David S. Warner, M.D., Editor

Preparation of Modern Anesthesia Workstations for Malignant Hyperthermia–susceptible Patients

A Review of Past and Present Practice

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ABSTRACT

Patients with malignant hyperthermia experience an exaggerated metabolic response when exposed to volatile anesthetic gases and succinylcholine. The minimum concentration of anesthetic gas needed to trigger a malignant hyperthermia crisis in humans is unknown and may remain so because of the inherent risks associated with studying the complex nature of this rare and lethal genetic disorder. The Malignant Hyperthermia Association of the United States provides specific instructions on purging anesthesia machines of volatile agents to reduce the risk of exposure. However, these recommendations were developed from studies of older generation machines. Modern anesthesia workstations are more complex and contain more gas absorbing materials. A review of the literature found the current guidelines inadequate to prepare newer generation workstations, which require more time for purging anesthetic gases, autoclaving or replacement of parts, and modifications to the gas delivery system. Protocols must be developed to prepare newer generation anesthesia machines.

MALIGNANT hyperthermia (MH) is a potentially fatal genetic disorder triggered by exposure to volatile anesthetic gases and succinylcholine. MH events are characterized by hypermetabolism of skeletal muscle, which results in increased carbon dioxide production, increased core temperature, and generalized muscle rigidity with resultant rhabdomyolysis, acidosis, and hyperkalemia. If untreated, MH ultimately results in cardiac arrhythmia, multiorgan system failure, and death. The Malignant Hyperthermia Association of the United States (MHAUS)‖ established a treatment protocol that focuses on discontinuation of triggering agents, maintenance of adequate oxygenation and ventilation, institution of aggressive cooling measures, administration of dantrolene, and appropriate treatment for hyperkalemia. Despite prompt recognition and aggressive treatment, MH has a reported mortality as high as 11.7%.[1] Therefore, effective management of MH-susceptible patients places particular emphasis on prevention.

MHAUS# has published guidelines to provide a trigger-free anesthetic by avoiding provocative medications. Avoidance of succinylcholine is straightforward; however, avoidance of potent vapor anesthetics is more challenging because anesthesia machines retain anesthetic vapors long after discontinuation. Instructions for clearing residual anesthetic gases include removal or disabling of vaporizers, flushing the machine with a fresh gas flow rate more than 10 l/min using the ventilator for at least 20 min, and replacement of the fresh gas outlet hose, carbon dioxide absorbent, and anesthesia circuit. The goal is to decrease the residual anesthetic vapor concentration within the breathing circuit. These precautions represent the standard of care for the management of MH-susceptible patients.

The current MHAUS instructions for purging anesthetic gases were derived from studies designed to optimize gas clearance in older generation machines. These machines

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Received from the Department of Anesthesiology and Critical Care Medicine, The Johns Hopkins Hospital, Baltimore, Maryland. Submitted for publication December 16, 2009. Accepted for publication June 17, 2010. Support was provided solely from institutional and/or departmental sources. Presented in part at the Winter Meeting of the Society for Pediatric Anesthesia, San Antonio, Texas, April 17, 2010.

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 Anesthesiology 2011; 114: 205–12

were simple in design. At the time, the anesthesia ventilator consisted of a pneumatically driven bellows, and the fresh gas flow was conveyed directly to the inspiratory limb through unidirectional valves. The machines did not have the capability to adjust tidal volume automatically in response to alterations in lung compliance and fresh gas flow rates. As such, these machines could be purged quickly by increasing the fresh gas flow rate, which resulted in larger tidal volumes. The direct input of fresh gas to the inspiratory limb flushed trace anesthetic gases out through the expiratory limb during all phases of mechanical ventilation. In addition, adding the fresh gas directly to the inspiratory limb resulted in significant dilution of trace anesthetic vapors within the circuit, especially if the anesthetic gases were redistributing from internal components.

An early report studying how gas solubility and fresh gas flow rates influence clearance of anesthetic agent in an older anesthesia machine was conducted by Tarq *et al.*[2] They examined the effect of anesthetic gas solubility on residual anesthetic concentration by measuring the solubility of halothane, I-653 (desflurane), isoflurane, and sevoflurane in various plastic and rubber machine components obtained from a conventional anesthesia circuit. From these data, plastic/gas and rubber/gas partition coefficients were determined, and the following order, from most soluble gas to least, was obtained: halothane > isoflurane > sevoflurane > I-653 (desflurane). The washout times of these gases from an older generation Ohmeda anesthesia machine (Ohmeda, Madison, WI) with a conventional breathing circuit were then measured. At a 5 l/min flow rate for 20 min, the concentration of desflurane was reduced by 99.9%; sevoflurane, 99.7%; halothane, 99%. The significance of the fresh gas flow rate on the washout kinetics of volatile anesthetics was noted when desflurane, a relatively insoluble gas, required greater than 1 h to reach a reduction of 99% when the flow rate was decreased to 1 l/min.

