasts much longer. The part which extends over forty-five minutes is of little practical importance (Guedel, 6). The second part of the administration of ether, which lasts from the time when equilibrium is reached until it is left, maintains this equilibrium by means of the maintenance dose. The last part of the administration of ether, which takes place after the maintenance dose is decreased, requires little discussion.

The induction, the maintenance, and the emergence will be discussed. It will be seen that both induction and maintenance can be divided into two phases. These phases have their characteristic differences on the curves and have differences in the principles which should guide the anesthetist when carrying anesthesia through these phases.

First Phase of Induction.—This phase lasts from the beginning of anesthesia (*A*) until the second stage is passed (*C*). It includes the first stage and the second stage. The depth curve shows at first a gradually increasing depth (*A* to *B*) and then a rapid increase (*B* to *C*). The latter section is the steepest part of the depth curve throughout its entirety and corresponds to the second stage. The ether curve shows at first a gradual and then a rapid increase in the amount of ether given. The highest dose (saturation of the mask) is reached shortly after the second stage was entered (*b*). This highest dose is maintained then until the second stage is left, i.e., until this phase is passed (*c*).

In other words, the second stage, delirium, representing the potentially dangerous stage of anesthesia, is passed through as rapidly as possible. The ether is given in the maximal dose as soon as possible.

Guiding principles of this phase. The faster it is passed through the better; it cannot be passed through too rapidly. Ether should be given in the highest concentration which is just tolerated by the patient without bringing his respiratory defense reflexes (cough, pharyngeal spasm, laryngeal spasm, holding of the breath) into action. This principle applies only to patients under normal conditions (normal respiratory volume, normal respiratory threshold).

Second Phase of Induction.—This phase lasts from the time when the third stage is entered (*C*) until the desired depth is reached (*D*). It includes the first plane and a certain part of the second plane of the third stage. The depth curve is at first almost as steep as in the second stage. About the middle of the first plane it becomes less steep and then gradually becomes horizontal at the end of this phase when the desired depth is reached (*D*). The ether curve shows a gradual decline throughout this phase. At the end of this phase it is still fairly high. (This end is not recorded on the ether curve by any point, but is represented only on the depth curve by *point D.*)

In other words, the depth is increased fairly rapidly at the beginning of this phase in order to get far beyond the dangerous second stage, and is increased less rapidly later. The amount of ether given at first hardly varies from that given at the end of the previous phase. Then there is a gradual decrease in the amount administered. This decrease of the amount of ether given is by no means proportional to the increase in depth. The increase in depth reaches its maximum at the end of this phase (*D*), whereas the decrease of the amount of ether given reaches its maximum much later (*d*). This fact is explained by the process of tissue activity, as previously elaborated. It is this phase during which those mechanisms are most applicable.

Guiding principles of this phase. There should be a rapid increase in depth in the neighborhood of the second stage, and then this rapidity should gradually decrease until the desired depth is reached. The ether should be given in a high, but not maximal, dose. The administration should be controlled vigilantly by the physical signs present.

Variations of the Second Phase of Induction.—The time required for this phase is variable, i.e., the desired depth may be reached within a short time after the first phase of the induction is passed, or it may require a longer time to reach it. On figure 2 the dotted lines show the optimal depth and ether curves (same as in fig. 1). The other regular solid and broken lines show the respective variations.

There is a "number one" depth curve which is steeper than the optimal depth curve and reaches the desired depth (*point* D_1) about fifteen minutes after the anesthesia is begun. The "number one" ether curve (which corresponds to the "number one" depth curve) at first shows that the maximal dose of ether was accompanied by increased respiration. This is the case when the induction is hurried.

The other extreme, when induction is slow, is represented by the "number two" depth and ether curves. The "number two" depth curve is less steep than the optimal, and the "number two" ether curve starts with a definite decline.

In the first case, i.e., to induce anesthesia rapidly, it must be noted that rapid induction cannot be done with safety, for it will be hardly possible to stop exactly at the desired depth. The second case, in which the induction is slow, has the disadvantage that the anesthesia is unnecessarily prolonged. Therefore, it may be concluded that there exists an optimal speed which lies between these two extremes.

