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PRESENT STATUS OF THE PROBLEM OF PREVENTING ANESTHETIC EXPLOSIONS *

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RECENT statistics have sometimes been interpreted as indicating that the more recent inhalation anesthetics, namely, ethylene and cyclopropane, have brought with them a considerable increase in the hazard of death or injury by explosion. It would be not only erroneous, it would be actually dangerous, to proceed on the assumption that ether does not also involve this hazard. Fortunately, anesthetic explosions are so rare that statistics are inadequate to show whether one gas is relatively more dangerous than another, or whether there is an increasing frequency of occurrence of anesthetic explosions (1). In any case, such an increase could not properly be construed as demonstrating that the new gases are more likely to explode than those previously used. It must be remembered that the new gases are not the only variables which have been brought into the problem. There are new forms of surgical equipment and new technics in surgical practice which may well increase the possibility of ignition. Should it be a fact that there is a growing likelihood of explosion, it would be quite as logical to attribute it to the increased use of rubber soled shoes in the operating room as to the increased use of cyclopropane or ethylene.

This consideration of relative hazard is presented in order that there shall be no misconception as to the reason behind the present investigation. It accepts the fact that all the hydrocarbon anesthetics form explosive mixtures. The problem set is to devise ways and means of reducing to a minimum the risk of explosion inherent in any one of them. This requires that the fundamental factors contributing to this hazard be well understood. In the past, specific remedies have been proposed to avoid the recurrence of specific causes of explosion. In some cases these remedies have increased the hazard due to other causes. We must, therefore, consider the whole problem in terms as broadly basic as possible, in order to devise the most generally effec-

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tive safeguards and to disclose any potential hazards which might lie hidden in future new technics or new equipment.

There appear to be three main approaches to the problem. The most obvious is to endeavor to prevent the ignition of such gases. Another is to prepare and maintain the anesthetic mixture so that its composition lies outside the explosive range. Finally, there is the possibility of developing quenching devices which, when installed on the anesthesia equipment, shall extinguish any explosion originating at a distance from the patient and thus prevent injury to him.

Protection should be sought along all three of these lines. Reliance upon a single defense appears unjustified if more are available. Both the infrequent occurrence of anesthetic explosions and studies of the conditions under which they have taken place indicate clearly that they result when a number of events, in themselves of infrequent occurrence coincide in an improbable manner. To reduce the frequency of occurrence of a single group of these events is to reduce by a large factor the probability of an undesired coincidence. To reduce the frequency of two or more such groups is to reduce the probability by the product of the factors applying to the individual groups. This is straightforward statistical reasoning. All three of the approaches mentioned are being examined with encouraging results.

PREVENTION OF IGNITION

In discussing measures for preventing the explosion of anesthetic mixtures we must consider the possibility of ignition by any of the following causes: by direct contact with an open flame or with a hot body; by a spark from the electric power circuits; by electrostatic discharge; and by spontaneous combustion.

Ignition by Hot Body

It is believed that no precautions which may be taken are adequate to eliminate the danger of inflammable anesthetics in the presence of any kindling agent such as an open flame or hot body. This applies both to the open drop method and to the closed system method, either circulatory or to-and-fro.

It has been estimated that any explosive gas escaping from a closed rebreathing system becomes so diluted upon entering the atmosphere that it is explosive only within a distance of approximately one foot from the leak. Theoretically, therefore, it might be considered safe to use these anesthetic agents and cautery equipment simultaneously, provided they were kept well separated. However, it is impossible to specify a safe separation with any assurance. Gas leaks may continue for some time before being detected and the movements of any escaped gas are subject to accidental and uncontrollable conditions. Consequently it is felt that it is unsafe to use hydrocarbon anesthetics for operations requiring cautery. Where it can not be avoided, shielding by drapes and judicious ventilation provide some measure of safety.

It is obvious that lighted cigarettes, matches, open flames and similar kindling agents should never be allowed in an operating room nor in any other place where explosive anesthetic gases are present.

Electrical Wiring

A spark accompanies every operation of a switch in a circuit which is carrying current. Sparks also result from the withdrawal or insertion of an attachment plug at an outlet. The only method approved by the National Board of Fire Underwriters for preventing these sparks from causing explosions is to enclose those portions of the circuit at which sparks may occur. The so-called "explosion-proof" fittings are designed in such a way that any sparks are confined inside an enclosure from which a flame can not escape. The objective is not to keep inflammable gases from reaching the spark, but to segregate any such gas in which combustion may start so that it shall not extend to the outside atmosphere.

