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Fire and explosion hazard of combustible inhalation anesthetics

John F. Knox
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FIRE AND EXPLOSION HAZARD

OF

COMBUSTIBLE INHALATION ANESTHETICS

*****

by

John F. Knox

Senior Thesis

*****

Presented to the College of Medicine

University of Nebraska, Omaha

1940
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INTRODUCTION

Anesthesia is a surgical necessity. There are two main considerations in anesthesia, from a surgical viewpoint, first, the safety of the patient, and, second, the efficient application of the anesthetic agent to the operative maneuvers. Hospital executives and surgeons have however, feared, and rightfully so, the dramatic and devastating effect of the explosion or fire caused by any accidental ignition of a combustible inhalation anesthetic.

Accidents, avoidable or not, have constantly occurred within the operating rooms and the daily papers apparently enjoy publishing the serious consequences in any property damage and in loss of human life, by setting the headlines in large bold print. An explosion of an ammonia system occurs in some large ice plant, due to some defect in the machinery; trains collide; automobiles by the thousands are in serious accidents each year, maiming and killing scores of citizens annually. In fact, we even hear the various experts calmly predict the number of lives that will be lost in the coming year for any given area from one type of accident or other, and the entire public will accept the prediction with serene resignation. But, when a fatality occurs from the explosion of some type of anesthetic vapor in a hospital, the news is broadcast immediately, and printed throughout the country as a sensation. The more excitable individuals will
condemn the anesthetic, the hospital in general and surgery in particular, without ever considering the circumstances or wishing to secure the facts of the accident.

Casual, injudicious statements have occasionally given the erroneous impression that such incidents are extremely rare and may be practically ignored. The danger, however, is real and great as fires and explosions occurring during administration of inflammable anesthetics are a constant menace. It must be so recognized by everyone who is connected with surgery or has anything to do with the handling of anesthetics. Although this hazard is not great in comparison with the other hazards of surgery, it is for the most part a preventable hazard.

In considering the literature on this subject, it may be stated that the loss of life from such accidents have not been exceedingly numerous, and the incidence of these may be further minimized if the physical and chemical properties of the anesthetic agents and their various mixtures are carefully considered and the means by which they may become accidentally ignited while being administered, are properly safeguarded.

This problem, therefore, mainly amounts to this: What are the conditions during and after anesthesia which occasionally initiate fires and explosions, and how may these conditions be eliminated? It appears that many surgeons and hospital personnel are living in a sense of false security because of all the various expedients which they have adapted and to which they attribute their freedom
from accidents in surgery just as long as they do not have any untoward effects. Many of these measures of protection can be shown on the physical ground to be actually ineffective or to even increase the hazards of accidents.

Proper safeguarding against the various hazards calls for a full understanding of the subject and the principles involved, and then for the ceaseless vigilance on the part of the surgical personnel. This knowledge must embrace the fundamentals because it is unlikely that any code of procedure can be written to take into account every conceivable dangerous combination of factors.

It is my wish, in presenting this paper, to accumulate statistics which will illustrate the past experience of accidents, their source, and finally a comprehensive review of the possible safeguards which may be effectively used to prevent further sad, demoralizing accidents, to some extent, in the future.
GENERAL CONSIDERATIONS

In considering the subject of hazards of fire and explosions of combustible anesthetics, I will limit the discussion to those anesthetic agents which are inhalatory and the principle source of the majority of such accidents. This scope will, therefore, include ether, ethylene, nitrous oxide, ethyl chloride and cyclopropane.

It has been established, and will be shown, that all the commonly used anesthetic gases, when mixed with air, oxygen or nitrous oxide in proportions which are usually within the limits employed in induction or maintenance of surgical anesthesia, are explosible, and a cyclopropane-oxygen mixture shares this common risk. Contrary to popular opinion, an ethylene-oxygen gas mixture has apparently only the same relative danger, from the explosive point of view, as any other gas-oxygen mixture. None of these anesthetic agents, except acetylene, which is not considered in this paper, can explode without some source of oxygen; but any gas or vapor consisting chiefly of carbon and hydrogen, if ignited in the presence of air, oxygen or nitrous oxide, may undergo the rapid form of combustion, evolution of heat and expansive force, constituting explosion (24).

Finch (18), states that three phases have been distinguished in the process of gaseous combustion, namely: (a) A slow (non-self-propellant) flame-propagation below the ignition point, (b) a self-propellant flame-propagation, and sometimes, also (c) a short pre-flame period during which combustion is self-propellant. The point
at which the process becomes self-propellant is sometimes called ignition point. It is necessary to have energy in some form or other imparted to a given combustible system, before the combustion can be determined in it. Whether or not ignition can be brought about by an electric spark of given characteristics, depends upon the properties of the gaseous system, in particular its composition and pressure, and of these the composition alone is of primary interest, because explosive anesthetic mixtures are not normally formed except at atmospheric pressures.

It is necessary to understand clearly what is meant by upper or lower limits of the explosible mixture. According to Morgan (32), mixtures lying outside the limits are those in which any flame will not spread indefinitely. Such mixtures are capable of being ignited but the flame resulting from ignition will sooner or later become extinguished, and will not travel indefinitely through any considerable volume of the mixture. Finch (18), however, states that when the gaseous mixture lies outside the so-called "explosion limit", flame propagation and ignition is no longer possible. These, the upper and lower limits of explosion, vary widely according to the nature of the combustible and the supporting atmosphere. The extent of the explosion limit range, in conjunction with the volatility of the combustible, may be regarded as a measure of the ease with which an explosive mixture may be formed under accidental conditions.

There are three factors which seem likely to increase the risk of anesthetic explosions. First, the administration of
ether-oxygen mixtures has become increasingly common in recent years. Second, there has been a considerable extension of the use of electrical apparatus with the development of such instruments as the sigmoidoscope, the cystoscope, cautery, and surgical diathermy appliances. X-ray apparatus, too, is now often used more in the presence of inflammable anesthetics. Thirdly, the problem of static electricity as a determining cause in these explosions has been brought to the foreground recently and is regarded as an increasing risk, since the introduction of artificial ventilation systems has produced conditions more favorable than formerly for its production (16) (12).

In general, less combustible is required to give a lower explosive limit in air than in oxygen. This has been thought to be due to the fact that the mean molecular heat of oxygen is higher than that of nitrogen over the range of temperatures from that of the laboratory to the flame-propagating temperatures, usually 1,200° to 1,500° centigrade, according to Jones (25). The upper limits of all combustible gases are much higher in oxygen than in air; hence the range of explosibility in oxygen is very much greater than in air and likewise the speed of the flame and violence produced on explosion are greater in these mixtures. Excellent laboratory reports on the inflammability of various widely employed anesthetic gases and vapors have been presented by Brown (3), Bloomfield (1), Dixon (9), Jones (25), Phillips (36), and Wardell (47). Taking all of these reports into consideration, it is my opinion
that the experimental work of the United States Bureau of Mines would furnish the most precise and accurate data upon which to base the following conclusions as to the limits of inflammability of the combustible anesthetics. The following table was taken from this latter reference (25).

<table>
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<tr>
<th>Anesthetic</th>
<th>Density In Air = 1</th>
<th>Limits of Inflammability</th>
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<tr>
<td></td>
<td>Lower</td>
<td>Upper</td>
</tr>
<tr>
<td>Ether</td>
<td>2.56</td>
<td>1.65</td>
</tr>
<tr>
<td>Ethylene</td>
<td>0.97</td>
<td>2.75</td>
</tr>
<tr>
<td>Ethyl Chloride</td>
<td>2.23</td>
<td>4.00</td>
</tr>
<tr>
<td>Cyclopropane</td>
<td>1.45</td>
<td>2.40</td>
</tr>
<tr>
<td>Nitrous Oxide</td>
<td>1.52</td>
<td>Not Inflammbable</td>
</tr>
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It is only reasonable that any combustible anesthetic that produces explosive mixtures with air or oxygen at laboratory temperatures and pressures must at the outset be considered as a hazardous material and be treated as such.