First Phase of Maintenance (cf. fig. 1).—This phase lasts from the arrival at the desired depth (*D*) until equilibrium is reached. The end of this phase is not recorded on the depth curve by any point, but is represented only on the ether curve by *point d.* It includes that part of the maintenance which is characterized by the administration of varying amounts of ether. The depth curve is a straight horizontal line. The ether curve has a characteristic shape in this phase. As mentioned

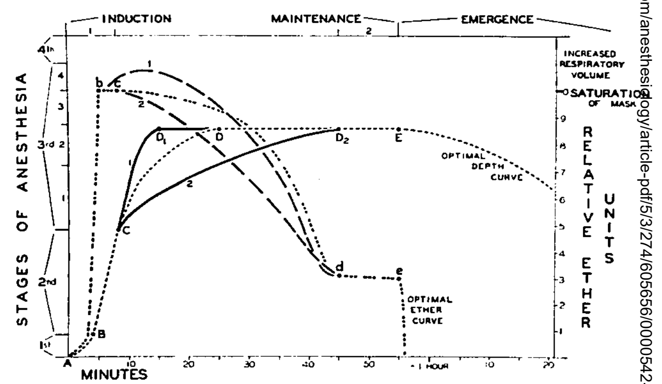

Fig. 2. Variation in curves when induction is hurried or prolonged.

before, there is no marking point on the ether curve showing the end of the previous phase or the beginning of this phase because there is no characteristic change of the ether curve here. The gradual decline of the curve in the previous phase continues at the beginning of this phase. Then the decline becomes rapid, before the end of the phase it becomes gradual again, and at the end of the phase it becomes horizontal (*d*).

In other words, the depth of anesthesia is constant. The ether which was administered in a high dose at the previous phase is administered in a relatively high dose at the beginning of this phase. Using the physical signs as a guide for the dosage of ether, it will be noted that, after this relatively high dose in the beginning, if the same depth is kept there follows a decrease in the dosage until this phase is passed.

Guiding principles of this phase. The necessary depth should be maintained and the physical signs should be constantly taken as a guide in regulating the dosage of ether. However, it should be borne in mind that throughout this phase larger amounts of ether than the maintenance dose must be given in spite of the fact that maintenance is already reached.

As can be seen in figure 2, *point d* on the ether curves, which marks both the end of this phase and the reaching of equilibrium, is the same regardless of whether induction was hurried or slow. This is due to the fact that the time required to reach full saturation or any percentage of saturation of the body is the same for all ether concentrations (Haggard, 2). This time is about forty-five minutes. Therefore, if the induction were hurried, and the desired depth was reached in fifteen minutes (D_1), then the first phase of the maintenance will last thirty minutes longer.

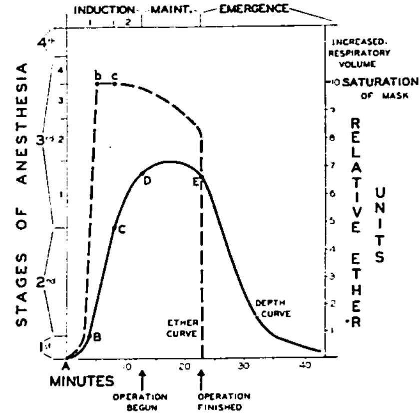

FIG. 3. Depth and ether curves during a short operative procedure.

If the induction itself required forty-five minutes, and the desired depth was reached at the same time that the tissues became saturated (D_2), there will be no first phase of maintenance, but the maintenance will begin with its second phase.

Second Phase of Maintenance (cf. fig. 1).—This phase lasts from the time equilibrium is reached until the desired depth is left. The beginning of this phase is marked only on the ether curve (*d*). The end of this phase is marked on both curves (*E* and *e*). The depth curve is a straight horizontal line. The ether curve is nearly straight and horizontal.

The depth is maintained by the administration of ether in amounts which just replace the ether lost by expiration.

Guiding principles of this phase. The depth should be kept by giving only the maintenance dose.

Emergence.—This part of anesthesia receives relatively little attention because it presents no particular problems to the anesthetist. It is characterized by the elimination of ether from the organism. This process occurs without requiring any interference on the part of the anesthetist. The only procedure that may be necessary is to delay or hurry the elimination of ether, thus causing the emergence to be slower or faster.

Only the beginning of emergence is represented by the depth curve in figure 1.

Variations.—Two types of cases which differ from the main representative case in figure 1 will be discussed briefly (figs. 3 and 4).

Figure 3 represents a case when a short operative procedure is performed and lower first plane anesthesia is required for about ten minutes. As can be seen in the figure, both the depth and ether curves of the first phase of induction (*A* to *C* and *A* to *c*) are identical with those of figure 1. The same also applies to the respective parts of the second phase of induction (*C* to *D* and from *c* onward), with the exception that the desired depth (*D*) is less, and, therefore, is placed on the same depth curve closer to *point C*.

