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THE OXIMETER—A TECHNICAL AID FOR THE ANESTHESIOLOGIST * †

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IN recent years physiologists and biochemists have been placing emphasis on the disturbances in body economy which may result from the development of hypoxia in a patient. These alterations of metabolism are particularly likely to occur in the patient undergoing a surgical procedure, because his organic functions and reflexes may be upset to some extent by the anesthetic agent and the surgical trauma. In the constant search for improvement, the operating team is recognizing the importance of adequate oxygenation and realizing that it is usually one of the controllable factors in the care of the patient.

In the past the anesthesiologist has been handicapped by his inability to detect the lesser degrees of anoxemia. It has been shown (1) that cyanosis is not discernible, even to the trained observer, until the arterial oxygen saturation has fallen as much as 30 per cent below normal. The oximeter will overcome this deficiency, as it provides a continuous method of recording the changes in saturation of arterial blood. It will indicate the slightest oxygen unsaturation in the peripheral arteries, and thus allow an anoxemic trend to be recognized early.

In 1934 two German scientists, Kramer (2) and Matthes (3) independently published a method of determining the oxygen content of arterial blood by a photoelectric technic. The War gave impetus to the development of this principle in North America, and Millikan (4)

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adapted the instrument to the practical use of informing high altitude flyers when extra oxygen was necessary to maintain normal arterial tension. One limitation inherent in the Millikan oximeter, and others like it (5), is that they record only relative changes in oxygen saturation. After the War, Wood (6) devised an instrument which records absolute values accurate to within ± 3 per cent. The importance of absolute values is self-evident, particularly when one is concerned with patients who may have a degree of unsaturation at the time of the first reading.

PRINCIPLES

The instrument that was employed in our studies has been developed as a joint project of the Department of Physiology, McGill University, and the Children's Memorial Hospital, Montreal. It utilizes the same basic absorption bands as the Milliken oximeter, but differs

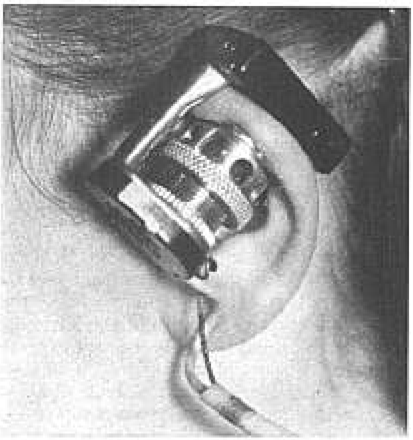

FIG. 1a. Millikan earpiece in position on pinna.

from it with respect to the electrical circuits and mode of operation. A Milliken type of earpiece is attached to the ear (fig. 1a). On one side of the ear is an electric bulb from which light of controlled intensity is emitted. The heat from this bulb causes vasodilatation of the ear tissues. There is good reason to believe that when the ear is flushed with heat, the blood contained within it has an oxygen content practically equivalent to that in the peripheral arteries. The illumination passes through the substance of the pinna to fall upon two filters which transmit red and infrared radiations, respectively. Light which has been transmitted through the ear and through these filters then falls upon two light sensitive photoelectric cells. The potential developed by these cells is fed into electrical circuits of suitable arrangement incorporating a sensitive galvanometer (fig. 1b). From the position of the light spot illuminating the galvanometer scale, the percentage of oxygen saturation may be ascertained by calculations or by use of a nomogram. The circuit is arranged so that increased sensitivity to changes in oxygen saturation has been achieved by enlarging the actual scale to several times that visible on the galvanometer.