Density of the gaseous anesthetics is a very important consideration in dealing with this subject. For example, a gas law states, "The rate at which a gas or vapor will diffuse or mix with air is inversely proportional to the square root of its density" (26). Therefore, the anesthetics with a low density are readily diffusible in air, allowing the anesthetic mixture to pass from a concentrated explosive mixture to the range of nonexplosibility within a relatively
short period of time. Refering to Table I, ethylene has a density of 0.97, whereas ether is 2.56, illustrating the reason that ether being a relatively heavy vapor, will naturally remain in a highly concentrated condition longer and also will tend to accumulate at the floor level. Ethylene, however, will diffuse very rapidly into the surrounding air. This matter will be given more detailed consideration in reviewing the specific anesthetics agents.

Hoping that the material thus far presented on the generalities of the combustible anesthetics will enable the reader to have a working basis for further, more detailed consideration of the gaseous vapors, I will attempt to discuss the various inhalation anesthetics specifically as to their relative dangers and cause of accidents.
ETHYLENE

Shortly after the introduction of ethylene as a general anesthetic there were several catastrophic accidents which, of course, were widely publicized, without considering the underlying facts of the explosions. This, unfortunately, fixed the idea in the minds of many that the use of ethylene was very dangerous, not only to the patient, but also to the anesthetist, surgeon, and any others of the surgical personnel.

The opinion seems to be widely held among those who have had a considerable experience with ethylene that, apart from the risk of explosion, this substance has some marked advantages as an anesthetic. Reports from hospitals in which ethylene has been used show that there is generally a strong desire to eliminate this risk of explosion and to continue this form of anesthesia (21).

It will be my endeavor to present sufficient data with proper reasoning, to enable the reader to understand that ethylene is probably as safe as ether, if not safer, when using the just precautions.

Brown (3) stated that there are four places in which ethylene might conceivably explode: (a) While compressed in the cylinder; (b) after emerging from the cylinder; (c) from the mixing chamber to the patient, while mixed with oxygen; (d) when allowed to escape into the air through the spill valve in the face piece. In the first two locations one is presumably dealing with the pure gas, and whether or not explosions can occur at these points depends
on the inherent character of the gas. In order to settle this question definitely, one must know whether it is possible to cause the pure gas to explode or whether it can explode spontaneously. Cabot (4) claims that experience has shown that ethylene is not unstable when under high pressure, and that the pure gas cannot be made to explode. Brown (3) has shown that ethylene unmixed with oxygen will not explode, and, furthermore, that explosions do not occur in mixtures of ethylene and oxygen unless at least forty per cent of the mixture is oxygen. This work was confirmed by Hornor and Gardenier (19), although their results show that ethylene-oxygen mixtures containing a minimum of thirty per cent of oxygen may explode. It may be said, that the criterion established by the latter workers was very rigid. If the mixture was not exploded at once by a spark, a continuous arc was passed through it for one minute before it was definitely said to be nonexplosive. One might also say that the manufacturers of the gas, consider that there is no danger of the cylinders exploding, as they ship them quite freely by freight or express.

Herb (22) stated that following an explosion in the distributing portions of the anesthetic apparatus, there is no tendency for the explosion to flare back into the machine or up to the tanks.

Chemists have used this gas in industry for many years. If the pure gas were unstable or if its use were fraught with danger of mishap, it would only be reasonable to expect to find warnings of these dangerous properties.
In considering the third possibility of Brown's statement (3), i.e., that gas which is delivered to the patient and which fills the mixing chamber and delivery tube, we can conclusively demonstrate that it is explosible. The ethylene in this circumstance is mixed with oxygen or some other supporter of combustion. Of course, the mixture has to lie within the limits of inflammability which has been explained in the general discussion. In practice this mixture will vary from 10 - 25 per cent of oxygen, the remainder being ethylene. Such a mixture as this cannot be exploded by means of an electric spark, according to Brown (3), Cabot (4), the experimental work presented by Jones (25) and others. Brown states that the mixture they found to explode contained a minimum of from 40-45 per cent of oxygen. Any higher mixture of oxygen would explode with violence, then increasing directly with the oxygen percentage, the maximum violence being reached with the three volumes of oxygen to one volume of ethylene.

Again, at an upper limit of 80 per cent of ethylene mixed with 20 per cent of oxygen, explosibility ceases. Henderson (21) explains that the oxygen is insufficient to carry on the combustion or permit the transmission of the explosion wave or even a flare. The difference between mixtures of a combustible gas in air and mixtures in oxygen is that the upper limit, above which the flame is not transmitted and explosion cannot occur, is much lower in air than in oxygen, and the range of the mixture that may explode is decreased.
It should be mentioned that ethylene in mixture with nitrous oxide within certain proportions may be extremely explosive. Horner and Gardenier (19) show that mixtures of nitrous oxide and ethylene are explosive when the latter gas is present in concentrations of from 5 to 35 per cent. Above 35 per cent ethylene, the explosion hazard is nil. Therefore, we can see that small amounts of nitrous oxide in ethylene will not lead to explosion but that small amounts of ethylene in a nitrous oxide tank may be very dangerous.

Pressure under which a gas is acting, is also important from the standpoint of explosion. According to Dixon (9), "The crucial pressure for ethylene in nitrous oxide is about 500 mm.; at this pressure ethylene ignites within half a second at 605° centigrade. At the atmospheric pressure, ethylene ignites rapidly at 592° centigrade, which is only 14° centigrade below the ignition point in oxygen, but when the mingling gases are in contact with a heated surface the difference between the ignition points is more marked. Under the same conditions, ethylene ignites at a lower temperature in nitrous oxide than in oxygen; but at low pressures the ethylene fails to ignite when the lag period exceeds one second". When the pressure is increased above the normal, the ignition point of ethylene in oxygen falls slowly and nearly regularly. For example, at two atmospheres, the ethylene ignites in oxygen at 580° centigrade, and at three atmospheres pressure, it ignites in oxygen at 557° centigrade, according to Blomfield (1). This demonstrates the
practical point that the risk is increased if ethylene is used under pressure, and also if the gas is used in conjunction with nitrous oxide.

In view of all the evidence that has been accumulated on the subject it seems that pure ethylene will not explode either when ignited as the free gas or spontaneously when compressed in steel cylinders.

The reason that, in the operating room, explosions of ethylene, when they do occur, are generally much more violent than those of ether is that 80 per cent or more ethylene is required for full surgical anesthesia of the same depth of unconsciousness and relaxation as are obtained with only 6 - 7 per cent of ether vapor. The concentration of ethylene required for full surgical anesthesia, is even above the point of combustion. Explosions of ethylene inside anesthetic apparatus do not usually occur during full anesthesia, in fact, it is scarcely possible for one to occur. It is, according to Henderson (21), at the end of anesthesia, while the gas is being washed out with oxygen, that mixtures within the highly explosive limits are produced. During this period the mixtures in the anesthetic apparatus passes from the upper limit down to the lower through the whole explosive range.

The fourth possibility of the explosion of an ethylene mixture is that the expired ethylene, coming out of the spill valve in the mask, might in time form a mixture with air that would explode. Brown (3), in his early reports on the explosibility of
ethylene mixtures, concluded that explosion due to gas that had escaped into the operating room was a negligible possibility. He stated that from his experimental work, it was shown that a mixture of from 5 - 10 per cent of ethylene in air forms an explosive mixture. How long then, would it require an operating room to become full of such a mixture? Brown (3) said, "Supposing the normal ventilating of a patient to be 8,000 cubic centimeters per minute, and the average operating room to contain 2,700 cubic feet, it would require somewhat in excess of six hours, of continuous anesthesia to form a mixture of 5 per cent, which is the minimum explosive mixture, and this without the slightest room ventilation. Most operating rooms are ventilated from the top, and since ethylene is lighter than air, it would rise and be drawn off, thus rendering the possibility of an explosive mixture from this source as being only in the remote realms of possibility."