In this connection it should be pointed out that the various types of mercury switch which are frequently recommended for use in operating rooms do not satisfy the requirements of the National Electrical Code, on which the approval of the Fire Underwriters is based. These mercury switches do, it is true, enclose the point at which the spark takes place in such a manner that they normally exclude any vapors or gases which may be present in the atmosphere. To this extent they provide a considerable measure of protection. They offer no more protection than do the ordinary snap switches against interruptions of the circuit which may result from defects in the switch. For this reason none of the mercury type switches is considered to afford complete protection unless it is made explosion-proof by enclosure in a flame-tight housing.

There are a number of explosion-proof switches and explosion-proof attachment plug receptacles on the market. They will be found catalogued in the "List of Inspected Electrical Equipment" published by the Underwriters' Laboratories, Incorporated. Those which are considered satisfactory for use in operating rooms, in accordance with the regulations of the National Electrical Code, are listed under Class I, Group C, in the section covering equipment for use in hazardous locations.

Having installed explosion-proof fittings at the wall, it is obvious that all portable equipment to be attached thereto should include no means whereby the circuit may be opened unless it is also of the explosion-proof type. It is rather startling to find, as is possible in many operating rooms, an extension cord, having an ordinary cord connector, plugged in to an elaborate explosion-proof outlet. In these cases it is evident that safeguards have been provided, at great expense, at points where there is little likelihood that an explosive mixture will ever be found, but that all precautions have been ignored in regions where an indisputable hazard exists.

In addition to the sparks which accompany the normal use of electrical circuits, sparks may result from defects in the electrical equipment. Fortunately the safeguards which good practice requires for the prevention of electrical shock also afford protection against these accidental sparks. It is doubly important, therefore, to consider carefully the details which should be taken into account in the installation and use of electrical equipment.

Complete specifications covering installations believed to provide maximum safety are given in the regulations of the National Electrical Code. These require that one of the two wires carrying current be grounded at the main distributing panel. The term "ground" is understood to mean direct electrical connection to some metallic body having good contact with the earth. It, therefore, implies good electrical contact with any metallic frame of the building and hence with heating, ventilating and plumbing systems. From this it is clear that a person making accidental contact with any grounded metallic object, such as a plumbing fixture, thereby establishes direct electrical contact with one side of the power circuit. Should he make contact at the same time with the other side of the circuit, referred to as the ungrounded or live side, he will receive an electrical shock. Similarly, a direct contact between any grounded object and this live side of the line must inevitably result in a spark or, unless the fuse blows, in a sustained arc. For these reasons the ungrounded side of the line is required to be connected to that portion of the current-carrying element of the equipment which is least likely to come in contact with persons or which, through defective insulation, is least likely to come in contact with the frame or housing of the equipment.

To provide additional protection both of the current-carrying wires are required to be enclosed in a metallic conduit which is connected to the building ground at the distributing panel. The housing of the equipment is electrically connected to this conduit, and hence to ground. To insure that both conduit and housing are always at ground potential no fuse is permitted in this connection. There should be no fuse between the grounded current-carrying wire and the building ground.

When this method of wiring is employed it is clear that the housing of the equipment must always be at ground potential regardless of any defects which may develop. In other words, it can never be at the potential of the live side of the line. As a result both the shock and the spark hazards are greatly reduced.

The method of installation described above is almost universally employed in this country for permanently installed equipment. Unfortunately it is rarely employed for portable apparatus. It is particularly desirable in an operating room where the portable equipment is more likely to be found in a hazardous location than is the permanently installed equipment.

It is a simple matter to extend these safeguards to portable equipment. In the permanently installed wiring there are three conductors: the grounded wire, the live wire, and the grounded conduit. To continue these to the portable equipment, therefore, it is necessary that the receptacles, the attachment plugs and the extension cords all be of the three-conductor type and that the receptacles and plugs be so polarized that each wire in the extension cord is always connected to the proper conductor of the permanent installation.

Commercial forms of receptacles and plugs are generally available for use in systems having a third-wire ground. If of substantial construction, with provision against accidental withdrawal, they offer very effective protection against both shock and spark which may result from defects in equipment. They offer no protection, *per se,* against sparks which accompany the opening of the circuit by the removal of the plug from the receptacle. Complete protection against sparks is obtained only through the installation of the specially designed explosion-proof fittings and switches.

