Anesthetic Explosions: A Continuing Threat

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An elderly surgeon, now demised, had opposed the "nonsense" of National Fire Protection Association Code 50 on the basis that a lifelong experience had demonstrated the safety of the operating room where he was chief of staff. One evening he insisted on viewing an appendectomy on his teenage son. He climbed onto the viewing stand clad in leather-soled shoes, woolen trousers, a long cotton coat, cap and mask. After the procedure was completed and the dressing was being applied, he stopped to pat his lad's cheek. There was an explosion that killed the boy and propelled the father into the corridor.

Combustion of flammable anesthetic and disinfecting agents in the hospital is accomplished by properly assembling four essential components. Both qualitative and quantitative requirements must be met. These imply a timeliness of combination that demands either careful planning or repetitive trials to achieve combustion.

An obvious requirement for combustion is a flammable agent. The most benign of the anesthetic agents are either flammable or support combustion. Currently, toxic manifestations, principally cardiac or hepatic, discourage more widespread use of nonflammable agents for inhalation anesthesia.

During the course of an anesthesia, flammable mixtures of anesthetic and the second essential component, oxygen, are encountered. Flammability is extended by enriching the anesthetic mixture with oxygen. This is usually accomplished in a closed rebreathing system where the inerting effect of nitrogen is diminished.

Ignition of the flammable mixture of anesthetic gas and oxygen is the third indispensable component for combustion. The energy from a source of heat at but 312° F. suffices to ignite anesthetic mixtures of ethyl ether. Radiation from objects at this temperature is invisible. Visual perception of incipient glow occurs from objects hotter than 900° F. So anything that glows obviously radiates enough energy to ignite. Electric sparks and arcs are important transient and usually unexpected sources of ignition. The energy of a 12 volt spark or a 1,200 volt electrostatic discharge is enough. Any arc will ignite.

The crucial component of a fire, often of explosive violence, involving anesthetic mixtures is the fool who accomplishes a timely concoction of the essentials—flammable agent, oxygen, igniter. Experienced ignorance, routine carelessness, arrogant complacency, and wilful negligence characterize the foolhardy who persistently and cunningly assemble the components to achieve ultimate disaster.

Institutional safeguards can minimize the chance of the timely concurrence of the factors essential for disaster. These involve the design and maintenance of structure, selection, maintenance and use of safe equipment, and adoption and enforcement of proper techniques. This body of knowledge has been accumulated and codified over the past 30 years by a group of experts under the auspices of the National Fire Protection Association. That body is a voluntary association of individuals and groups banded together to prevent loss of life and property. A special committee, the Committee on Hospitals, has promulgated NFPA no. 50, "Code for the Use of Flammable Anesthetics."

Unfortunately the most enlightened routine of a precaution-conscious group is jeopardized by the careless or negligent behavior of any individual who enters the anesthetizing location. Continual education and militantly critical supervision are therefore essential to assure safety for each patient and all personnel, however transient. It is ironical that success
of group effort in establishing safeguards may accentuate the hazard caused by individual dereliction. Perfection of the chain of structural and mechanical safety may intensify the hazard of breaches in technique as may be seen subsequently. Accumulating experience without accident lulls the group into condoning expedient practices or defiant behavior.

A prime safeguard is to confine the hazard to recognizable regions. The use of closed systems for the administration of anesthetic gases confines the hazardous region to a distance of two feet from the gas-transmitting biomechanical system of patient and anesthesia machine. Experience has shown that the jet from a leaky administration system is difficult to ignite beyond a distance of six inches.

Liquid anesthetic agents or disinfectants are subject to spilling and most have vapors that are heavier than air, so potentially flammable mixtures cascade beneath the anesthesia system and pool on the floor. The hazardous area is therefore defined as extending to a radius two feet from the anesthesia machine and the patient's head and a similar distance above the floor. Secluding the area occupied by the anesthetist, the anesthesia machine and the patient's head—the anesthesia stage—effectively decreases the opportunity for ignition as will be seen further on.

Because anesthesia machines are portable, the hazardous area is considered to lie within the region likely to be flooded with a flammable gas escaping from a leaky machine. Thus, the region up to five feet above the floor is defined as the anesthetizing location and is considered hazardous.