The determination of the arterial oxygen saturation by photoelectric means is based on the fact that certain radiations are differently absorbed by oxygenated and reduced hemoglobin. One of the photocells is covered by a red filter which transmits light of wave lengths above 600 millimicrons. The percentage transmission of red light is

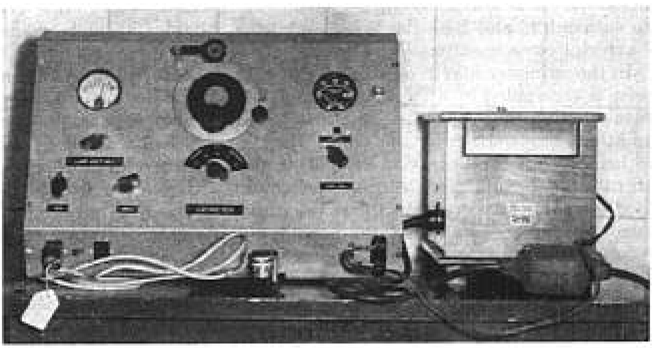

FIG. 1b. Adjustment dials on oximeter and galvanometer recording scale are shown.

very different for oxygenated and reduced hemoglobin in that oxyhemoglobin transmits red light more readily than does reduced hemoglobin.

The other photocell is covered by a green filter which transmits light in the spectral region of 480 to 600 millimicrons and in the region of approximately 750 to 800 millimicrons. The ear absorbs practically all radiations shorter than 600 millimicrons but transmits radiations in the near infrared. The percentage transmission of infrared light is practically independent of the degree of oxygenation of the hemoglobin in that oxygenated and reduced hemoglobin transmit this light to practically the same degree.

The pinna varies in its thickness, pigmentation and blood content from one individual to another. These variations must be accounted for and standardized in some way.

In the Milliken oximeter the amount of light absorbed by the ear tissue is not measured, but allowed for by adjusting the instrument to indicate a known value of oxygen saturation (presetting the instrument to 98 to 100 per cent when the subject is breathing room air or pure oxygen). Compensation for differences in the amount of blood in the light path is provided by bucking the output of the infrared filtered photocell against the output of the red filtered photocell. The Milliken oximeter provides only relative measurements of oxygen saturation.

In the oximeters of Wood and Geraci, the absorption in the tissues of the ear is distinguished from the absorption due to hemoglobin by measuring separately both radiations transmitted by the pinna when it is flushed with blood and when the blood is excluded by pressure. From the four readings obtained, the value of the oxygen saturation can be calculated. It is not necessary to preset the instrument to known oxygen saturation, and thus the Wood oximeter provides absolute values of arterial oxygen saturation.

In the oximeter herein described, the effect of absorption by the ear tissue is eliminated by a suitable arrangement of the instrument. Separate readings can then be obtained by measuring separately both radiations transmitted by the pinna when it is flushed with blood. If the hemoglobin concentration of the blood is known, absolute oxygen saturation determinations can be carried out without resorting to the bloodless ear. In a normal subject breathing room air or pure oxygen when the earpiece is applied, the percentage of oxygen saturation can be determined quickly by use of a nomogram. If a patient is suspected of having some degree of hypoxia or anemia when the earpiece is first applied, the absolute value of oxygen saturation can be calculated if the hemoglobin concentration is known. In a cyanotic patient with right-to-left shunt, an absolute value can also be obtained if the hemoglobin concentration is known.

ACCURACY

Calibration and standardization of this oximeter were accomplished in the following manner. Three or four samples of arterial blood were withdrawn from 40 children preoperatively at various levels of oxygen saturation. Each child was premedicated with morphine and scopolamine, brought to the operating room, and put to sleep with an ultra short-acting barbiturate called kemithal (7). This drug was thought to have less central respiratory depressant effect than others available. The earpiece was fitted in place, and preparations completed for arterial puncture while the necessary vasodilatation of the pinna was attained. In all cases the femoral artery in the groin was selected for puncture. The first blood specimen was withdrawn with the patient breathing 100 per cent oxygen, respirations being assisted if necessary. Then the oxygen was diluted with nitrogen from the gas machine, and the oximeter reading stabilized at different levels of arterial saturation. Attempts were made to take blood specimens in the range between 40 and 100 per cent saturation. Various observers were unable to recognize cyanosis until the arterial saturation fell to approximately 70 per cent. The oxygen content and capacity of the samples withdrawn were determined by the method of Van Slyke and Neill (8); from these data the corresponding degrees of oxygen saturation were