The National Electrical Code contains explicit specifications for the installation of electrical wiring and equipment to be used in hazardous locations, which include operating rooms. These specifications cover both permanent fixtures and portable equipment. In many localities compliance with them is mandatory although enforcement is not as strict for portable equipment as for that which is permanently installed. This code represents the coordinated effort of many groups. Long experience and broad knowledge went into its preparation. Its recommendations should be scrupulously followed by every hospital.

Electrostatics

Any discussion of the electrostatic hazard in anesthesia may take as a starting point one incontrovertible fact. A spark between two bodies can occur only when there is no electrical path of good conductivity between them. If there is even moderate conductivity any charge which might otherwise collect on one will promptly spread over both in such a manner that they will come to the same electrostatic potential. In fact, every spark is a manifestation of the natural tendency of electrostatic charge to distribute itself in such a way as to bring adjoining conducting surfaces to the same potential. Having completed this distribution the potentials of various points on the conducting surface are said to be equalized. Sparks can occur only when there is no other path available for this equalization.

To prevent sparks between conductive bodies, then, it is sufficient merely to provide a suitable path for potential equalization. If all conductive bodies in an operating room are coupled by metallic conductors there can never be a spark between them.

This solution to the problem has been suggested many times. However, certain factors have to be taken into account in its application. One is that the mechanical difficulty of electrically connecting all persons and objects in the operating room is considerable and likely to be hazardous in itself. Another is that if all bodies in an operating room are electrically intercoupled any person thereby suffers increased risk of electric shock through contact with the ungrounded side of the power circuits.

High Resistance Intercoupling

To provide a simple remedy, which takes these factors into account, the use of high resistance intercoupling for a limited group was recommended. This method, suggested somewhat over a year ago, has been fully described elsewhere (2). Briefly, it involves a small electrical unit having a number of terminals. Between any two of these terminals is a conductive path having a resistance of one megohm (1,000,000 ohms). The unit is so designed that the resistance between any two terminals is unaffected by any connection between other terminals. The objective is to intercouple those bodies most likely to be present in the area most likely to contain an explosive mixture of gases. The bodies usually intercoupled are the patient, the anesthetist, the gas machine and the operating table.

A resistance of one megohm is sufficiently low to equalize electrostatic potentials promptly. At the same time it is sufficiently high to prevent shock in the event that the intercoupler accidentally makes contact between a person and the lighting circuit. Although the ideal intercoupler, from the standpoint of equalizing potentials, should have negligible resistance, one megohm is actually reasonably effective. Measurements made to determine the rate at which one megohm will equalize the potential on the body of a person or on any of the major objects commonly found in an operating room show that any potential on such a body will be reduced to one per cent. in an interval not exceeding one thousandth of a second.

It is frequently asked, "Should the intercoupled group be grounded?" The answer is that, on the average, there will be less likelihood of an electrostatic discharge with the intercoupled group grounded than with it ungrounded. A spark discharge can occur between any member of the intercoupled group and any outside body which is at a different potential. Now any outside body, on the average, is more likely to be at ground potential than at any other single potential. It is apparent, therefore, that if the intercoupled group is maintained at ground potential it is least likely to receive a spark from any external body. As long as the ground connection is through a high resistance it is accompanied by no increase in the hazard of electric shock.

For these reasons five terminals are now provided on all intercouplers.

If the fifth terminal is required for the intercoupling of a third person, direct grounding of the table or of the anesthesia machine may be used. This does not increase the hazard of shock through the intercoupler, as there is still one megohm in the connection to each person. It is true, of course, that any person making direct contact with a grounded table, as with any other grounded conductor, will receive a shock should he also come in direct contact with the live side of the power circuit.

Experience during the past year or more, in a large number of operating rooms, has disclosed nothing to indicate that the intercoupler fails to function exactly as intended. There have been no reports of discharges of sparks of the type it was designed to eliminate. There have been no reports of electrical shock received as a result of its use. There have been no reports of any fatal explosion during anesthesias protected by it. In fact, of nineteen explosions during the 1939–1940 season, only one occurred in the presence of an intercoupler. This particular explosion is believed to have resulted from a spark of a type discussed later, against which the intercoupler is known to offer no protection.

In spite of its apparent success we must not lose sight of the fact that the purpose of high resistance intercoupling is merely to provide an immediately available partial remedy which may be used until more complete and permanent remedies are installed.

Conductive Flooring

As a more permanent and inclusive method of intercoupling, an electrically conductive floor is ideal. It does not add to the confusion of the operating room by a network of wires enmeshing the occupants. It makes almost no demands upon human behavior. Provided shoes with conductive soles are worn, no person entering the operating room can fail to make electrical connection with all other persons and objects there present.