According to Pinson (38), a small room of 1,000 cubic feet would require a cylinder of five hundred gallons of ethylene to evenly saturate it, to provide the air with a mixture of one in twelve. But he continues by saying that the saturation will ordinarily not be even. Cabot (4) strengthens this point of view by explaining the fact that the gas is only slightly lighter than air, and therefore, it forms currents and strata much like those formed by tobacco smoke. However, Salzar (43) argues against the latter two scientists, by declaring, that during an hours anesthesia, not more than twelve cubic feet of ethylene is used, and if all of this
should be present in an operating room at one time, no explosion could occur, because the average operating room contains not less than 4,000 cubic feet, which would make the proportion of gas in the room 0.3 per cent. In other words, the mixture would be too lean.

Considering the arguments presented above, it would be most logical for us to assume that there is a slight possibility of danger of explosion near the mask, due to the greater concentration of ethylene in the immediate area. This slight possibility should warrant consideration in the manner of preventing ignition of the mixture.

Ethylene does have nearly the same molecular weight and specific gravity as the average of gases composing air. It is therefore highly diffusible. When liberated into the air of the operating room it spreads so quickly that the concentration at even a short distance falls below the danger point. Within a few feet from the anesthetic apparatus and operating table only minute amounts can be detected. Even in the neighborhood of the anesthetic mask, ignitable concentrations are not maintained, except within a distance of less than one foot in a direct line of the exhalation valve of the mask during an ethylene anesthesia (21). However, this has to be set aside as a possibility, as a spark from a static charge or some other source of ignition, may cause a violent and tragic explosion.

After discovering the fact that certain mixtures of ethylene
and oxygen, or some other supporter of combustion, do explode, we naturally would wish to know whether such mixtures may explode spontaneously. It is a general point of agreement among the investigators in this subject, that at normal pressures even the most explosive concentration of ethylene in oxygen will not blow up in the absence of a definite exciting cause. The cause, as will be fully discussed later, has been either actual flame, caut­ery, electric sparks, or various other sources of ignition of the combustible mixture.

At this point, it would be well to sum up the report of the various ethylene anesthesia accidents as they have occurred throughout the country, always attempting to keep in mind the possible cause of explosion, if it is at all possible.

Shortly after the introduction of ethylene-oxygen for anesthesia at the Presbyterian Hospital of Chicago, March 14, 1923, two minor explosions occurred in the delivery room. Herb (22), makes a report on the accidents, stating that, "The first one took place when the breathing tube and cone were placed on the head of the machine; the other occurred while the anesthetist was holding the cone preparatory to its application to the patient's face. In the first instance, a spark was produced when the metal on the tube came in contact with the metal on the head of the machine. In the second case, the anesthetist thought it probable that he had struck the metal table with the cone, causing a spark".

In contrast to the full anesthesias, the much lower concent-
ration of gas required, sometimes used for obstetric analgesia, are highly explosive. The use of ethylene during labor is on this account probably much more hazardous than for major surgical operations, according to Henderson (21).

Henderson (21) made a report from a questionnaire which was sent to 478 hospitals, each having two hundred beds or over, inquiring about their experience in the use of ethylene anesthetics. He received 288 replies, of which 129 reported that they use ethylene for anesthesia, and 158 had never used it. The motive which this latter group seemed to entertain, was that they were uncertain as to the hazard of this anesthetic. Of these replies, only six hospitals had experience with explosion in connection with the use of ethylene. A patient apparently died of heart failure, instead of ethylene accident, in one of the hospitals. In another, an explosion occurred when a cautery was applied to a carbuncle of the neck, during the flow of ethylene for anesthesia, causing the patient's death. The anesthetist was literally 'blown to bits' in an accident in which an ethylene cylinder exploded. This cylinder was reportedly previously filled with nitrous oxide gas. How the ignition in this case occurred, was not entirely clear. All the other accidents reported consist of nine explosions. These accidents were all on the inside of the apparatus, but in none did it extend to the cylinders, or beyond the mask. It merely shattered the glass vessels on the anesthetic apparatus, burst the hose to the mask or tore the breathing bag; and greatly
startled the personnel of the operating room.

A questionnaire was sent to 75 hospitals, by Dr. Hugh Cabot (4). Among these hospitals 146,000 ethylene anesthesias were reported. In one of the hospitals, an explosion occurred when a cautery was applied to an abscessed lung with a patient under ethylene. In another, the ethylene mixture was ignited by a cautery, producing a slight burn. In still another, a serious explosion of ethylene occurred, with the cause unknown, and even the circumstance unknown. However, this same hospital reported that ethylene has been used for several thousand anesthesias since without an accident.

Fifty-eight prominent surgeons, throughout the country, received a questionnaire, which they returned with the report of 163,000 ethylene anesthesias. Of these anesthesias, there were 18 explosions, of which five were serious and one fatal, (17). In all of these explosions, static electricity or suction apparatus was given as the initiating cause.

Salzar (43) in 1929 collected 425,000 ethylene anesthesias with a report of 10 explosions. Two were mere flashes, three resulted in minor injuries, four in destruction of equipment, and one in death.

In 1933, Herb (22) reported on 1,005,375 anesthesias of ethylene, which had been administered by 220 anesthetists. In this extensive survey, it was discovered that 20 explosions had occurred with a result of one injury and five deaths in the series.

The explosion which apparently caused the greatest unrest in the use of ethylene, and initiated the investigation of this
anesthesia by numerous questionnaires, was the one that occurred at Evansville, Indiana. A physician who was working with a gas machine carrying tanks of oxygen, nitrous oxide, and ethylene was killed by the terrific explosion which was reportedly due to ethylene. It was discovered at subsequent investigation, that some ethylene might have passed into the nitrous oxide tank through the connecting tubes, proving again the great instability of mixtures of nitrous oxide and ethylene under pressure. Guedal (20), Livingstone, Engel and Shank (17), stated that with an apparatus, the nitrous oxide and ethylene cylinder should never be opened at the same time.

A more detailed discussion as to the possible causes of explosion with the recognized methods of prevention will be considered at another point of this paper.

The investigators of this subject have all come to the conclusion, that with proper understanding of the fundamental dangers and prevention of such dangers in the use of ethylene, that it is attended by no more hazard from explosion than the use of ether.
ETHER

It has been known since the introduction of ether as an anesthetic agent, that there was great danger of fire and explosion from accidental ignition of the vapor. Therefore, the inflammability of this anesthetic has always been somewhat feared, and the known precautions are usually observed.

Ether is normally administered from a gas machine in a much lower concentration than in the case of ethylene, and practically all of these concentrations, according to Phillips (37), are within the explosible range. The inflammable range for ether was stated as 1.85 - 36.5 in air for lower and upper limits respectively; and 2.10 - 82.0 as the range for the oxygen-ether mixture. Thus, ether which boils at 35° centigrade, under normal conditions forms explosive mixtures with air between the above stated limits, and must therefore be regarded as very liable to form dangerous mixture. It so happens, in addition to this, that ether-air mixture containing as much as 50 per cent ether vapor, are capable of propagating what is known as the 'cool flame', according to Finch (18). This cool flame is relatively harmless in itself, travelling slowly, and is able to pass through a suitable mixture without necessarily being perceived. It is cold from the point of view of any sensation which it might give rise to in coming into contact with any bare skin area. This type of flame gives a blue luminosity which is so exceedingly faint as to be visible only in a well darkened room. The danger of this cool flame is
that it may ignite normal explosive mixtures, whether of ether or of other gases (18).

The vapor of ether is two and one half times as heavy as air, so that it does not diffuse so readily as in the case of ethylene. Therefore the ether is less likely to become diluted to concentrations below the inflammable or explosive range, as was stated by Phillips (37). Instead of diffusing rapidly throughout the operating room, it will naturally drop, and tend to collect along the floor. Phillips (36) found that the vapor also collects in pockets which may be formed by the operating table coverings and screens. These pockets and streams of ether vapor may easily be ignited if there is a possible cause for ignition present, with a resultant flare or explosion, more frequently the former. If the ignition of the gas forms a flare, the usual result is for this flare to travel back along the ether stream to the patient and the anesthetic machine and result in an explosion (16) (37).

Swan (45) stated, it was found by experiment that the room distribution of ether vapor during operations under open-mask anesthesia resulted in low concentration. The air at about two inches from the patient's mouth contained less ether than would form an explosive mixture, and the proportion fell off rapidly as the distance from the patient increased.