A second study examining the washout kinetics of anesthetic gases was conducted by Reber *et al.*[3] using a Sulla 808V (Dräger, Lübeck, Germany). That study looked at the effects of three variables on the washout of isoflurane: increasing the fresh gas flow rate alone, increasing the fresh gas flow rate and adding a charcoal filter (G. J. Veenemans, Incentra AG, Wangen a.A., Switzerland) to the inspiratory limb of the patient breathing circuit, and increasing the fresh gas flow rate and exchanging the anesthesia machine and breathing system to a new one. These authors found that isoflurane was reduced to less than 90% within 1 min in all preparations when the gas flow rate was greater than 8 l/min. Although the addition of the charcoal filter resulted in a statistically significant reduction in washout time, the authors questioned its clinical significance because the time disparity amounted to only 14 s. The replacement of the anesthesia machine was felt to be unnecessary because increasing the fresh gas flow rate alone resulted in comparable results, and the amount of time (54 s) and personnel needed to replace the machine distracted from patient care. The authors concluded that increasing the fresh gas flow rate was the simplest and most effective method to purge an anesthesia machine of residual anesthetic agents.

A more comprehensive approach to purging anesthesia machines of anesthetic gases for MH-susceptible patients was conducted by Beebe and Sessler.[4] Using an Ohio® Modulus I anesthesia machine (Ohmeda) equipped with the Air-Shields® ventilator (Air-Shields Vickers, Hatboro, PA), they studied the effects of different anesthetic gases, fresh gas flow rates, and machine configurations on residual anesthetic gas concentrations. In the first experiment, the anesthesia machine was primed with 2% halothane and 2% isoflurane in a 1-l/min fresh gas flow of oxygen for 18 h. Analysis by gas chromatography allowed for simultaneous testing and determination of different elution rates. The remaining studies involved 2% halothane alone, which represented a common anesthetic agent in use at the time and the most soluble gas in the different components of the anesthesia machine.

The results of their study confirmed that the most soluble anesthetic, halothane, was three to four times slower to eliminate relative to isoflurane, an effect attributed to its increased solubility in rubber and plastic components of the anesthesia machine. Reduction of the fresh gas flow rate during washout from 10 l/min to 1 l/min resulted in a 10-fold increase in the residual halothane concentration within the breathing circuit, reflecting the soluble nature of halothane and its slow release from absorbent materials. The optimal machine configuration involved replacing the fresh gas outlet hose and circle system with new replacements and using a 10-l/min fresh gas flow. This change in configuration produced a 10-fold difference in residual anesthetic (5 ppm after 5 min washout), whereas replacement of the soda lime or ventilator bellows had negligible effects.

A follow-up study by McGraw and Keon[5] using Ohio® Modulus II anesthesia machines (Ohmeda) and halothane found similar results. All machines were primed with 5% halothane in oxygen at 4 l/min for 10 min. Halothane was discontinued by turning off the vaporizer and increasing the oxygen flow rate to 12 l/min. Samples taken from the common gas outlet showed a reduction to zero by 6 min, and the room air pollution ranged from 0 to 1 ppm. Interestingly, there is no reference to purging the anesthesia machine using the ventilator as in the previous study. The authors concluded anesthesia machines should be prepared by removing the vaporizers, flushing with high-flow oxygen for 15 min, and using circuit tubing, gas outlet hoses, and carbon dioxide absorbent never exposed to anesthetic gases.

However, the evolution of the basic anesthesia machine has presented new challenges in optimizing their use for MH-susceptible patients. The machines are more complex and incorporate new technology and materials in their designs. The component of the anesthesia machine that has undergone the greatest change is the ventilator and the materials incorporated into the internal gas delivery system.

These components are unique to each workstation. As compared with older generation machines, the internal breathing circuitry of newer machines incorporates more plastic and rubber parts. These parts serve as a significant reservoir of anesthetic gas, which is released back into the breathing circuit after anesthetic discontinuation.[6,7] Different anesthesia workstations use varying amounts of these absorptive materials, and the time needed to purge them will differ based upon the amount of stored gas.