The differences lie in the maintenance and emergence. The depth curve in the maintenance (*D* to *E*) is not a straight horizontal line but is curved and nearly horizontal. The ether curve shows at first a slow and then a rapid decline. The administration of ether is stopped as soon as the maintenance of the lower first plane is no longer necessary. As can be seen, the time is not sufficient to reach equilibrium, therefore, maintenance cannot be divided. Emergence will be rapid because of the small amount of ether that is being eliminated from the body and because saturation of the body tissues has never occurred.

Figure 4 represents a case when a longer intra-abdominal surgical procedure is performed. The time between the opening and closing of the peritoneum is one hour. Complete relaxation (lower second plane) is needed only when the opening and closing of the peritoneum is performed. Only lower first plane is needed while manipulating the viscera. The induction is identical with that of figure 1 on both curves (*A* to *D* and from *A* to the corresponding part), with the same difference that was seen in figure 3, i.e., the desired depth (*D*) is less (lower first plane).

During maintenance, the depth curve (*D* to *E*) is not a straight horizontal line but shows two peaks which correspond to the opening and closing of the peritoneum. The ether curve shows its usual decline in the first phase of the maintenance (up to *d*), and has an additional rise corresponding to the first peak on the depth curve. In the second phase of the maintenance, the ether curve (from *d*) is the usual nearly straight horizontal line until shortly before the second peak of the depth curve is reached. Here it has a rise, soon after which it falls rapidly to the base line. Emergence is the same, with the exception that it starts on a lower level (less deep, *E*) and therefore lasts for a shorter time.

In the case shown in figure 4 the real maintenance level is in the lower first plane, and to this depth additional depths (to lower second plane) were added when necessary, according to the surgical procedure performed.

This type of depth curve is not necessarily characteristic of operations of long duration. It may apply to cases lasting no longer than that shown in figure 1. The curves in figure 4 may be the true graphic representation of the anesthesia of abdominal surgery, because in most abdominal surgical cases, complete relaxation is not required throughout the entire intra-abdominal procedure.

Finally, the *desired depth* may vary (as has already been shown in figures 3 and 4). Different operations require different depths, varying

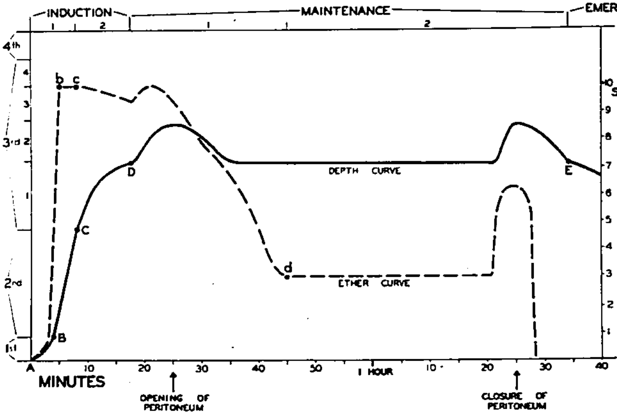

FIG. 4. Depth and ether curves during an intra-abdominal surgical procedure.

from the upper first plane to the lower second plane, or even deeper. This being the case, *point D* could be placed anywhere on the depth curve of the second phase of induction in figure 1, and thus maintenance would start at that point.

PRACTICAL CONSIDERATIONS

The foregoing discussion is not to be considered a complete exposition of the problems to be met in giving an inhalation anesthetic. It will, however, be of considerable value to the beginner as part of his knowledge of fundamentals, and its full value will be clearly recognized by the anesthetist well-versed in (1) physical signs; (2) technical requirements, and (3) physiology.

A thorough knowledge of the *physical signs* is the most important prerequisite. They (cf. Guedel, 6) are the guide for the anesthetist throughout his activity. They are the only means by which he may be informed as to the depth of anesthesia. Without this information in regard to the depth of anesthesia, he is treading upon uncertain grounds and in such a case he will be unable to apply the principles discussed.

The second prerequisite, that of *technical requirements*, must likewise be thoroughly mastered. By this is meant that the anesthetist must have complete control over the process of producing the desired concentration of the anesthetic agent in the inspired air, and over the process of bringing this concentration to the alveoli of the lungs. The following examples illustrate what is meant by this statement. In the case of ether anesthesia, the size of the vaporizing surface which is not adequate for the various respiratory volumes, the varying losses of ether vapor under the cone and through the cone at different times, the leakage of the anesthetic mixture from a closed system, varying with the pressure within the bag, are but a few of many details which can easily upset any calculation if they are not under control. The partially obstructed air passage is likewise of exceedingly great importance. If an air passage is not completely unobstructed, it will be difficult to estimate the amount of anesthetic agent reaching the alveoli, regardless of the amount administered. If the probable carbon dioxide accumulation and oxygen lack, which are the usual consequences of insufficient exchange, are added to the uncertain amount of anesthetic agent reaching the alveoli (all these factors vary according to the varying degree of obstruction throughout the anesthesia), it will be impossible to recognize any relationship between the above considerations and the actual happenings.