At least one hundred explosions probably occur every year with ether in this country, causing trifling or serious burns of the eyebrows, lips, and pharynx, but not extending into the
lungs, because the mixture is too weak to burn there. The mixture is richer in the mouth, if delivered by a tube, or a soaked mask (38). Pinson (38) states that within two to three minutes after the mask is removed, the expired air would contain too weak of an anesthetic concentration to be ignited.

Ether vapor will form explosive mixtures within a combination of any of the supporters of combustion. However, it is quite generally known that a rich ether-oxygen mixture is more dangerous than a corresponding ether-air mixture, and a very small spark will suffice for ignition. Phillips (37) remind us though, that ether given by the drop method and the resultant mixture with air forms a highly inflammable rather than a violently explosive mixture.

According to Williams (49), there are very real dangers accompanying the use of ether with nitrous oxide and oxygen, for ether-air or ether-oxygen vapors are able to mix with nitrous oxide in the rebreathing bag. Brown (3) confirms this view by exclaiming that nitrous-oxygen mixture or even pure nitrous oxide passing thru an ether chamber forms a highly explosive mixture.

A few of the stories of ether accidents have been gathered, and will now be presented, placing special emphasis upon the method or circumstance that was at hand, and the possible source of ignition.

Dr. Ironside (24), at a special section of the Anesthetists of the Royal Society of Medicine in England, described an explosion that took place in a hospital. "The anesthetic trolley had been
in use for two and one half hour's, with oxygen passing over ether. While it was being wheeled out of the operating theatre into the anesthetic room a violent explosion occurred. The ether container broke into small pieces, and two bottles of ether on the other side of the room exploded. The theatre attendant was knocked down, a sister was blown over, the patient fell off of the trolley, and the whole room was a sheet of flame. In considering the circumstance of this explosion, one might say that every conceivable situation was present to augment the possibility of violent explosion. The floors and corridors of the hospital were laid with rubber, those of the operating room were granolithic flooring. The air in these rooms was very dry, as the sterilizers were steamless. Nurses had complained of sparks from the trolley carrying food or patients. The trolleys were insulated with rubber wheels, and the anesthetic table also was equipped with rubber wheels. The anesthetist had obtained the highest explosive mixture of 75 per cent oxygen and 5 per cent ether. A spark from the trolley was evidently the initiating cause.

In answer to the same questionnaire which Dr. Hugh Cabot (4) had sent out to the 75 hospitals in regard to the use and explosions that had occurred with ethylene, there were 19 of these hospitals that reported ether flares. In 6 cases the flare was initiated by cautery; in 2 by the fluoroscope; in 12 by a spark from a motor on the suction apparatus used in conjunction with tonsillectomy, and in 4 by an exposed wire to a headlight.
In most cases the form of anesthesia was apparently open ether or insufflation, but in four the explosions occurred in connection with the use of anesthetic apparatus administering nitrous oxide, oxygen, and ether.

In Iowa, cautery was used for the removal of carcinoma of the tongue following open drop ether and removal of the ether mask. A violent explosion occurred with a result of fracturing the base of the tongue, and forcing the patient's eyeballs out of their sockets until they rested on the cheeks. Hemorrhage was severe, and passed into the air passages. The patient died several hours later (17).

Another serious and fatal accident occurred while ether was being given to reduce a fracture of the mandible. A syringe delivering warm air was used on the teeth to keep them dry, at which time a violent explosion occurred at the back of the throat and the patient died ten minutes later from rupture of the bronchi and collapse of the lungs.

Henerson (21) reviewed a few other accidents which had occurred. "The turning on an electric light near the patient ignited and burned the patient." There was evidently a spark produced when the light was turned on. "Ether-oxygen ignited from an electric bulb of a laryngoscope and the patient was burned. An ether explosion occurred when cautery was employed during a hemorrhoidectomy. A spark from a motor driven suction machine ignited ether, and the force of the explosion blew out some of the nearby wall
of the operating room. Static spark from the hands of a nurse who had walked some distance after folding linen and then touched an open drop ether mask, ignited the mask."

Cole reported a pharyngeal ether-oxygen explosion with death of the patient from rupture of bronchus and collapse of the lungs. The cause of ignition was not stated.

Salzar (43) reported two fires when actual cautery was used during mouth operations.

Henderson (21) says, "The discontinuation of an eth administration followed by the use of an electric 'pencil-lamp' resulted in an explosion, followed by the death of the patient from putrid bronchitis. A necropsy revealed that the flames had been transmitted down the bronchial tree. The surgeon was burned. This same surgeon had had two similar explosion."

Henderson also reported two other accidents which he had received in an answer to a questionnaire. The one accident occurred in Stuttgart, Germany, in which a Draeger machine administered ether-oxygen. The machine exploded, while the patient and the machine were being wheeled into the room. This apparently was ignited by some source of static spark. The patient was severely injured. The other accident was apparently about under the same circumstances with a static spark igniting an ether-oxygen mixture in a Roth-Draeger apparatus. The apices of both lungs were ruptured, but the patient eventually recovered.

In comparing the ether vapor and ethylene, it appears that
the hazard when using ethylene may be only very slightly greater than when using ether, because the explosion range of the two is substantially the same, although the rate of propagation of flame with ethylene is greater and the explosions tend toward greater violence and destructive force, as a rule.
NITROUS OXIDE

Nitrous oxide, when used alone or in combination with oxygen, are not explosive, if these two substances are in a very pure form, according to Wardell (46). However, in almost all of the other possible combinations with this gas, an explosive mixture results. In general, it may be stated, that in such possible mixtures ignition temperatures are low, explosive limits are wide, and the rate of flame propagation is high.

In the absence of oil or the other dangerous substances, nitrous oxide - oxygen mixtures are not combustible. It is a generally known fact that in the presence of even minute quantities of oil, oxygen is combustible. Often, if the needle valve of a cylinder of oxygen or of nitrous oxide turns with difficulty, the anesthetist sometimes unwisely puts a drop of oil on it. Therefore, as a result, the next time the cylinder is used the valve may be projected up through the ceiling or into the body of the operator by the explosion of the oil in the presence of these gases, Henderson (21).

Further, how many of the anesthetists in using the nitrous oxide - oxygen mixture have not many times allowed the mixture to flow through ether or over gauze saturated with ether, in order to obtain a deeper anesthesia? It probably never even occurred to them that they were using a mixture of very great explosibility - equally as great as ethylene or certain other mixtures.
Brown (3) confirms this idea, by his experimental work showing that any nitrous oxide - oxygen mixture, or even pure nitrous oxide passing through an ether chamber turned fully on, forms a violently explosive mixture, and that this explosibility continued until the ether was half shut off, when no explosion could be obtained. The following table, taken from Brown's work with 'Explosibility of Anesthetic Mixtures', illustrates the results of this experiment.

<table>
<thead>
<tr>
<th>ETHER</th>
<th>NITROUS OXIDE</th>
<th>OXYGEN</th>
<th>EXPLOSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>80</td>
<td>20</td>
<td>Yes</td>
</tr>
<tr>
<td>Full</td>
<td>90</td>
<td>10</td>
<td>Yes</td>
</tr>
<tr>
<td>3/4</td>
<td>100</td>
<td>0</td>
<td>Yes</td>
</tr>
<tr>
<td>3/4</td>
<td>80</td>
<td>20</td>
<td>Yes</td>
</tr>
<tr>
<td>1/2</td>
<td>100</td>
<td>0</td>
<td>Yes</td>
</tr>
<tr>
<td>1/2</td>
<td>80</td>
<td>20</td>
<td>No</td>
</tr>
<tr>
<td>1/4</td>
<td>80</td>
<td>20</td>
<td>No</td>
</tr>
</tbody>
</table>

There is, however, three so-called nitrous oxide - oxygen explosions which are reported in literature. In Missouri a high frequency electrical converter was used to cauterize a wound after removal of a urethral caruncle. Nitrous oxide - oxygen anesthesia was in use, and an explosion occurred, injuring the patient's eye and face, and a $3000.00 judgement was obtained (17) (31). Two other nitrous oxide - oxygen explosions were reported to have occurred in England, both during the use of a bronchoscope. In the one case, the patient's throat was scorched and in the other the patient's lung was ruptured, with death ensuing from pulmonary hemorrhage. The question still is, whether in any of these three
instances ether or oil was present in the apparatus, or if some carbon or foreign substances was in the nitrous oxide.