Limiting the quantity of flammable agents kept in an area is also important. For example, the storage of but one anesthesia machine in an unventilated room reduces the possibility of the accumulation of a quantity of flammable mixture that might endanger structure should leakage occur. Anesthesia machines must not be covered with drapes. Combustible mixtures may accumulate, and removal of the drapes may produce the electrostatic spark that ignites the mixture trapped in the tented drape. Every precaution must be taken to shut off the cylinders of gas prior to storage because the accumulation of as little as 5 per cent of the net volume of the room is sufficient to cause explosive damage to structure should ignition occur.

Storage of supplies of flammable gases must be in special rooms ventilated sufficiently to dissipate any gases that may be released accidentally or unwittingly. Oxygen or nitrous oxide must not be stored with flammable agents. Both support combustion.

Spillage of flammable agents must be avoided. Liquid ether should not be used as a cleansing or defatting agent.

Oxygen must be handled with the recognition of several facts. First, increasing the concentration of oxygen in an atmosphere augments the rate of combustion. Smoldering materials will burst into flame. Flame is intensified and commonly nonflammable materials support combustion as temperature mounts. Second, increased tension of oxygen may cause greases and oils to ignite as the chemical reaction resulting from the adsorption of oxygen liberates heat. Neither greases nor oil must be used on equipment supplying oxygen. Third, the adiabatic compression of oxygen by abrupt change in pressure across an orifice may result in temperatures sufficient to ignite the materials. Valves on oxygen systems must always be opened slowly to permit gradual build-up of pressure downstream.

Prohibition of sources of ignition is the paramount safety measure. These include obvious ones such as flames from lighters or matches; alcohol lamps and burning electrical insulation. Glowing and heated, electric heaters, cautery tips are less evident. The black hot plate, dry heat sterilizer, the "cold" cautery or overloaded electric wiring are unrecognized hazards. Exposed incandescent lamps and photographic lights are overlooked igniters. Sources of light for photography often cause controversy—the photographic record of an operation is seemingly more important than successful surgery. With proper equipment, photography need present no hazard. Flimsy wiring, unprotected lamps, sparking switches are intolerable hazards.

The most frequently involved igniters are sparks from electric power or static electricity. It is ironic that surgeons using the electric cautery or radiofrequency knife cause fires almost as frequently as electrostatic discharge.
Sparking electrical contacts and commutators can be protected or eliminated by proper design. Sparks due to failure of electrical equipment or faults in insulation are unpredictable and can be guarded against only by constant critical inspection and maintenance. Sparks due to electrostatic discharge are more subtle and mysterious.

Electrical equipment that does not function properly must not be used until repaired by a qualified electrician. Aged or frayed insulation, broken plugs or switches must never be used. The "just this time" may well be the disastrous time. Only electrical equipment approved for use in the anesthetizing location must be permitted. Approval includes a permanently attached anesthetizing location plug.

To minimize the likelihood of sparks from electrical power occurring in the hazardous area, and to confine the heat that results from the operation or failure of electrical appliances, special circuits and design practices have been devised.

Ungrounded circuits are used for the distribution of power. This is achieved by feeding power through an isolation transformer (figs. 1A, B, and C). This interposes a magnetic field between the power supply and the secondary circuits that distribute the power within the anesthetizing location. Unlike conventional distribution circuits where one conductor is grounded, the output of this transformer remains ungrounded because there is no electrical connection with the grounded feeders. Hence, simultaneous faults must occur in contiguous areas of insulation on both conductors to permit sparking. This system also protects patients and personnel who are grounded, often unwittingly, against shocks due to inadvertent contact with a single live conductor of the ungrounded circuit or due to leakage currents through an inadequate or faulty ground circuit.

The ungrounded circuit also permits continuous monitoring of the wiring and equipment against faults in insulation that result in leakage of current to ground. Leakage of more than two milliamperes results in both an audible and visible alarm. A room in which the ground contact indicator is alarming, must not be used for anesthesia. Appliances that cause an alarm must be disconnected immediately.

Portable equipment is made safe for use in the anesthetizing location in one of five ways. (1) The simplest is to provide for its elevation out of the hazardous area. Thus, equipment enclosed in a grounded metal case mounted above the five-foot level does not constitute a hazard. (2) Another way is to ventilate the metal enclosure of appliances. This not only keeps the equipment cool, but also purges the enclosure of any combustible gas that might diffuse into it. The source of ventilating air can be either compressed air released within the enclosure, or blower-forced ventilation with the air intake through a snorkel.
to cause ignition. Generally it is only suitable for extra low voltage, low energy equipment such as endoscopic instruments, pacemakers and the like.