The electrical characteristics of a conductive flooring require careful consideration. Both the distances between the objects which it interconnects and the characteristics of the contacts which they make with it vary greatly. Therefore, the flooring should be as highly conductive as is practicable in order that the maximum resistance which is likely to be encountered shall still be low enough to equalize potentials promptly.

The objection may be made that a highly conductive flooring greatly increases the hazard of shock from the power circuits. This hazard does not arise, however, if the wiring complies with the regulations of the National Electrical Code. In fact, under these conditions, the necessity for high resistance in any intercoupling system vanishes and five ordinary wires, fastened to the operating table, become a better means of intercoupling than the high resistance intercoupler.

There remains the question of whether or not a conductive floor should be grounded. It has been argued by some that it should be ungrounded or else grounded only through a high resistance in order to reduce the hazard of shock should a person in contact with the floor also make contact with the ungrounded side of the power circuit. The wiring regulations, however, demand that the outer metallic portions of all electrical equipment be at ground potential. This immediately fixes the necessary potential of the flooring. The fundamental purpose of intercoupling is to maintain all objects in the room at a single potential; some objects in the room are required to be at ground potential; hence, all objects in the room must be at ground potential.

One method of constructing a floor having conductive properties, which has been used quite extensively, is to incorporate metal strips in a flooring of terrazzo or of tile. Measurements made on a large number of such floors have shown that the resistance of any intercoupling path thus provided is both excessively high and excessively variable. In fact, a number of fatal explosions, believed to have been of electrostatic origin, have taken place in operating rooms equipped with these floors.

An effective solution to this problem is to be found in a flooring of conductive rubber developed by the Boston Woven Hose and Rubber Company at the request of the Massachusetts Institute of Technology Committee on Anesthetic Hazards. To meet the desired performance specifications there was developed a special rubber compound having both the high conductivity needed for intercoupling and the mechanical properties needed for a flooring material. This material has high intrinsic conductivity. To insure that there shall be low resistance between all bodies and ground, independent of the length of flooring separating them, a highly conductive wire screening is imbedded in the finished sheet. As a result the resistance between any two points on the surface, as measured between metal electrodes 2 inches in diameter, is under 100 ohms. However, the resistance between any two objects chosen at random is likely to vary considerably, depending chiefly on the area in contact with the flooring, on the material making contact, and on the pressure.

Another method of obtaining a conductive flooring is to imbed a copper screening in the upper surface of a layer of cement on which thin porous tiles are laid. The conductivity of such a flooring depends to a large extent upon the moisture which it absorbs. Therefore, it varies with the relative humidity and with the temperature of the atmosphere. Measurements made on a few samples of this flooring indicate that it is less conductive than the conductive rubber described above. It is, therefore, believed to be less effective.

Attempts have been made to improve the conductivity of both tile and terrazzo flooring by treatment with calcium chloride. Repeated washings with a solution containing 2 to 4 per cent. calcium chloride will cause the floor to retain more moisture than would otherwise be the case. This moisture, moreover, is highly conductive because of the presence of the salt. Even with these treatments, however, the resistance of tile or of terrazzo flooring remains dangerously high and variable.

In considering the relative advantages of a conductive rubber flooring and of a specially prepared tile or terrazzo floor it is necessary to remember that it is possible to produce sparks from tile by striking them with certain materials, particularly steel. Persons having nails or metal plates on their shoes should not enter an operating room having a tiled floor. Metal furniture should be so designed that its feet can not strike sparks from the floor. If drag chains are used on any of the furnishings they must be of bronze rather than of iron or steel.

Shoes

Given a conductive flooring, it is necessary to make sure that all persons and objects in the room make electrical contact with it. Rubber-soled shoes act as an effective insulating barrier against the equalization of potential. They are also effective generators of static electricity. Crepe-soled shoes are the worst offenders in this regard.

Shoes with soles of rubber or composition should never be permitted in an operating room unless some effective means is employed to annul their electrostatic action. This has been done by a number of people by means of a small drag chain worn on each shoe. Although this idea appears startling at first glance it does not involve any particular inconvenience. In any design of drag chain some provision must be made for connecting the portion of the chain making contact with the floor to the foot of the wearer. A metal plate inside the shoe is entirely adequate for this purpose.