Henderson (21) states that although the cylinders of nitrous oxide and oxygen should never explode if properly tested before filling, they become a danger if they are old or if a pressure test has been neglected at the filling plant.

In considering the subject of ethylene, it was mentioned that shortly after the introduction of ethylene, two minor explosions had occurred in the Presbyterian Hospital of Chicago. The staff became excited over this and substituted nitrous oxide - oxygen for the ethylene - oxygen. But within a few weeks two explosions had also occurred with this gas. Herb (22) described these cases, stating that the first took place when the patient and the gas machine were being wheeled into the operating room during anesthesia. In regard to the cause, that is still a mystery. The second explosion occurred during the administration of nitrous oxide - oxygen at the completion, where the breathing tube was being disconnected.

As was stated previously, since nitrous oxide - oxygen in the absence of oil does not explode but only supports combustion, the fact that the addition of ether to this mixture makes a highly explosive combustion combination has been too frequently ignored. The very presence of this mixture in an apparatus, whether or not it is in use, is to be treated with great respect.

Livingstone, Engel, and Shank (17) described the following
accidents which had occurred with the use of nitrous oxide - oxygen and ether mixtures. A spark from a bronchoscope ignited the mixture and burned a patient's throat. A patient was being wheeled into the operating room, when an explosion occurred, presumably the result of a static spark, and all that resulted was discoloration about the patient's eyes. In Los Angeles, a diathermy was being used when an explosion occurred, resulting in the death of the patient.

In an Illinois Hospital, an explosion occurred during the administration of the above mixture, when a spark ignited the gas. This static spark was produced by an individual wearing woolen clothing, crossing the room and touching the operating table near the anesthetist. The patient was burned and the anesthetist died of burns (17).

Another accident, under similar circumstance, occurred when a Sister in her woolen habit, brushed against a face mask that had just been used for this type of anesthesia. A spark resulted between the woolen skirt and face mask.

Other occasions of accidents resulted when a wall plug was pulled from a socket during anesthesia; when electric cautery was used; and a static spark being produced by the lifting of the mask from the patient's face. Naturally, others have occurred, but were not reported, because too few hospitals desire to publicize their carelessness in regard to the accidents, unless there is some legal action in progress.
CYCLOPROPANE

Cyclopropane is a hydrocarbon gas which was formerly called trimethylene, and is an isomer of the well-known propylene.

This gas is one of the latest inhalation anesthetics, possessing definite beneficial properties in regard to a good anesthesia under certain situations. However, it is another of the common gaseous anesthetics that has placed the personnel of all surgical procedures under a slight fear because of its inflammability and explosiveness.

In considering the generalities of the various anesthetics to be discussed in this paper, it was stated that all the commonly used anesthetic gases, when mixed with air, oxygen or nitrous oxide in proportions which are usually within the limits employed in induction or maintenance of surgical anesthesia, are explosible, and a cyclopropane — oxygen mixture shares this common risk. We also know, if the figures of the United States Bureau of Mines are accepted, that in air, the limits of inflammability of cyclopropane are 2.40 - 10.3; whereas they are 2.45 - 63.1 in oxygen. Any mixture of cyclopropane — oxygen falling within these limits, are therefore, exceptionally dangerous if the source of ignition is present.

The introductory remarks presented on the subject of cyclopropane anesthesia, should be sufficient for us to understand the dangers and possible hazards of explosion with this anesthetic.
Of course, since it is relatively new in the field of inhalation anesthesias, very little has been specifically stated in the literature with regard to this hazard. It may be stated in general, that cyclopropane is affected by the various elements and sources of ignition as any of the other anesthetics, only it can be further generalized by saying that cyclopropane has characteristics which are more similar to ethylene than to ether (37).

Toland and Kroger (27) in their article on 'Anesthetic Gas Mixtures: Their Explosion Hazards', reported on the first cyclopropane - oxygen explosion. This explosion occurred in 1937 in a Los Angeles hospital, but the cause of the ignition and the circumstance of the surrounding conditions were not mentioned. These writers stated that this was the only explosion reported in more than 75,000 cyclopropane anesthesias, since its introduction a few years ago.

In October 1938, an explosion occurred in Boston, and was reported by Woodbridge, Horton and Connell, (6). It remained a puzzling question to the hospital staff as to the reason this explosion occurred as all methods of prevention of explosions that are known, that were in force at his hospital, but still the explosion occurred. According to these men, "The humidity was given at 60 - 65 per cent. There was an electrical connection by chains between the operating table, the gas machine, and the patient by wire around the breathing tubes and embedded in the rubber of the mask, and thence by dangle chains to the patient's face."
The floor was of terrazo with the embedded brass grids, and this was grounded. The anesthetist's stool was of painted metal with rubber feet, and was covered with felt-like cloth and protected by a casing of a white textile similar to oil cloth or fabricloth. Cyclopropane with the carbon dioxide absorption method was in use in a closed circuit of a Connell Deluxe machine for twenty-five minutes. The oxygen was running at 250 cubic centimeters per minute. As the wound was just about to be closed, the surgeon left the operating table and walked to a corner of the room when the explosion occurred. The patient died fifteen hours later with lacerations of the posterior pharyngeal wall and subcutaneous emphysema. The expiratory valve was blown off the machine and the inspiratory flutter was jammed in its seat -- indicating the explosion started not in the machine, but in the vicinity of the mask and breathing tubes."

When the cause of explosions and their prevention are read in this paper, it is possible to see various faulty procedures and set-up of this operating room, all of which might possibly explain the source of static spark to produce ignition of the mixture.

Livingstone, Engel and Shank briefly mentioned the other explosions that have occurred with the use of cyclopropane anesthesia. In the one case, a falling mask brushed the drapes, and was then picked up by an individual who had not previously touched the machine. A static spark was produced which ignited the gaseous
mixture. On another occasion, the static spark was generated and discharged by the pulling of a cover off the gas machine. The rheostat of a laryngoscope was imperfect, and caused an explosion. The death of a patient under cyclopropane anesthesia in a Massachusetts hospital resulted from the ignition of gas by the static spark from some source. The last report that they had record of was being emptied from the anesthetic bag to give the patient 100 per cent of oxygen. This occurred in California in March of 1939.

Of course, there have been many other explosions with the use of this gas, but the above is a well rounded representative group of causes and situations, with the result. Cyclopropane explosions have occurred in Omaha, Nebraska, but since the publicity was very limited, the hospital staffs undoubtedly did not wish to publish the details at the present.
ETHYL CHLORIDE

The use of ethyl chloride has become more popular as an inhalation anesthetic, for induction in children especially.

This gas is inflammable, and yields a vapor that forms an explosive mixture with air. It is especially dangerous in this mixture in the proximity to flames or any apparatus likely to involve a spark and hot wire (16) (12).

Statistics or reports of the accidents which have possibly occurred with this anesthetic were not found in any of the available literature. Therefore, it will be necessary to consider this subject when speaking of the generalities of the anesthetics regarding their source of ignition and the available preventative methods.
EXCITING CAUSES OF GAS EXPLOSION

The essential nature of the gas mixture used is not the cause of anesthetic gas explosions. There are, however, two factors necessary before explosion can take place, namely, the presence of an explosive gas, and the presence of an open flame or spark or sufficient heat to explode the gas. As it has been stated before, no matter how explosive the gaseous mixture is, it seems to be true that it will not explode spontaneously, and no explosion can take place except when the ignition factor is present.

According to Phillips (36), and others, an explosion results from the combination of (a) an inflammable gas, vapor or other substances; (b) oxygen or other substance which provides oxygen (such as nitrous oxide); and (c) a source of ignition.

Rovenstine (41) explains that the sources of ignition in general include: (a) any electric spark either from static electricity or from electric circuits; (b) open flames; and (c) objects heated to a temperature of at least 400° Fahrenheit, including cautery and lighted cigarettes.