The most hazardous part of any electrical appliance is its power cord. Cords are easily damaged by kinking or compression and either end may be subjected to disruptive strain. The end at the appliance should be firmly anchored in a strain relief that protects the insulation. The plug should be attached so that continuity of the insulation is protected. Proper cords are of the type designated for extra hard usage and have three conductors. The third conductor forms a grounding connection between the ground terminal of the anesthetizing location plug and the exposed metal parts of the appliance. The cord must

**Fig. 1B.** Ungrounded circuit described in text. Spark or shock occurs only when both live conductors are in circuit. Insulation failure (A) permits a current of 2 milliamperes to flow to ground. The ground contact indicator is activated to warn of the failure. No spark or shock hazard is established.

located above the five-foot level. (3) Another technique used particularly for lamps, is to enclose the hot lamp in a shell that is ventilated through a porous metal or ceramic radiator with interstices so small that flame cannot be propagated from within. The porous radiator must be designed to dissipate heat rapidly enough to prevent development of temperature higher than 150° F. (4) The conventional method is to seal the equipment in a case sufficiently rugged to contain the explosive combustion of any gas that might gain access into the case. Equipment explosion-proofed in this manner is heavy, cumbersome and expensive. (5) Intrinsically safe equipment and wiring can be used. This is incapable of releasing sufficient electrical energy under normal or abnormal conditions

**Fig. 1C.** Conventional three-wire circuit. Failure of insulation (A) establishes short circuit with ground. Sparks fly, molten metal spatters, and the fuse blows. Spark or shock occurs when circuit is made between live conductor and either the grounded wire (B) or any other grounded object (C).
be continuous and without switches from appliance to attachment plug and be long enough to reach diagonally across the operating room. A device must be provided to permit storage of the cord without kinking.

Extension cords must never be used because the connector lying on the floor is in the most hazardous region and is subject to wetting and damage.

The plug should be of the specific type for anesthetizing locations (fig. 2A). It should be watertight, lock into the receptacle to prevent accidental dislodgment and be designed to confine any sparks that may occur when the plug is disconnected.

Two forms of receptacle are permitted. An inexpensive type can be located in the nonhazardous area above five feet from the floor. The other, located within the hazardous area, is enclosed in an explosion proof case and contains a switch that activates the circuit in proper sequence to insertion or removal of the plug to prevent sparking or arcing. Anesthetizing location plugs can be inserted interchangeably with matching receptacles located in either the nonhazardous or hazardous areas. When appliances fitted with anesthetizing location plugs are used elsewhere, an adapter such as illustrated (fig. 2B) provides for a safe source of power.

It is a travesty that hospitals continue to purchase unsafe portable equipment for use in anesthetizing locations. Indeed, purchasing policies are so lax that industry has not troubled to provide equipment that complies with safe practices. Hospitals incur heavy expense to provide safe structure but permit the use of outdated or makeshift portable equipment that completely negates the purpose of the investment in the building. Until hospitals demand equipment that is approved for use in anesthetizing locations, industry continues reluctant to comply with safe standards.

Electrostatic sparks are responsible for ignition in the majority of accidents. Control of electrostatic charges is difficult because static electrification occurs wherever motion separates electrons from their equilibrium orbits under conditions where there is no conductive path to permit neutralization to occur. Good insulating materials such as glass, rubber, wool, silk and plastics retain electrostatic charges better than materials that adsorb or absorb moisture and thus become electrically conductive. In an atmosphere with a relative humidity of 50 per cent or more, conductivity of many materials is sufficient to eliminate electrostatic effects. The accumulation of electrostatic charge is negligible where there is a conductive pathway for its dissipation with a resistance value of less than 10 megohms.
Exclusion of materials with resistances greater than this from the operating room is a significant factor in the control of electrostatic spark. Thus, wool, silk and synthetic textiles are prohibited unless worn in contact with the skin. Close fitting underclothing or hosiery of synthetic fiber is safe because the skin which it contacts provides the conductive pathway. It is important to note that some garments are not safe even though a portion may be in contact with the skin. The bodice of a slip, for example, presents no hazard, while its free-hanging nonconductive skirt is an extreme hazard because friction against the thighs creates a charge.