Unfortunately, leather soles are neither quite good enough nor quite bad enough to permit a clean-cut decision regarding their use. Observations of the resistance of leather soles have been in progress for a number of months. During the winter fairly acceptable values were found with the majority of samples. As streets and sidewalks become dried out with summer, however, soles contain less moisture and a marked increase in resistance is observed. In general, the resistance between ground and the body of a person wearing leather-soled shoes and standing on a conductive rubber flooring having a grounded mesh is of the order of one megohm. In many cases, particularly with well-worn shoes in the winter, the resistance may be as low as 10,000 ohms. In the summer, however, resistances as high as 10 megohms are frequently found.

One solution of this difficulty is to measure the conductivity of shoes to be worn in the operating room. This can be done simply and at trivial cost. Two squares of conductive rubber flooring are placed side by side on an insulating support, such as a rectangle of non-conductive rubber. A wire is brought from the copper mesh imbedded in each of the conductive squares. These wires are connected to any suitable resistance-measuring device, such as an ohmeter. The instrument chosen should have an accuracy of at least 10 per cent. for resistances between 0.5 and 10 megohms. To determine the resistance between the body of a person and ground he stands with one foot on each of the conductive squares. The resistance as measured between the two wires is then four times the resistance between his body and ground when he is standing with both feet on a conductive floor. It is believed that this method of measurement is more reliable than one in which the person stands with both feet upon a single conducting element and completes the circuit by an electrode held in the hand.

Although it is a simple matter to determine the effective conductivity through shoes, it is by no means as easy to specify an acceptable value. The question becomes one of deciding upon the length of interval during which a charge may safely be retained by the body of the wearer. Any interval is too long if it includes the instant at which a spark jumps. If the resistance of the shoe soles is one megohm, any potential on the body of the wearer will fall to one per cent. in one thousandth of a second. If the resistance is 10 megohms it will require 10 thousandths of a second, or 0.01 second, for the same drop to take place. Although it would be desirable to set the maximum allowable resistance between the body and ground at something under 100,000 ohms, it must be conceded that resistances as high as one megohm are probably tolerable.

The ideal shoe for wear in the operating room is one having a sole of the same conductive rubber as that developed for the flooring. Soles of this material have already been made and tests have shown that they meet all requirements. At the moment the only difficulties are those of manufacture and distribution.

Furniture

At the present time it is undoubtedly true that there are very few pieces of equipment to be found in any operating room which are not insulated from the floor. Heavy equipment, such as the operating table, stretchers, instrument stands and the like, have rubber-tired casters. Smaller furnishings, such as stools and small tables, have rubber feet of the type commonly used as crutch tips. This effective insulation of large objects constitutes a grave hazard. No hospital can profess to have adopted adequate precautions as long as this situation exists. An ideal remedy is to make the tires and crutch tips of conductive rubber. Again, as with shoe soles, difficulties arise with details of manufacture and distribution.

The simplest alternative solution is some form of drag chain. It must be recognized, however, that chains are by no means ideal electrical conductors. The large number of joints and the possibility of collecting oil or other insulating material at these joints result in frequent interruptions of the electrical continuity. This is offset to some extent by the active motion of the links against each other. To insure reasonable continuity, however, it is recommended that the actual drag be made of a group of from three to six individual small chains of very nearly the same length. One end of each should be fastened to a common terminal at one end of the equipment in question; the other ends should be fastened to a similar common terminal at the other end of the equipment. The length of the chains should be so chosen that, as they hang naturally, the major portion is in contact with the flooring. They should not, however, extend outside the limits of the equipment as it is being moved.

All drag chains should be made of bronze in order to prevent sparks due to any striking contact with tile, marble or other flint-like substances. Many bronze chains available on the open market are protected by an insulating lacquer coating which makes them worthless as electrical connectors.

With many types of furniture it is unnecessary to go so far as to install a drag chain. Stools and tables, for example, now equipped with rubber crutch-tips may be modified by the substitution of metal feet. Many satisfactory varieties of metal feet are available. In general, they consist of round plates which are slightly convex on the bottom and which slide smoothly over ordinary flooring surfaces. Such feet must, of course, be in electrical contact with all metal parts of the unit.

Practically all surgeons' platforms, or "step-ups," are insulators. If they have metal frames they almost invariably have rubber crutch-tip feet and rubber matting surfaces. They present an especially serious hazard. By stepping upon a platform the potential energy represented by an electrostatic charge on a person's body may be increased as much as two-fold. Platforms can generally be made electrically conducting by removing any rubber feet with which they may be supplied, installing suitable metal feet, and replacing any non-conducting rubber matting by a matting of conductive rubber. If the conductive rubber is attached to a metal surface by an ordinary rubber cement, electrical contact must be provided between the imbedded copper screen and the metal frame.