Regarding the sources of ignition in a more detailed, specific sense of the word, let me illustrate by a chart, taken from the statistics accumulated by Livingstone, Engel, and Shank (17), the anesthetic agents used at the time of accident, and the possible or probable source of ignition.
<table>
<thead>
<tr>
<th>Anesthetic Agent</th>
<th>Cases</th>
<th>Cause of Accident</th>
<th>Inj.</th>
<th>Deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ether, or</td>
<td>34</td>
<td>Static spark ---------------------</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Ether-Oxygen</td>
<td></td>
<td>Cautery -------------------------</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spark from motor ----------------</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pencil lamp ----------------------</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not stated -----------------------</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open flame -----------------------</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Elect. bulb laryngoscope ---------</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Turning on light ----------------</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diathermy ------------------------</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fulgurator -----------------------</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lamp socket spark ----------------</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Warm air from syringe --------------</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Nitrous oxide-</td>
<td>14</td>
<td>Static spark ---------------------</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>oxygen-ether</td>
<td></td>
<td>Cautery -------------------------</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bronchoscope ---------------------</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diathermy ------------------------</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fulgurator -----------------------</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Elect. plug from wall --------------</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spirit lamp ----------------------</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Ethylene -</td>
<td>14</td>
<td>Static spark ---------------------</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>oxygen-ether</td>
<td></td>
<td>Cautery -------------------------</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open flame -----------------------</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>High per cent oxygen -------------</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Cyclopropane -</td>
<td>11</td>
<td>Static spark ---------------------</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>oxygen</td>
<td></td>
<td>Laryngoscope ---------------------</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cautery -------------------------</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unstated -------------------------</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>9</td>
<td>Oil -----------------------------</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Static spark ---------------------</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open flame -----------------------</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unknown --------------------------</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Nitrous oxide-</td>
<td>3</td>
<td>Cautery -------------------------</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>oxygen</td>
<td></td>
<td>Bronchoscope ---------------------</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
One can readily understand the real dangers of explosion hazards, when he studies the above record as the source of ignition. Static spark and cautery were outstanding causes of such accidents, considering and accepting these statistics. Naturally, it would be well for us to study the cause of static spark in detail, to enable us to establish modes of prevention of such a well recognized hazard in the operating room.

STATIC ELECTRICITY: According to Livingstone (28), as early as 600 B.C., Thales of Miletus, one of the 'seven wise men' of early Greece, knew that certain substances would become electrified when rubbed with silk. We know now that one way of creating static electricity is by the contact or separation of two substances, one or both of which may be a non-conductor (27).

Static electricity is a serious danger which is always present when flammable, volatile gaseous material is used. The opportunities for the generation of electric potentials in an operating room are very numerous, as will be shown. Once an electrostatic potential is established, until that potential is discharged, it remains on the charged object ready to cause trouble if it escapes by jumping or sparking. Naturally, if this occurs in the vicinity of an explosive gas mixture, there is great danger and most likely an explosion resulting.

The difference between a static spark and an ordinary electric power or lighting current, depends largely on the duration, voltage and amperage, according to Wardell (46). The static spark
will only last for a fraction of a second and has a relatively high voltage. For example, if we walk across the carpet of our home in dry winter weather, we obtain a spark of considerable size when we bring the finger close to the grounded object such as a radiator, water pipe, or lighting fixture, etc. Under proper conditions, meaning this dry atmosphere and the walking across an insulated floor covering, the spark would be sufficient to cause a fire in any establishment having exposure to flammable vapor.

Draper (11) found that taking four steps on the tiled floor of the operating room gave an individual wearing leather shoes a potential of over 500 volts on the electroscope. This, however, was the maximum reading their instrument would record, so the actual potential may have been much higher.

It is interesting to learn something about potentials that may develop from static so as to be able to appreciate how frequent must be the occurrence of hazardous charges, and therefore, how urgent it is to provide secure means for leading them away. Swan (45) exclaims that in the absence of a suitable instrument, a charge can be detected by holding a finger-tip 1/8 of an inch away from the metal work of the operative vehicle while a dry blanket is smartly pulled away. Newcomer (33) made some measurements with an electrostatic voltmeter of a rather novel type, in which the potential to be measured supplies the field circuit of the machine. The charge is induced into an alternating current or charge, which is then led to an alternating current amplifier.
This in turn passes to a voltmeter, which is calibrated to read on three scales, zero to 1,000 to 10,000 to 100,000 volts. High potential charges on objects of small capacity give true readings with the instrument. With this instrument, recordings were observed of the static charges induced on objects and persons in an operating room set-up. The accompanying table illustrates the findings as were recorded by Newcomer.

OBSERVED OPERATING ROOM POTENTIALS

<table>
<thead>
<tr>
<th>Activity</th>
<th>I*</th>
<th>II***</th>
<th>III**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nurse walking 20 ft. over tiled floor</td>
<td>1250</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Nurse sitting down on stool</td>
<td>500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scuffling feet on tiled floor</td>
<td>2500</td>
<td>350</td>
<td></td>
</tr>
<tr>
<td>Movements of anesthetist</td>
<td>700</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>Using electrical cautery</td>
<td></td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Stretcher as patient leaves room</td>
<td>500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Covering patient with blanket</td>
<td></td>
<td></td>
<td>2500</td>
</tr>
<tr>
<td>Turning over rubber covered ped on table</td>
<td></td>
<td></td>
<td>1500</td>
</tr>
<tr>
<td>Pulling cloth off operating table</td>
<td></td>
<td></td>
<td>3500</td>
</tr>
<tr>
<td>Cystocoel operation with patient in lithotomy position (voltmeter connected to entire system).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) Draping patient</td>
<td></td>
<td></td>
<td>4000</td>
</tr>
<tr>
<td>(b) Anesthetist in cotton suit</td>
<td></td>
<td></td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>rising from stool.</td>
<td></td>
<td>300</td>
</tr>
<tr>
<td>(c) Anesthetist scuffling feet along.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(d) Elect. Cautery in use -- gas machine connected to floor by wet towel.</td>
<td></td>
<td></td>
<td>800</td>
</tr>
<tr>
<td>(e) Removing drape sheet</td>
<td></td>
<td></td>
<td>800</td>
</tr>
<tr>
<td>(f) Redraping patient with wet towel to floor.</td>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>(g) Lifting patient on table -- wet towel not in use.</td>
<td></td>
<td></td>
<td>2000</td>
</tr>
<tr>
<td>(h) Lifting patient off table -- wet towel in use.</td>
<td></td>
<td></td>
<td>500</td>
</tr>
</tbody>
</table>

* I. Voltmeter only.
** III. Voltmeter connected to the operating table.
*** II. Voltmeter connected to gas machine.
Woodbridge, Horton and Connell (6) explain that the commonly practiced maneuvers in the operating room increase the potential of the object involved. For example, an anesthetist wearing cotton garments acquired a potential of several hundred volts merely by sliding forward on a cushioned stool and then rising. It was also demonstrated that a draft of air accompanying the opening of a door raised the potential of the operating table some 50 volts. Even insertion of gauze pads between the sterile sheet and the neck increased the potential 150 volts. Removal of the stand for the instrument tray from the foot of the table gave the patient a potential of 50 volts.

Static charges may be produced by the contact or separation of any two unlike materials whether solid, liquid, or gaseous, by friction, or by a gas in motion whether through a pipe, tubing or in air, according to Wardell (46). It is a matter of controversy just how electro-static charges are produced by the flow of gases past solid surfaces, however, experimental evidence seems to confirm the belief that they are caused by the presence of minute dust particles or droplets of liquid carried along the stream of gas (47). It is relatively easy to understand then, how there is production of such charges when the gas passes through the modern anesthetic apparatus. These charges may accumulate in the apparatus, until they can exhaust themselves by contact of the machine to some other object allowing the discharging spark.