Electrostatic charges can be induced on stationary objects, even though these may be electrical conductors, by the proximity of an electrostatic charge. Induction may occur despite the interposition of walls or doors between the charged body and the inductively charged conductor. Discharge of an induced charge on a conductor can result in a hot spark. Hence, all objects, whether insulators or conductors, are electrostatically inter-related.

This emphasizes the fact that the introduction of one charged body into an environment where all other objects are interconnected by a conductive path can cause a spark from any of the objects in the common circuit to the charged body.

Electrical interconnection of all objects and people, including the patient, in the anesthetizing location is accomplished by means of a conductive floor (fig. 3). Although a low resistance connection provides the optimal protection against electrostatic sparks, the hazard of electric shock or sparks from electric power is too great. Hence, a high resistance floor is provided to limit the electric power current that can flow when faulty equipment is used or electric conductors are inadvertently contacted.

Furniture and equipment are equipped with conductive casters or feet to provide electrical contact with the conductive floor. Accumulation of an insulating layer of soil, broken glass, or ends of sutures may interrupt this connection. Hence, casters and feet must be cleaned after each day’s use. To assure
maintenance of a conductive pathway, the resistance between the furniture and the floor must be measured periodically.

People are the greatest electrostatic hazard. The human body is an electrical conductor with capacity to store a large electrostatic charge generated by its own motion or by friction of articles of clothing. Ambulatory people carry electrostatic charges into electrical environments where hazardous inductive effects may occur. Each individual must therefore provide a conductive pathway from his skin to the conductive floor. Conductive footwear must be worn. Its conductivity must be demonstrated at the start of each period of wear. The accumulation of wax, dirt or insulating bits of glass, suture and other trash occurs too readily to overlook the necessity for frequent demonstration of a conductive pathway. A resistance measuring device at the entrance to the restricted corridor of the operating room makes this easy. Yet experience has shown that but few bother to step on the metal plates to demonstrate conductivity. A maximum resistance of 2 megohms is permissible. Booties, conductive strips, conductive buttons have too limited a contact with either the skin or the floor to be dependable.

The patient must be specifically connected to the conductive system. Bedding often insulates him from it. A conductive strap (fig. 4) fastened to the metal operating table, should be placed in contact with the patient's skin.

Rapid motion must be discouraged to avoid the accumulation of an electrostatic charge more rapidly than it can be dissipated. The contact with a conductive floor while running is too brief to be reliably effective.

Whenever the secluded anesthesia stage must be entered, the moving person should touch the back of the neck of the anesthetist to equalize charges at a distance from the gas transmission system.

Perusal of this essay may well leave the reader with the conviction that the hazard being considered has become remote; that compliance with a complex system of rules is not worth the effort. After all, there is only one chance in 300,000 that an accident may happen. With 13 million anesthetics annually, the 40 accidents are insignificant as compared to the 40,000 deaths accepted as inevitable on the highway. However, it is important to realize that any relaxation increases the likelihood of an accident many fold. Discarding conductive footwear, for example, could easily increase the risk to one in 50,000 anesthetics. Electrostatic and the induced charges they generate as they move about the anesthetizing location are the paramount factor in setting the stage for a disastrous spark.

Accident Reports

The case reports—five of them from the author's experience—illustrate the human problem that needlessly causes morbidity and mortality.

Accident 1. At the end of a difficult delivery, a nurse anesthetist poured ether into the shoe of a youthful obstetrician. Revenge took the form of pouring ether down her bosom. In reprisal for the cold front, she loaded a syringe and shot a stream of ether at the back of the obstetrician's head who was now sprawled in a chair in the doctor's lounge. A cigarette ignited the target area and flame spread along the vapor trail to ignite the anesthetist's clothing. Scorched scalp and neck and burned breasts rewarded the horseplay.

Accident 2. An otorlaryngologist had just completed a tonsillelectomy under ether anesthesia. He turned up his head mirror and pulled the chain to turn off the 100 watt lamp located behind the patient's head. An explosion occurred that killed the patient. Ten days later a similar accident occurred under identical circumstances. The surgeon had refused to give up the gooseneck lamp with the pull chain socket that cause the fatal spark.