Pads and Pillows

The operating table pad presents another serious hazard. In spite of all the conductive flooring and drag chains which may have been installed, the patient lying on the customary pad is as completely isolated, electrically, as though he had been levitated. In moving a patient from the stretcher to the operating table he may acquire and retain an electrostatic charge of dangerous magnitude. A simple and effective means of eliminating this hazard is to provide an intercoupling link permanently attached to the operating table. This may be a bracelet of flexible wire mesh permanently attached to a substantial flexible wire similar to those used in the high resistance intercoupler unit. There is, of course, no occasion to provide a high resistance in this intercoupling.

This direct connection of patient and table is believed to be superior to the use of fabric covers which have been treated with calcium chloride. Such an arrangement does not provide as complete electrical interconnection as does the flexible wire and bracelet. Moreover, it is known that the conductivity of fabrics treated with calcium chloride is greatly influenced by humidity and temperature. Also, should an untreated cover find its way into the operating room, there would be nothing in its appearance to indicate that it did not contain the safeguard which it was assumed to carry.

The situation arising with the operating table pad exists with other insulating pads or cushions. At least one fatal explosion is believed to have resulted directly from the use of a sponge-rubber cushion on the stool used by the anesthetist. Such cushions not only constitute barriers preventing the equalization of electrostatic potentials, but also constitute the most effective generators of electrostatic charge. All such pads which are not necessary should be kept out of the operating room.

Pillows of non-conductive rubber introduce a similar hazard. In particular, there should be a prohibition against removing a fabric case from a rubber pillow in the operating room or in any room containing anesthetic equipment. This would be almost certain to leave both materials with charges of dangerous magnitude.

Fabrics

From the foregoing it is evident that the danger of electrostatic discharge arises almost wholly because of the presence of rubber in the operating room. Almost the only other materials contributing to this hazard are the fabrics.

It has been recognized for many years that frictional contacts between wool and other insulators are capable of producing dangerously high electrostatic potentials. Because of this the customary prohibition against the use of woolen blankets in the operating room should most certainly remain in force.

Silk, rayon and other silk substitutes, including "sharkskin," are such effective generators of static that they should never be allowed in the operating room.

Undergarments of either silk or wool involve a hazard which is negligible when compared to that arising from the use of these fabrics in outer garments. While it is true that frictional contact between an outer garment of cotton and an undergarment of silk will produce charges on both, it is also true that there will be no electrostatic potential, and hence no discharge, as long as these garments remain in contact. For this reason it is felt that it is unnecessary to impose any restrictions on the choice of materials used for undergarments by the operating room personnel.

Charged Insulators

In the foregoing discussion we have limited our attention to discharges between conducting bodies. Sparks between insulators are almost invariably of small magnitude. The crackling sounds which frequently accompany the stroking of a cat's back, or the separation of woolen fabrics from silk, attest that such discharges can occur. However, electricity can not move over the surface of an insulator with sufficient freedom to maintain a discharge of appreciable magnitude. The chief danger of a charged insulator results from the charges which it may induce on neighboring conductive bodies. Practically all charges on conductors arise in this way. Discharges between the conductors, as we have seen, may be effectively prevented by intercoupling. There remains, however, one hazard due to a charged insulator which no amount of intercoupling can ever annul. If an insulator, such as a rubber bag, is charged by frictional contact with some fabric, the charge is distributed over the surface at random. Because of the non-conducting character of the surface, equalization can not take place. Large differences of potential may appear between points separated by short distances. As the insulator is flexed it is entirely possible for minute discharges to take place between points on its surface. This, however, is not the major hazard. The entire charge retained by the surface of the insulator acts as a single aggregate charge in affecting neighboring bodies. It is entirely possible for the mass effect of a charged insulator to be so great that it will cause a spark discharge from a sharp point on a neighboring conductor. It should be noted that this discharge does not take place between two conductors but rather from one special form of conductor to the randomly distributed charge on the insulator. Discharges of considerable magnitude have been found between a grounded conductor having a sharp point and a charged rubber tube 6 or 8 inches distant.