Doane (10) explained that as the rubber rebreathing bag
expands and contracts synchronously with the patients expiration and inspiration, there is an appreciable amount of friction between the inside of the bag and the metal chamber or tube to which the bag is attached to the particular apparatus. A negative charge is built up, by this friction on the inside of the bag, while an equal and opposite charge is imparted to the metal piece. This piece, however, is joined to the entire metal framework of the apparatus and cannot, therefore, keep the charge produced upon it, as it is distributed to all the interconnected metal parts and in this way is greatly attenuated. The negative charge on the inside of the bag is bound by the nonconducting nature of the material to remain in situ. Doane continues by saying, "Doubtless some of the charge is dissipated to the metal part every time the bag is sucked up against it. Apparently, however, this momentary and imperfect contact does not suffice to discharge the bag but, on the contrary, the friction occurring at each contact tends rather to build up higher charges on it." Therefore a high negative charge is developed on the inner surface of the breathing bag while the metallic parts of the apparatus are without appreciable charge (46) (10). Wardell (47) states that when this condition exists, someone may touch the bag, or the machine bringing about a spark. Or the machine may be moved, so that the bag and hose are made to sway against a metal part, allowing the discharge of a spark.

OPEN FLAMES: This source of ignition is self-explanatory,
and will not have to be discussed in detail. It is a very common source of explosion and should therefore be regarded with utmost interest.

**ELECTRICAL APPARATUS:** Swan (45) states that attention should be focused, in the first instance at least, on the electrical ignition risks in the near vicinity of the patient, and of these risks, those attending nose and throat operations appeared to be the most important. It must not be assumed, however, that risk in the other positions can be dismissed as negligible, especially where ventilation is poor.

With hot wires, such as cauteries, ignition can occur within limits as wide a 3 - 80 per cent of ether in oxygen; whereas with sparks the limits are generally much narrower. Swan (45) continues by discussing the fact that second only to hot wires as a possible risk are the fizzling sparks which may occur between fine wire ends, such as at an intermittent break in a fine wire flexible. Although circuits incorporating the prescribed value of resistance may be safe as regards most forms of sparks, a special case arises when a circuit is completed through a single strand of fine wire which may get hot. Under certain conditions the temperature of the ether mixture may be thus raised above its ignition point, causing explosion.

According to Wardell (46) heaters that are constructed so that the elements are not vapor-proof, are a definite source of danger and should be subjected to the replacement by a vapor-proof
type of apparatus. Worn electric cords and cables, as well as those of loose connections present a serious danger and should be subjected to periodic inspection and replacement. Motors which are not enclosed and are not vapor-proof are a definite hazard.

Henderson (21) states that while using ethylene, the use of cautery near the head or the chest is very dangerous. However, the use of cautery in the abdomen is safe only when a screen or curtain is placed between it and the patient's face. But roentgenographic, diathermy, and other electrical apparatus always involve serious risk of initiating explosions when used in the presence of a volatile combustible anesthetic.

Electric lights and switches not of the vapor-proof type, or if the light bulbs are not screwed tightly into their fixtures, constitute a source of ignition, according to Wardell (46).

**HUMIDITY:** The relative humidity in an operating is another factor which must be considered, especially in attempting to eliminate the source of static spark. It has been found, according to Wardell (47), that the relative humidity in most operating rooms is very low. This fact is due in a large measure, to the unusually high temperatures which are prevalent in surgery. Wardell states that Lake investigated twelve operating rooms, the humidity of five being 25 and 30 per cent, and of six between 30 to 34 per cent, and only one was 40 per cent.

A humidity of from 55 - 60 per cent produces a film of
moisture over the surface of all the operating room equipment, and therefore, when static electricity is developed in some part of the apparatus, the charge may be possible dissipated by passing through the conducting adjacent parts to the ground (46).

Persons with dry skins are more prone to such accumulations of static because they do not have a sufficient film of moisture to conduct the charge to the ground (46).

Humidity, therefore, is a very important associative cause of increasing the hazard of fire and explosions, due to the above stated relationship with static electricity.

If we understand the possible sources of ignition of the volatile combustible anesthetic mixtures, it will be much easier to comprehend why certain postulated precautionary measures have been developed.
PREVENTION

When explosive risks may be anticipated, there are, of course, the following methods of anesthesia: Basal narcosis, local analgesia, nitrous oxide - oxygen, and chloroform. However, these methods of anesthesia may be inadvisable for the case concerned, and therefore one of the explosible inhalation anesthetics would be required. If this is the case, we will have to put into practice all the available procedures to lessen the explosion and fire hazard, and the chance of accident should be negligible.

STATIC ELECTRICITY: Livingstone (28) described a method of an attempt to keep all bodies in as near an equal potential as possible. This was in use in 1930, and probably is still used in some of the hospitals today. It consisted of anti-static tubing, which has a woven metallic lining, used between the large cylinders and gas machine and also for the face inhaler. This, they claimed, eliminated the accumulation of static charge on the inside of the tubing, which was produced by the passage of dry gas. The outside of the tubing was discharged by the application of special wire. A circular metal band made contact at each end of the spiral wire, with the rest of the apparatus. A metal contact was made to the patient's cheek by means of a small dangle chain. Woodbridge, Horton and Connell (6) explain that this presents a serious hazard by stating, "If when the mask is being removed, the interruption of the connection between the chain and
the face should occur simultaneously with some event tending to produce a charge on the patient or on the machine, there might well be a spark discharge between the face and the chain. The spark would occur directly in the spill of the explosive gas from the machine." Naturally there would also be a danger of break in continuity of the embedded wire, and possibility of spark from this point. This is illustrated in the accompanying figure.

Horton (6) has developed a device which has been named the 'Horton Intercoupler'. With the Intercouple Unit, it is possible to connect electrically, the patient, the anesthetist, the gas machine, and the operating table. Considering the fact that the greatest danger of ignition of explosive mixture is in the immediate vicinity of the patient's head, i.e., at the escape valve, and between the mask and the patient's face, we can feel assured that the major portion of the electrostatic potentials having dangerous possibilities is eliminated. The following two figures illustrate where this danger zone is and how the potentials are equalized by the Horton Intercoupler.
The Horton Intercoupler Unit provides five terminals and is so arranged that the resistance between any pair of terminals is one megohm (1,000,000 ohms). This high resistance naturally eliminates certain risks which are involved in direct coupling with wires or chains. If the surface of the floor is conductive, the unit is placed on the floor, allowing a one megohm leak in this manner. The other terminals are arranged as follows: One to the anesthetist and one to the patient by means of chain brace-
lets. The other two leads are connected to the operating table and to the gas machine, making certain that the contact is on bare metal and not through painted surfaces. If the floor is not conductive, the unit may be attached to the gas machine or to the operating table.

Although the group may receive more energy from any charged body than would one member alone, a considerable portion of the excess is dissipated harmlessly in the resistors, as illustrated by the accompanying figure taken from the works of Woodbridge, Horton, and Connell (6).

![Diagram](Image)

If the floor of the operating room is conductive, then any person entering the room will automatically join the inter-coupled group through the medium of the floor (6). Similarly, connection to the building ground will bring all grounded bodies to the same electrostatic potential or the intercoupled group. Also, if any unintercoupled person or object nears the region of possible escape of explosive gas without first making contact with one of the group at a point remote from such regions or to a grounding post, there will be much danger of spark ignition.
Draper (10) explained a system that the Colorado General Hospital was employing in 1928, to equalize the potentials around the well-recognized danger zone. They had four large galvanized iron mats laid upon the floor, to accommodate the operating table, surgeon, and his assistants, the sterile nurse, anesthetist and his apparatus. The mats were grounded by attaching them to a water pipe by means of a metal chain. He tested the efficiency of these mats by means of an electroscope, and found that it was highly efficient according to his findings. The Horton Intercoupler would seem, however, to be much more efficient in all respects, and is of reasonable price, not bulky, and proven to be highly effective in equalizing the potentials.

Livingstone, Engel and Shank (17) state that floors should be constructed in the form of a grill of small brass strips, which are jointed with brass, and in turn grounded to the building. The surface of the floor should be smooth, so that the metal strips are even with the surface.

Humidity has been discussed in the previous section of this paper, as to the source of ignition of gaseous mixture. The subject of humidity is very important in regard to static electricity. According to Livingstone (28), it has been found that raising humidity to 65 per cent air saturation is the best method of dissipating static charges outside of the anesthetic apparatus. However, any reading above 54 per cent in the operating rooms is considered a good humidity. In order to avoid working with a
false sense of security, the humidification should be tested at frequent intervals with some type of hygrometer (17) (21) (46).