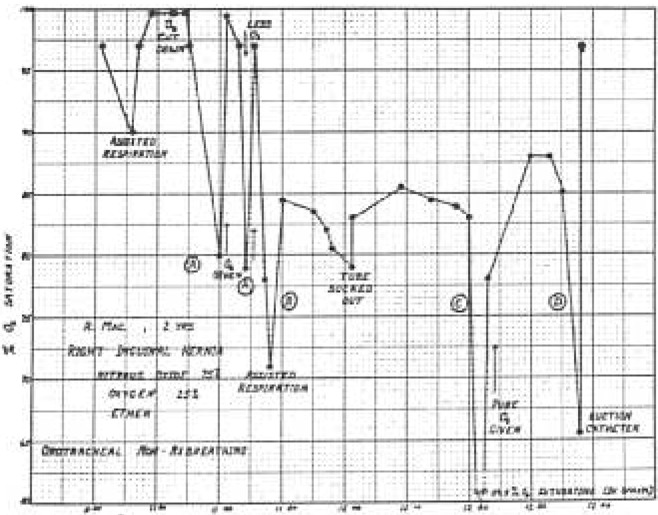

FIG. 2. Variations in arterial oxygen saturation during anesthesia are shown. Decreases at A and A¹ are due to reducing oxygen in inspired air to 15 per cent. Between B and C only 20 per cent oxygen is administered, and this is not sufficient to raise saturation to normal levels after previous falls. C, Severe anoxemia associated with marked spasm resulting from extubation. Administration of 100 per cent oxygen does not relieve anoxemia completely because of mucus in throat and partial laryngospasm. D, Sharp drop in saturation associated with employment of suction catheter. Full oxygenation is now obtained because airway is clear.

calculated and plotted against the values which had been estimated from the oximeter readings. On the basis of more than 100 comparisons, the average discrepancy between Van Slyke and oximeter values was about ± 2.5 per cent in the range noted above for patients with normal circulation. In subjects with cardiovascular anomalies with marked arterial unsaturation and varying degrees of polycythemia, the values obtained by the two methods agreed on the average within ± 5 per cent.

Clinical Application

The value of oximetry in clinical practice has been noted previously (9). The anesthetist has a special interest in it because during operations the arterial oxygen saturation of the patient is dependent primarily on the percentage of oxygen supplied by him and the ease with which it reaches the alveolar surfaces. Oximeter values from moment to moment may be plotted on a graph to demonstrate the manner in which the anesthetist's manipulations may impede or facilitate full arterial saturation. The course of 89 children was followed carefully with this instrument during operation, and useful information was obtained by observing the changes which occurred in oxygen saturation. Figure 2, A and A[1], shows the record of one patient in whom arterial unsaturation occurred because less than 20 per cent oxygen was supplied in the anesthetic mixture. When such a fall in arterial

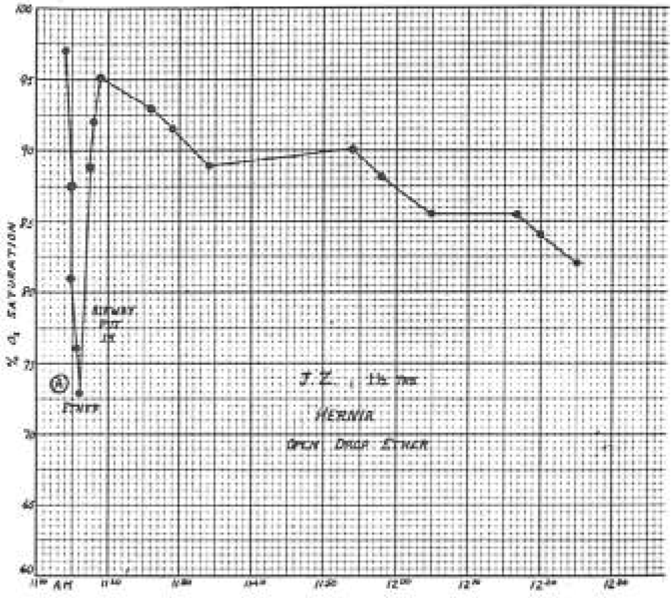

Fig. 3. A, Fall in saturation resulting from upper respiratory obstruction in vinethene, ether induction. Improvement is immediate following insertion of oropharyngeal airway. Note gradual fall in arterial oxygen saturation over period of one hour during employment of open drop ether technic without added oxygen.