A mastery of the underlying *physiology* of anesthesia is a prerequisite of no less importance than knowledge of the technical requirements and physical signs. A human being is not a machine which consumes the administered anesthetic agent and then shows the resulting physical signs according to certain definite rules. He is the subject of certain physiologic functions, such as the circulation, respiration, the activity of the nervous centers in the medulla, and bodily metabolism, in addition to the process of becoming saturated with ether. All these functions are intimately correlated with each other in a complex manner by many chemical and nervous reflexes. Only a slight interference with any one of these functions is necessary to bring about widespread changes in all remaining functions. The process of saturation with an anesthetic agent is directly dependent upon all of these functions. It can be readily seen that any change in any one of these functions will cause varying interferences in the process of anesthesia. In addition to this fact, it should be remembered that the physical signs are not only produced by anesthesia but are also dependent on those same physiologic processes. For example, respiration, an important physical sign, cannot be relied on to show the true depth of anesthesia when the respiratory rate is increased and the character of respiration is changed by accumulation of carbon dioxide. Thus, unless the anesthetist possesses a thorough knowledge not only of the physical signs but also of the underlying physiology, he will be unable to make correct diagnoses in regard to the actual depth of anesthesia and changes in the physiologic functions.

The amount of anesthetic agent used during the anesthesia requires some discussion. The anesthetist has endeavored to administer the smallest possible amount of an anesthetic, which is good judgment. However, from this discussion it can be seen that the amount of the anesthetic is not of primary importance. The attainment of the proper depth and the avoidance of any unnecessary changes in this depth, with the smallest possible amount of agent, are of greatest importance. Only the minimal amount may be used if the depth is to be no greater than necessary, and if the induction and maintenance were carried out as shown in the representative cases (i.e., figs. 1, 3 and 4). This does not apply to those cases in which the anesthetic agent is wasted; for example, when ether has not been vaporized and inhaled but remains in liquid form inside or outside the cone.

These examples are to be seen only in ideal cases. Practically speaking, these curves representing anesthesia are never so simple and straightforward, but always contain upward or downward deviations from the ideals. The anesthetist must find and maintain the proper depth by means of the signs, which may show that anesthesia is a little deeper or a little lighter than should be the case. If these deviations can be reduced to a minimum, if both the induction and maintenance can be made to approximate the ideals, and if the physiologic functions can be maintained with the least possible change, one can then truthfully speak of the art of anesthesia.

SUMMARY

The saturation of body tissues by the anesthetic agent is one of the most important of the processes which regulate the blood-ether level, on which the depth of anesthesia is directly dependent. This is of importance when the correlation of the depth of anesthesia and the dosage of anesthetic agent is considered. A diagram (fig. 1) is given, showing the depth of anesthesia and the corresponding dosage of ether. By analysis of the curves of the diagram it can be seen that the course of anesthesia may be divided into three parts: induction, maintenance, and emergence. Both the induction and maintenance can be subdivided into two phases. The characteristic differences of these phases and the different principles which should guide the anesthetist when carrying anesthesia through each of these phases are discussed in detail. The possible variations of one of the phases and of the entire anesthesia in regard to the various depths required are presented. The prerequisites which must be mastered by the anesthetist are elaborated. The importance of using the least possible amount of anesthetic agent and of administering anesthesia in the best possible manner is discussed.

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BLOOD PLASMA AVAILABLE WITHOUT COST THROUGHOUT MICHIGAN

Broadening medicine's field of service to the people of the United States, the state of Michigan has put into effect a free blood plasma service for all physicians in the state, by which the vital plasma is now available to medical men without regard to the patient's ability to pay for this life-saving assistance.

As described by C. C. Young, director of the Bureau of Laboratories for the Michigan Department of Health, the free plasma service solves a problem which has bothered many medical men, especially in sparsely settled areas. Writing in the March issue of HOSPITALS, the Journal of the American Hospital Association, he tells how the blood, procured from individual donors through locally-sponsored donation clinics, is processed at the department's Lansing laboratories and distributed for storage throughout the state against the day of its eventual use.

The initial number of units of plasma credited to a participating community is determined by the donor response therein. The community is credited with the yield from its donors and debited a small amount reserved for O.C.D. and state emergency use. Thereafter replacement schedules are maintained on the basis of receipts from physicians showing the amounts used.