This is a situation for which intercoupling provides no remedy. Any charge distributed over an insulating surface cannot be removed unless all portions of the surface are brought into contact with a conductor. The only really effective safeguard against this hazard is to keep insulating materials out of the operating room. This, of course, is impracticable at the present time. The alternative is to treat the surfaces so that they are conductive. If all rubber parts are rinsed with a 2 per cent. solution of calcium chloride prior to use, they will be unlikely to acquire surface charges. Care must be taken, however, to make sure that parts which are to be in contact with any portion of the human body shall not retain an excess of calcium chloride. This is known to cause appreciable skin irritation. While it is desirable as a precaution to rinse the mask, tubes and bag of the anesthesia machine, it is a fact that any surfaces of these parts which have been in contact with respired air are reasonably conductive. Respired air has both a high water vapor content and a high carbon dioxide content. This makes any moisture film deposited more conductive than would otherwise be the case. There are under development semi-permanent coatings of a conductive nature for application to rubber parts. It is hoped that there will also be available shortly a conductive rubber which is sufficiently soft and flexible for use in anesthesia equipment and for mattress and pillow covers.

A question has frequently been raised as to the effect of rubber gloves. It is true that rubber gloves are insulators and may act as barriers preventing the equalization of potentials. This is not serious where other conducting paths are available. Frictional contact between a rubber glove and any fabric may also leave a slight charge on the latter. The close contact of the rubber glove with the body of the wearer, however, prevents any charge on the glove from exerting a mass effect. Such charge is immediately annulled, as far as its surroundings are concerned, by the induction of an equal and opposite charge on the hand. For this reason it is believed that rubber gloves do not contribute materially to the hazard of electrostatic discharge. The same argument applies to silk stockings.

The Anesthesia Machine

Much imagination has, from time to time, been called into play in an effort to explain certain anesthetic explosions of doubtful origin. In particular, suspicion has frequently been cast on the anesthesia machine itself. Many possible sources of electrostatic charge have been suggested. For example, it is known that paint guns operated by pneumatic pressure frequently develop considerable electrostatic charge. This suggests to some that the flow of gas within the anesthesia machine may likewise produce electrostatic charge. Of course, such flow can produce no charge on grounded metal parts. The only possible way in which a charge could be developed would be for gas to impinge at high velocity upon some insulated conductor or to emerge from some insulated conducting nozzle. It has been suggested that certain types of flow indicators, in which a ball rises and falls within a tapered glass tube, might generate static. This element is virtually floating on the moving gas stream. Should it become charged, there is the possibility of a discharge as it approaches any metal fittings.

To examine this situation there has been constructed in the Laboratories of Biological Engineering at the Massachusetts Institute of Technology an electrostatic voltmeter of such sensitivity that it can measure charges such as those developed by a drop of mercury sliding down a glass tube, or those produced on the walls of a blood-pressure manometer. Using this voltmeter a careful examination has been made of a Connell deluxe anesthesia machine. Particular attention was given to the flow indicators and also to the soda lime canister which is insulated by rubber gaskets from the remainder of the equipment. Oxygen gas was allowed to flow through the various orifices at normal velocities and at velocities many times higher than normal. During all of these tests no charge was detected on any part. Gas escaping at high velocity from one of the breathing tubes failed to produce a charge on the metal ferrule at the end. By flicking the tube lightly with a handkerchief, however, this ferrule immediately assumed a very appreciable potential. It is believed, therefore, that the anesthesia machine itself, as normally used, is not responsible for the ignition of anesthetic mixtures.

There are situations, however, in some types of machines, which may ignite the mixture. In fact, it is believed that several explosions have resulted from the use of metal collars on breathing bags. Assume an electrostatic charge to be distributed over the entire machine. Because of moisture on rubber parts this charge will distribute in such a way that no difference of potential exists between parts of the machine or between the machine and the patient. As the bag expands and contracts with respiration, charge must pass back and forth from the bag to the remainder of the machine in order to maintain this equilibrium. If, however, the collar of the bag becomes separated from the machine, the bag is immediately isolated, electrically, and this transfer of charge can no longer take place. At the same time the escape of gas permits the collapse of the bag. As the charge can now no longer pass between the bag and the machine, the change in electrical capacitance consequent upon the collapse must produce a potential difference between the collar and the machine. A spark discharge, therefore, might well take place. Such a spark must inevitably occur directly in the stream of escaping gas and would almost certainly cause its ignition.

This situation, which underlies the now prevalent warning against removing the bag from the anesthesia machine, may be remedied in either one of two ways. The bag may be made completely of rubber so that it has no metal ferrule from which a spark can jump, or it may be so firmly attached to the machine that it can neither fall off nor be easily removed.