saturation occurred, it can be seen (fig. 2, B to C) that some considerable time was required for the oximeter reading to return to normal when only 20 per cent oxygen, or the equivalent of room air, was supplied. When 100 per cent oxygen was given in the presence of a clear, unobstructed airway, however, the anoxemia was eliminated in three or four breaths (fig. 2 A, A[1], and D). At C in figure 2 full oxygenation was not achieved although 100 per cent oxygen was being supplied, because of moderate obstruction of the airway owing to the presence of

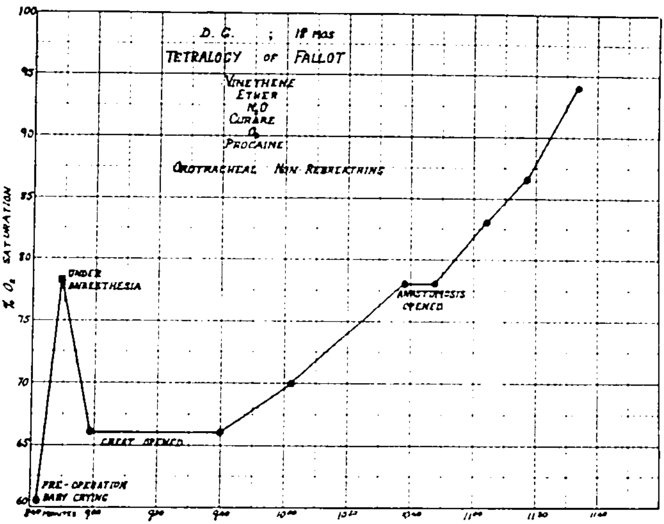

FIG. 4. Arterial oxygen saturation during operation for tetralogy of Fallot. Note that high oxygen concentration in anesthetic mixture increases oxygen saturation of arterial blood to some extent. Surgical anastomosis causes rapid increase in oxygen saturation to almost normal levels.

mucus and partial laryngospasm. When this was rectified by suction, the anoxemia disappeared rapidly.

This knowledge has particular application to patients who are being anesthetized with the open drop ether technic (10). During induction upper respiratory obstruction of some type or breath-holding may initiate an oxygen deficit which may not be corrected while the patient is breathing only room air. Of equal importance is the fact that under optimal conditions in the open drop ether technic the patient is usually inhaling less than 20 per cent oxygen. This becomes obvious when it is realized that the ether vapour occupies a certain volume in the inspired mixture, and also that in most circumstances some of the room air is displaced by carbon dioxide which is retained under the mask during exhalation and rebreathed at the next inhalation. Examples of gradually decreasing arterial oxygen saturation caused by the above factors are shown in figures 3 and 5. Of 40 patients who were anesthetized in this manner, 18 or 40 per cent, showed a trend toward arterial unsatur-