Maintaining humidity to the required safety level, is either possible by an air conditioning system, or by the exhaust of some steam from an adjoining room at occasional intervals (21) (41).

There are several other precautions in attempting to lessen the hazard of static spark, according to Livingstone (28). The room should be large enough to prevent excessive brushing of garments against one another. This can be kept in mind if a new building is to be constructed.

They also discuss a factor which is generally agreed upon by the other authors, i.e., there should be a thorough rinsing of the tubing and face inhaler with water immediately before starting the anesthesia in order to remove the dust particles and to decrease the chance of building a high potential as the gas passes through. This procedure should be repeated as soon as the anesthesia is completed, hanging the tubes in a vertical position to allow all gas to escape. Connell (6) states that the rubber parts should be washed inside and out with a 4 per cent solution of calcium chloride to make them more conductive and eliminate the building up of a difference in potential. This solution has been found to be very irritating to the eyes, however, and it will also markedly tarnish the apparatus' metal parts.

Woodbridge, Horton, and Connell (6) explain that the woolen
blankets and silk and woolen outer garments should never be
allowed in the operating room. These garments may rub together and
then separate, to allow discharge of the potential built up in
the form of a static spark. Undergarments, however, do not consti-
tute an electrical hazard, according to these writers.

Dr. Weinberg (48) says, "Blankets and sheets which have
been brought into the operating room during the course of operation
should be unfolded at a safe distance from the anesthesia apparatus
and operating table to allow them to reach the same saturation as
other objects in the room."

Rubber soled or composition soled shoes should be prohib-
ited to anyone likely to come near the anesthetic apparatus. Like-
wise, no rubber tired stretcher should be allowed in the operating
room, until the flow of anesthesia has stopped, and the equipment
washed with water in the procedure already stated (17).

Cushions on an anesthetists stool constitutes such a serious
hazard that they should not be permitted (6).

ELECTRICAL APPARATUS: The growing use of electrical appar-
atus in operating rooms has created additional ignition hazards.
In general, let us say, all such equipment should be flame- and
vapor-proof (25).

Hospital personnel should insist upon the production of
safest equipment possible, as, according to Livingstone, Engel
and Shank (17), inquiry among some well-known x-ray manufacturers
revealed that there still exists a question as to the advisability
of using any combustible anesthetic around the so-called 'shock-proof' x-ray apparatus.

Frequent periodic checks should be made of all the electric equipment of the operating rooms, enabling one to find any exposed wire, poor connections, defective plug and sockets, and any defect in the apparatus in general that might be the source of electric 'shorts' and sparking.

According to one editorial, it was considered unwise to use diathermic apparatus if ether, or some other combustible anesthetic mixture was to be employed, as the cutting arc could ignite the combustible, (12). A blanket or other screen between the patients head and the point of application of the electrode was not considered a reliable safeguard by this author. Henderson (21) was of the opinion, however, that the use of cautery in the chest is dangerous while using ethylene, but if using it in the abdomen a screen or curtain placed between the cautery and head of the patient offered a safeguard. Dr. Weinberg (48) further qualifies this question by stating, "Low voltage actual cautery can be used with relative safety if a screen is placed between the patient's face and the cautery."

Electrical devices should be carefully selected. According to Wardell (46), motors which are fully enclosed and vapor-proof, as well as those of the self-starting induction type (except the single phase variety which incorporates an automatic centrifugal switch) may be permitted. Other authors state that no motors are
to be used in the operating room during administration of the combustible anesthetic, this even including the suction apparatus. It would be most logical to accept the view that motors should not be used in the presence of explosive mixtures, even though they are supposed to be flame- and vapor-proof. Instead, if the use of a motor is anticipated, one of the non-combustible anesthetics should be used.

The same general idea accompanies the use of a heater. If at all possible, electric heater should not be used with the flammable anesthetics. Wardell (46) describes an hermetically sealed electric heater for gas machines which have been accepted by the fire underwriters. However, if this heater is to be used, a careful inspection of it is necessary to make certain that it is in good condition, and all loose connections tightened.

All the light switches in the operating theatres should be of the vapor-proof type (mercury-arc switches) (17). Phillips (37) believes that they should each have a pilot light to denote whether or not any current is flowing through. Then no connection or disconnections should be made with the wall outlet plug until the pilot light is off, denoting no current flowing. If such an arrangement is not immediately convenient, care should be taken that the light bulbs are screwed tightly into their fixtures, and switches should not be turned off or on during the course of the anesthesia.

X-rays and fluoroscopes, according to Wardell (46), may
be used in the presence of flammable anesthetics provided they are of the self-contained, oil-submerged type, and further provided that the switches are oil-submerged or of the remote-control type. He does state that the 'radio' knife of high frequency, the diathermy, and the hot or electric cautery should not be used in the presence of such anesthetics. In x-ray apparatus, careful construction of the electrical part and of the method of connection is essential for use in the presence of inflammable anesthesia (12).

Telephones or telephone ringing devices should not be located within the operating rooms (17).

"Electric fans may be used with relative safety at a distance of more than fifteen feet", according to Dr. Weinberg (48). Considering the cause of ignition of the anesthesia accidents that have been reported, it was observed that many occurred during the use of a bronchoscope, or with some other endoscopic work; therefore, it would be only natural to draw a conclusion that prohibits the use of endoscopic instruments under combustible anesthetic mixtures.

**OPEN FLAMES:** This is, as has been stated before, a self-explanatory cause of explosions, and likewise the simple precautions need but merely a mention.

No lighted tobacco should be permitted in the operating room units, elevators, and recovery room. A gas pilot light for an emergency use is not permitted. Likewise, no gas plate should be used in the operating room during anesthesia. Generally, it
may be stated, that it is essential to prevent any source of open fire or flame, in order to secure a decrease in incidence in accidents.

**STORAGE OF ANESTHETIC CYLINDERS:** The safe storage of reserve supplies of combustible anesthetics such as ethylene, ethyl chloride, etc. or gases used in connection with anesthesia such as oxygen and carbon dioxide should not present a difficult problem. When the reserve supply consists of only a few cylinders of each of the gases, any room in the cellar or basement which is well ventilated and away from open lights or arcing or sparking electrical devices can safely serve as a place of storage, according to Newell (34). It should be borne in mind that ethylene or similar combustible anesthetics must not be stored in close proximity to such gases as oxygen and nitrous oxide. If the room is of good size they may be segregated on the opposite side of the room safely (34), but it is better practice to store them in separate rooms.

Large quantities of combustible anesthetics in cylinder form should preferably be stored in a room or compartment on the roof or in an outside building, Newell (34). Supplies should be kept cool and in a well ventilated room.

Placards should warn of the presence of explosive gas, and should read 'No Smoking, Flames, or Cautery in this vicinity'.

**VENTILATION:** Thorough ventilation with frequent air changes is important during the use of anesthetics. Drafts,
however, must be avoided to prevent chilling of the patient. The air currents, according to Livingstone, Engel and Shank (17) should be directed from the head of the patient away from the operating table and any cautery or sparking device, if they are unwisely in use.

**MISCELLANEOUS FEATURES OF PREVENTATIVE TECHNIC:** It is well for the anesthetist to keep occasional attention on the rebreathing bag, because if the bag does not maintain its original excursion or fullness, this immediately enables him to check for a leak in the gas apparatus. This is of common occurrence between the mask and face of the patient.

It is an unwise procedure to flush the patient's lungs with rich oxygen at the end of the anesthesia, as the rapid flow of oxygen may generate a spark (48).

**CONCLUSION:** The field of explosion and fire hazard with the combustible anesthetics has a large scope, and the proposals that are presented for the control of such hazards are increasing monthly.

Instruction in the administration of anesthetics is very limited in most of the medical schools of today. In order to establish a better safeguard in handling the anesthetics, I would say that the subject of anesthesia should be a definite course in the medical schools, with some emphasis placed on the hazards to be encountered.

As was stated in the introduction, it would be unlikely
that any code or summary of procedure could be written to take into account every conceivable dangerous combination of factors. Therefore, it would seem superfluous to attempt to write a summary such as this regarding this subject.
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