Accident 3. To assure clean apparatus and full cylinders at the onset of each operation, an anesthetist was accustomed to leave the face mask dangling to the floor at the end of the procedure. He left the anesthetic gas flow so that the cylinders could empty. An explosion occurred that blew the windows out of the operating room. The source of ignition was a floor scrubbing machine that was wheeled into the room. Its operator suffered a concussion. The anesthetist was reprimanded, but persisted in his irresponsibly,
Fig. 4. View of an operating room illustrating coordination of structure and equipment to decrease the hazard of sparks due to power and electrostatic causes.

1. Ceiling-suspended surgical light is wired in conventional manner and may be fitted with 2) ordinary switch suitable for nonhazardous location.

3. Explosion-proof spotlight. The lamp is enclosed in a strong housing ventilated through porous radiator (3A). The metal frame is grounded. The casters are conductive to provide leakage path for electrostatic charge generated while moving the light when it is disconnected.

4. Wall switch for ceiling-mounted surgical light. Enclosed single-pole switch and conventional wiring for nonhazardous location above the five-foot level.

5. Receptacles for anesthetizing location plug supplied through isolation transformers need not be explosion-proof if located above the five-foot level.

6. View box above five-foot level connected to ungrounded distribution system. Ordinary switch is permissible.

7. Explosion-proof receptacle for anesthetizing location plug.

8. Reel to prevent kinking of cord.

9. Anesthetizing location plug (figure 2A) interchangeably used in either 5 or 7.

10. Operating table has unpainted metal top and conductive casters. Sponge rubber mattress is enclosed in conductive cover.

11. Conductive strap connected to metal frame of table bridges bedding that may insulate patient.

12. All metal instrument stand has conductive casters.

13. Metal basin is connected to conductive system through (14) moistened drape.

14. Solution is initially poured over rim of basin to moisten drape.

15. Explosion-proof electrocardioscope.

16. Unpainted metal stool.

17. Foot stool with conductive top and feet.

18. Anesthesia machine is fitted with a conductive rubber gas transmission system and conductive casters.

19. The metal instrument table is conductive when tested by placing an electrode on its top and another on the conductive floor.

20. Dado to five-foot level demarks extent of anesthetizing location.

21. Conductive floor with resistance high enough to mitigate the shock hazard.

22. Switches for conventionally grounded circuits are located outside the anesthetizing location.

(Adapted from: Hudenburg, R.: New recommendations for the control of operating room explosion hazards, Hospitals, December 1949.)
wasteful and hazardous practices until his discharge.

**Accident 4.** During the course of cyclopropane anesthesia, assisted respiration was begun by manual compression of the rebreathing bag. An explosion occurred that shattered the anesthesia machine, killed the patient, and propelled the anesthetist into the corridor.

The setting of this accident is of interest because of the number of violations of good practice that were condoned.

There was an adequately conductive floor. The furniture was equipped with conductive casters, feet and pads. The sole exception was the anesthesia machine which had a drag spring which was connected to the machine by means of resistors. One end of the spring had broken and was trailing on the floor. Sufficient floor soil had accumulated on the spring to break the conductive pathway. An illegal intercoupler was allegedly used to interconnect the patient, operating table and anesthesia machine. Its electrical connection with the machine was a loop of bead chain on which the device hung. The operating table was not fitted with a conductive strap to bridge the bedding between the patient and the conductive mattress. Because there was no evidence that the patient had been connected to the intercoupler, the bedding might well have insulated him from the conductive pathway and invited the accumulation of an induced charge.

All personnel wore conductive bootees. However, one-third of those who were at work on the second day following the fatal explosion had not troubled to tuck the conductive tab inside the shoe or sock to establish a conductive path.

The operating room was small. The corridor door was customarily propped open. The anesthetist sat practically in the doorway. Immediately outside the doorway there was an electrically powered water cooler of conventional design. The sparking contacts of this machine were a few feet from the anesthesia machine.

In an alcove opening off the operating room itself, there were two refrigerators that served as blood or bone banks. Both had sparking thermostats and electric over-temperature alarms. An open spark gap endothermy ma-

chine was stored in this alcove. The device had a detachable two-conductor cord with a domestic plug. A "cheater" to permit connection with an explosion-proof receptacle was held in place with adhesive tape.