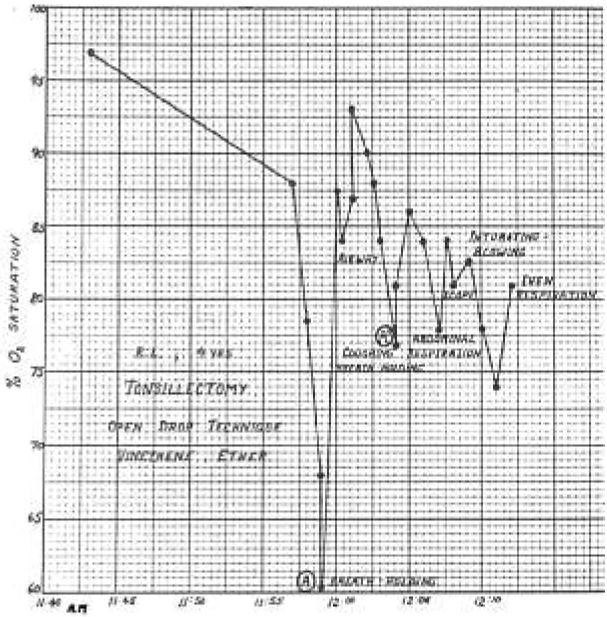

FIG. 5. A, A1, Effect of breath-holding on arterial saturation. Airway is beneficial at B, but there is gradual fall in saturation during entire induction period. No oxygen was added under mask.

ation during administration. If hypoxia is to be avoided, a constant flow of oxygen under the ether mask should be allowed to enrich the inspired air.

In cyanotic children suffering from congenital cardiac defects, the preoperative arterial oxygen saturation is usually low. By utilizing an oxygen-rich mixture for narcosis, such as can be done when cyclopropane or ether is employed, the oxygen saturation during the operative procedure can be kept 8 to 12 per cent higher, with the provision that adequate pulmonary ventilation is maintained at all times. In 4 of 6 such patients on whom oximeter readings were made, the benefits of high oxygen concentrations were apparent. Figure 4 provides a graphic record of one of these patients with tetralogy of Fallot during operation. Of particular interest is the objective demonstration of the rise in oxygen saturation to almost normal levels upon completion of the anastomosis.

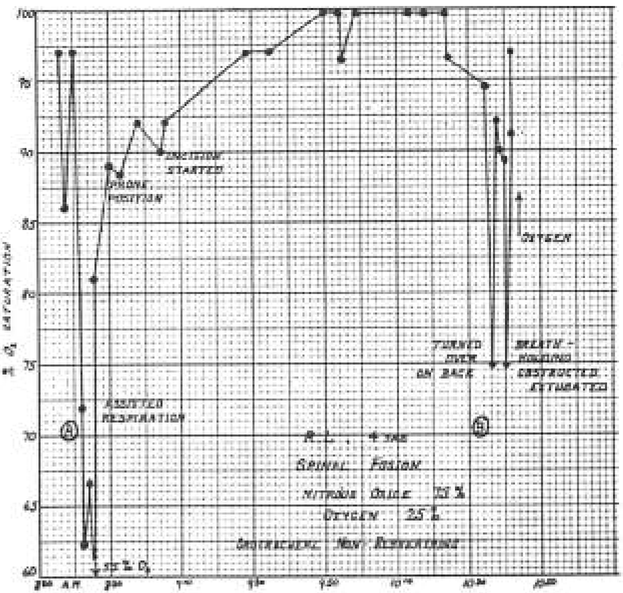

FIG. 6. A, Oxygen saturation falls rapidly when respirations are ineffectual after administration of pentothal-curare mixture. Saturation returns rapidly to normal with assisted respirations. B, When patient is turned, bucking on endotracheal tube lowers saturation; note that administration of pure oxygen quickly returns level to normal.

With the oximeter it is possible to show how the anesthetist in his manipulations may induce trends which often lead to severe anoxemia. If high concentrations of irritant ether vapor are built up too rapidly during induction, the patient may react by holding his breath for variable lengths of time. This is most marked in children, and the anesthetist may allow it to persist for dangerous periods. In 42 per cent of 59 cases in which vinethene and ether were used for induction, breath-holding occurred and caused arterial unsaturation. Figure 5 shows how rapidly the arterial oxygen saturation may fall after breath-holding for thirty seconds. A serious oxygen deficit may result if a child is allowed to hold his breath unduly and, as observed previously, this may persist after the resumption of breathing unless extra oxygen is supplied.