Air Conditioning

It is common knowledge that electrostatic discharges are rarely observed during the summer months and that this is due to the high relative humidity. Although relative humidities of 55 per cent. or higher have been recommended as a safeguard against electrostatic sparks, a number of fatal anesthetic explosions have occurred in atmospheres having relative humidities as high as 65 per cent. Careful measurements have shown that potentials of several thousand volts can be developed and retained in these atmospheres. Further examination has shown that the discrepancy arises because of the fact that air conditioning, when carried out by any of the so-called air-washing equipments, so reduces the carbon dioxide content that any moisture films formed in the operating room are not sufficiently conductive to provide adequate equalization of potential. In the presence of conductive flooring and other safeguards previously described, high humidity, without washing, is an additional but unnecessary safeguard.

COMBUSTIBLE PROPERTIES OF ANESTHETIC MIXTURES

The preceding discussion has been directed at avoiding causes of ignition. It may be equally profitable to see what can be done toward avoiding mixtures which are combustible. Data on the explosive limits of the various hydrocarbon anesthetics, when mixed with air or with oxygen, have been published frequently (3). Further work is actively in progress at the United States Bureau of Mines and at the Massachusetts Institute of Technology. The results thus far obtained are most promising in that they point to the possibility of preparing anesthetic mixtures which are non-inflammable.

A report recently published by the United States Bureau of Mines (4) gives very complete data on mixtures containing cyclopropane, oxygen and nitrogen and on mixtures containing cyclopropane, oxygen and helium. These show that over a considerable range of compositions, mixtures of these last three components, which are suitable for anesthetic use, are non-inflammable.

Work in progress at the Massachusetts Institute of Technology includes studies of four-component mixtures. Although this is by no means complete it has already gone far enough to show that the hazard of explosions may be reduced materially by using mixtures containing cyclopropane, ethylene and oxygen in proper combination. The addition of a fourth gas such as nitrogen, helium or hydrogen has been shown to increase the non-explosive range even further.

In any attempt to use these mixtures one important fact must be kept in mind. A mixture which is non-inflammable while within the closed system may still form an explosive mixture if it leaks into the air. Risk of injury to the patient by ignition outside the system, however, is small.

Any mention of developments in this direction at the moment should be considered primarily as a report of progress. Much remains to be done before these results may be utilized in daily anesthesia. Perhaps the greatest difficulty to be removed is in connection with the accurate maintenance of the correct mixture. The compositions of gaseous mixtures which are satisfactory as anesthetics and which, at the same time are non-explosive fall within a narrow range. Changes in composition during anesthesia, due to selective absorption or to other causes, may easily result in combustible mixtures. Before practical results can be derived from this portion of the investigation it appears that some form of indicating device will be required by which the composition of the anesthetic gas may be easily and accurately determined. Several possible types of indicators are under consideration and there is a reasonable prospect that an acceptable device may be forthcoming.

FLAME BARRIERS

In spite of all that may be done to prevent explosions of anesthetic gases the fact remains that explosive mixtures may be formed and that they may be ignited. Experience has shown that a significant proportion of all anesthetic explosions originate in parts of the system which are remote from the patient. The incorporation of some form of flame barrier at a suitable point, such as the junction between the breathing tubes and the anesthesia machine, might easily prevent injury to the patient in these cases. The use of flame barriers is well understood in the technology of gaseous combustion. Existing barriers are not, however, applicable to the present problem without change. In the first place they are inadequate to extinguish certain mixtures of cyclopropane and oxygen. It is gratifying to be able to report that experimental barriers have been constructed which have proved capable of extinguishing any mixture of cyclopropane and oxygen.

In the second place they must not offer significant obstruction to respiration. Finally, they must not permit injurious pressure pulses to pass. Because of the success with which automobile mufflers, gun silencers and other acoustical filters have been developed, it is confidently expected that a suitable pulse suppressor can be designed.

CONCLUSION

Although many phases of the problem of the prevention of explosions of anesthetic gases are clearly far from being satisfactorily solved, it is felt that sufficient progress has been made to justify the statement that their use may be continued with reasonable safety. If known and easily applied precautions are taken with respect to the electrical wiring and to the elimination of electrostatic discharge, it is believed that the already low frequency of anesthetic explosions will be reduced to a negligible figure. In spite of these precautions, however, there is one fact which must not be overlooked. The chief value in adequate physical equipment is not that it makes eternal vigilance unnecessary but that it makes eternal vigilance effective.

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