This unventilated alcove was equipped with shelves for the storage of cans of ether and jars of alcoholic germicide. Approximately 10 gallons of flammable liquid were present.

The spark that ignited the cyclopropane-oxygen mixture probably originated within the rebreathing bag. The rubber parts of the anesthesia transmitting system were of conductive rubber. However, these had aged and the surfaces of the parts, both inner and outer, were crazed and tacky. The inside of remnants of the rebreathing bag was heavily coated with starch. Inspection of the cleaning method showed that starch powder was used to dust the inside of the bag to prevent its walls sticking together. It is most likely that manual manipulation of this crazed bag with faulty conductivity electrified the starch and resulted in the disastrous spark. However, there were many other possible sources of ignition. Parsimony and expediency were responsible for each.

**Accident 5.** Simultaneous operations were in progress on two children using two anesthesia machines. Each machine contained a size E cyclopropane cylinder, a nitrous oxide cylinder and two oxygen cylinders. In addition to the two patients; three surgeons, two anesthesiologists and four nurses were in attendance.

Upon opening the valve on one of the cylinders supposedly containing only cyclopropane, the cylinder exploded. Failure originated in the shell and extensive fragmentation occurred. The sharp fragments were flung about the lower half of the room and were the cause of injury.

This explosion dislodged the second cyclopropane cylinder from its machine and the cylinder valve broke off releasing cyclopropane which ignited and burned as a torch. The valves of the nitrous oxide cylinder and the two oxygen cylinders which comprised the remainder of the cylinders on the machine of origin were broken, but only one cylinder of oxygen was dislodged from the machine. Three ether containers became involved with
a resulting small locally intense fire which burned out rapidly.

The two patients, two anesthesiologists and two surgeons died, either instantly or within 8 days, from burns and organic lesions. The left arm of another surgeon required amputation. Two nurses each lost one leg. Two other nurses sustained severe organic trauma, but were not mutilated.

Subsequent investigation revealed that the cylinder had been partially filled with oxygen by error and subsequently charged with cyclopropane. The cylinder valve was not suitable for oxygen and, in position in the anesthesia machine, the cylinder was connected to regulators, hoses, etc., which were also not suitable for oxygen. It is also likely that the cyclopropane apparatus was not kept as clean of grease, dust, etc., as is necessary for oxygen service. In addition, it is probable that the accidental mixture of cyclopropane and oxygen was in the explosive range.

Evidence indicates that the cylinder valve was opened more rapidly than usual. This was probably a factor in ignition either by producing heat from adiabatic compression or friction or possibly by creating a static spark. However, it may not have been necessary for the valve to have been opened fast.

Transfilling of cylinders is still common practice in spite of previous incidents. The practice must be prohibited. (Reference, Walls, W. L.)

Conclusion

These accidents and the one used in the introduction illustrate the foolhardy milieu that spawns disaster. Safe structure can be designed by competent engineers. The purchase of safe equipment can be specified. Proper maintenance of structure and equipment requires astute anticipation of failure, continual inspection and immediate repair of defects.

Education and cooperation of people are the continuing and crucial problems. Carelessness of but one creates an intolerable hazard for the many who collaborate.

REFERENCES AND SOURCE MATERIAL


CSA Standard Z 32-1963, Code for the use of flammable anesthetics, Canadian Standards Association, 235 Montreal Road, Ottawa 7, Canada ($3.00).

Motion Picture, Fire and Explosion Hazards from Flammable Anesthetics, available from Abbott Laboratories, Film Service Department, North Chicago, Illinois.

METHOTRIMEPRAZINE A double-blind study comparing methotrimeprazine 15 mg., meperidine 75 mg., and placebo for pain relief during labor was completed in 334 women. Both active compounds were significantly better in pain relief than the placebo; there was no significant difference in pain relief between the compounds. Obstetricians tended to be more enthusiastic in their evaluation of the effectiveness of the pain relief of the two compounds than the patients. Maternal drowsiness was the only side effect that could be demonstrated in this study. There was no significant difference in the effect of the drugs upon the infant crying time, Apgar score or serum bilirubin concentrations. (DeKornfeld, T. J., and others: Methotrimeprazine in the Treatment of Labor Pain, New Engl. J. Med. 270: 391 (Feb. 20) 1964.)