Induction of anesthesia with a combination of pentothal and curare has become a common practice. Either of these agents, however, can diminish tidal exchange or may cause complete apnoea. The necessity of maintaining adequate respirations by actively assisting the tidal

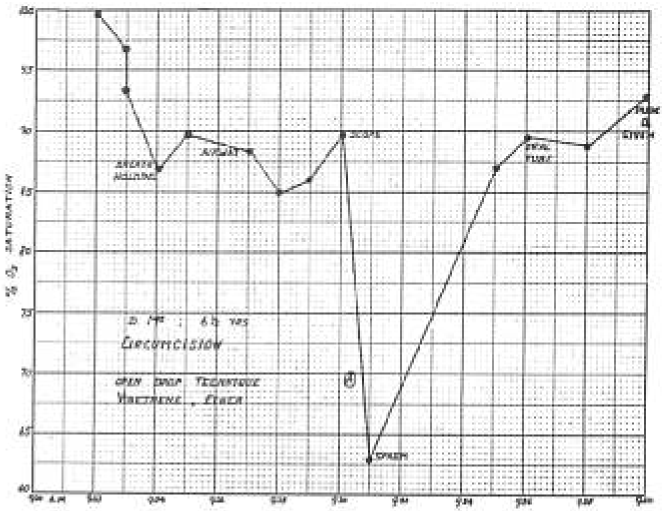

FIG. 7. A, Fall in oxygen saturation due to reflex spasm of vocal cords resulting from insertion of largyngoscope just prior to intubation.

exchange is demonstrated in figure 6. After the injection of pentothal-curare, the arterial oxygen saturation falls rapidly until assisted respirations with oxygen are instituted.

Induction with nitrous oxide often is chosen because of its pleasantness for the patient, but it is prone to cause falls in oxygen saturation because, being a weak narcotic, it can achieve anesthesia only at the expense of lowering the oxygen percentage in the inhaled mixture. Figure 8 exemplifies what happened in 5 of 7 children in whom anesthesia was induced in this manner. To guard against the danger of permanent unsaturation, patients anesthetized in this way should have more potent agents introduced as soon as they become unconscious. This allows oxygen to be supplied in adequate amount.

During the second and third stages of anesthesia, obstruction of the patient's airway may occur. This may be the result of salivary secretions, of laryngeal irritation by the anesthetic agent, or more often of the tongue falling back into the posterior pharynx. If allowed to persist, such obstructions will produce reductions in the arterial oxygen saturation. Often the insertion of an oropharyngeal airway will assist greatly in relieving the anoxia (fig. 3). In 24 per cent of 59

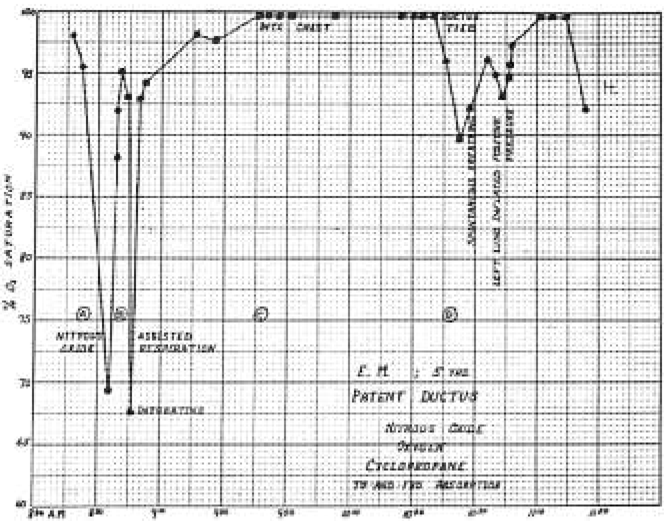

FIG. 8. Between C and D, when one lung is collapsed, arterial saturation remains at 100 per cent when abundant oxygen is supplied and respirations are assisted constantly. A, During induction phase, note decrease in saturation when oxygen supplied is less than 20 per cent. B, Fall in saturation is the result of spasm associated with endotracheal intubation.

cases in which anesthesia was induced with vinethene and ether, an oropharyngeal airway was successful in promoting better tidal exchange and improving the oxygen saturation. The oximeter has shown in an objective manner that even a minor obstruction of the airway cannot be tolerated if hypoxia is to be avoided.

Endotracheal intubation may be associated with changes which lead to anoxia. The insertion of the laryngoscope may obstruct the airway, lifting the epiglottis may cause a reflex spasm of the vocal cords, or the placement of the tube in the trachea may result in reflex apnoea or produce "bucking" and bronchospasm. Of the 78 children who were intubated during oximetry, 24 per cent showed immediate falls in arterial oxygen saturation (figs. 7 and 8). Most of these reactions can be avoided by waiting to intubate until a moderately deep plane of anesthesia has been reached.

Once the endotracheal tube is in place, a clear airway seems assured. Secretions may gather in the bronchial tree during operation, however, and must be removed if smooth anesthesia is to continue. Aspiration of the tracheobronchial tree is prone to cause severe drops in oxygen

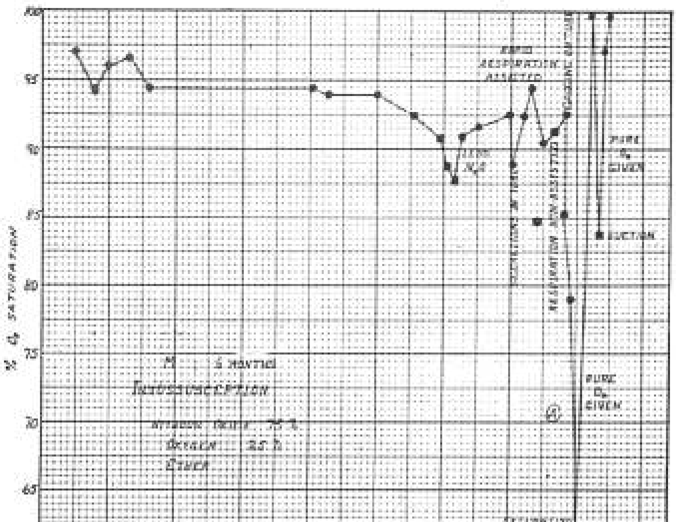

Fig. 9. A, Severe fall in oxygen saturation associated with spasm on extubation; note that administration of 100 per cent oxygen quickly relieves spasm and anoxemia.

saturation. Ten patients, or 55 per cent of those requiring suction during operation, showed a fall similar to that exemplied in figure 2. For this reason the suction catheter should not remain too long within the trachea and bronchi. Marked hypoxia may be avoided if the catheter is inserted several times, allowing three or four breaths of an oxygen-rich atmosphere between each aspiration.

Frequently the question has arisen as to how well oxygenation can be maintained during thoracic operations. If one lung is completely collapsed, and thus has only a small amount of blood circulating through it, it is plausible to suppose that adequate oxygenation can be maintained through the other lung. Figure 8 shows that such is the case when high concentrations of oxygen are being administered and when the respirations of the patient are being assisted properly. In 22 thoracic operations, 16 patients, or 73 per cent, showed no decrease in arterial oxygen saturation during the period in which one lung was collapsed.

The act of removing the endotracheal tube from the patient often produces a potent reflex larygospasm. This may lead to severe oxygen

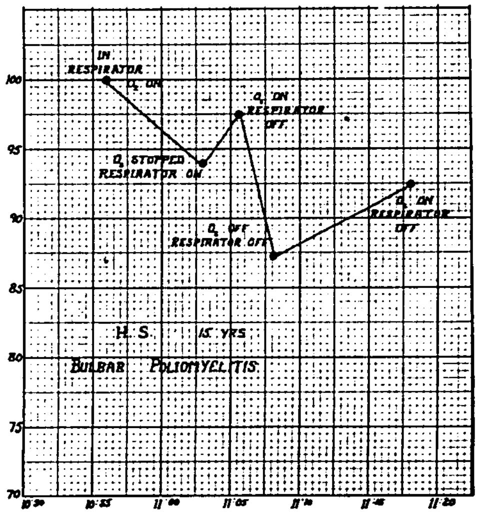

FIG. 10. Effect of respirator and nasopharyngeal oxygen on arterial saturation of patient with activity of accessory muscles of respiration only.

unsaturation of the blood, as exemplified in figures 2 and 9. Five of 30 patients who were observed during this period with the oximeter showed similar falls in oxygen saturation. Extubation during the expiratory phase of respiration may decrease the incidence of this hazardous reflex. Once it is present, administration of 100 per cent oxygen under slight positive pressure will not only reduce the anoxia but also relieve the laryngospasm rapidly.

In the wards the oximeter may serve as an accurate indication of respiratory function and of the value of oxygen therapy. For example, a patient with marked intercostal and partial diaphragmatic paralysis resulting from Landry's paralysis, at one time had an arterial oxygen saturation of 79 per cent. When oxygen was given by nasopharyngeal catheter at a rate of 6 litres per minute, the arterial saturation rose within two minutes to 92 per cent and was maintained there. Figure 10 shows the benefit derived from oxygen and a respirator by a patient with poliomyelitis who had the use of only his accessory muscles of respiration. The differences are not marked, but the patient became fatigued quickly when neither oxygen nor the respirator were being employed. Knowledge of the degree to which the arterial oxygen saturation could be maintained out of the respirator was a definite psychologic aid to the patient.

LIMITATIONS

In its present phase of development, the oximeter possesses certain limitations. It is a delicate instrument which should not be moved about or jolted unduly. The earpiece must remain fixed once it is placed in position, and the heat derived from the light may produce second degree burns of the pinna unless it is turned off temporarily at least every thirty minutes. Technical assistance is required for its proper operation and maintenance. At the moment it should be regarded as a clinical research tool which yields valuable information relative to the degree of oxygen saturation of the arterial blood from minute to minute. An instrument is now being completed, similar in principle but rugged in construction and with a new type earpiece, which will overcome many of the present difficulties. This new apparatus incorporates an electronic calculator which it is hoped will provide a direct reading of the percentage of oxygen saturation.

COMMENT

Any device which allows the anesthesiologist to assess more accurately the status of his patient is certain to be valuable. The oximeter eliminates the guesswork which must arise when the anesthesiologist is trying to determine, short of cyanosis, whether the patient is adequately oxygenated. On many occasions this instrument has detected anoxemia when observation of the pulse, blood pressure, color of the patient and peripheral vascular tone have shown no abnormalities. It will indicate a trend before anoxia has an opportunity to alter physiologic responses.

As can be seen from the examples presented, the oximeter will offer contributions to the understanding of respiratory physiology. Many investigative problems become possible or are facilitated through its use. It will aid greatly in elucidating the pathogenesis of anoxemia and in demonstrating the value of oxygen therapy.

SUMMARY

An improved type of oximeter and its method of standardization are described briefly.

Examples are given of the value of oximetry to the clinical anesthesiologist.

This instrument represents a forward step in the care of the patient during anesthesia.

We wish to express our appreciation to Miss Carol Horsborough, Mrs. Joan Oliver, Miss Lesley McBride, Mrs. Frances Boggis, Mrs. Peggy Blalock and Mrs. Rita Boshinski for technical and secretarial assistance which has facilitated these studies.

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ANNUAL MEETING
THE AMERICAN SOCIETY OF ANESTHESIOLOGISTS, INC.

SYMPOSIUM ON SHOCK

The following symposium will be presented Thursday afternoon, November 8, 1951, during the Annual Meeting of The American Society of Anesthesiologists, Inc., Washington, D. C.:

SYMPOSIUM ON SHOCK

Evaluation of Susceptibility to Shock—The Starting Point—Reserve, by Perry P. Volpitto, M.D., Augusta, Georgia.

The Relation of Light or Deep Anesthesia to Shock, by C. R. Stephen, M.D., Durham, N. C.

The Use of Drugs in Shock, by John Adriani, M.D., New Orleans, La.

Intra Arterial Transfusion in Shock Due to Hemorrhage, by J. Ross Veal, M.D., Washington, D. C.

The Relation of Heart Failure to Shock—Cardia Arrest, by E. M. Papper, M.D., New York City.

Moderator—Donald Stubbs, M.D., Washington, D. C.