One study looking at newer generation anesthesia machines was conducted by Schonell *et al.*[8] examining five Datex-Ohmeda anesthesia workstations (AS/3 Anesthesia Delivery Unit, Bromma, Sweden). As was the case with past studies, it was found that the anesthesia machine could be purged of gases quickly in 10 min using an oxygen flow rate of 10 l/min resulting in a gas concentration of 2 ppm of isoflurane at the common gas outlet. However, inclusion of the patient breathing circuit and ventilator required 30 min of ventilating an artificial lung (1-l breathing bag) at 10 l/min to achieve concentrations less than 5 ppm. The tidal volume of 1 l was chosen to ensure adequate gas volume to flush the bellows, tubing, and patient circuit. The effects of replacing the soda lime, patient circle circuit, 1-l breathing bag and hose, ventilator hose, and the ventilator bellows were studied as well. Their findings suggested that changing only the breathing hoses, breathing bag, and soda lime cartridge was necessary.

An important study evaluating how absorbent, internal materials in newer generation machines affect the washout times of halothane and isoflurane was undertaken by Petroz and Lerman[6] using the Siemens KION workstation (Siemens Elema, Solona, Sweden). The KION differed from the Ohmeda Modulus I and II machines by the inclusion of silicone and other rubber components within its internal circuitry. In the first part of their study, they sought to measure the impact of priming duration and fresh gas flow on the washout of halothane. The time to reach 10 ppm of halothane within the internal circuit (representing the components of the machine from the fresh gas inlet to the auxiliary gas outlet) and the external circuit (representing the ventilator and bellows, patient cassette, and anesthetic circuit) were measured in two machines with a 2-h prime and a fresh gas flow rate of 5 l/min and 10 l/min. A third machine had a 12-h prime and a fresh gas flow rate of 10 l/min. They found that egress from the internal circuit was dependent on the fresh gas flow rate, while the external circuit was dependent on the duration of priming. The authors explained this difference by noting that the external circuit possessed a greater surface area and had increased amounts of silicone/rubber materials that absorb anesthetic gases, especially during a prolonged period of exposure. The silicone and rubber components were proposed to act as a reservoir of anesthetic gases during these experiments.

In the second half of their study, the washout profiles of halothane and isoflurane were examined in the KION anesthesia machine and Ohmeda Excel 210 anesthesia machine with the Air-Shields Ventimeter® Controller II ventilator during controlled ventilation of a test lung using a circle circuit. The study examined the effect of the anesthesia machine and inhalational agent on the washout time. KION anesthesia machines were exposed to either 1% halothane or 1.5% isoflurane for 2 h. After priming, anesthetic gas concentrations were measured with a fresh gas flow rate of 10 l/min, until the gas level was reduced to 10 ppm. Next, sampling was continued while the fresh gas flow rate was reduced to 5 l/min until a concentration of 10 ppm was again achieved. As a comparison, Ohmeda anesthesia machines were primed and purged in an identical manner as the KION machines, except only halothane was used.

The study demonstrated that washout time was more dependent on the type of anesthesia machine rather than the anesthetic agent used when using high fresh gas flow rates (10 l/min). The washout time was 4-fold quicker in the Ohmeda compared with the KION anesthesia machine. When the fresh gas flow rate was reduced to 5 l/min, the KION machines exposed to 1% halothane and 1.5% isoflurane as well as the Ohmeda machines exposed to 1% halothane all showed initial increases in the concentration of effluent, 35 ppm, 32 ppm, and 21 ppm, respectively, before gradually returning to 10 ppm.

This increase in anesthetic gas concentration demonstrated the "rebound effect," an effect secondary to the release of anesthetic agents from silicone and rubber components into the breathing system with minimal dilution at low fresh gas flow rates. The faster washout of halothane compared with isoflurane in the KION anesthesia machine was postulated to reflect the higher concentration of isoflurane delivered during the exposure period and the possible differences in solubility of halothane and isoflurane in the silicone components of the KION anesthesia machine, which have yet to be studied. The subsequent return to 10 ppm of anesthetic gas concentration at the lower flow rate proceeded in the following order: Ohmeda, 1% halothane (9 min), KION, 1% halothane (34 min), and KION, 1.5% isoflurane (41 min). The difference in times was thought to be influenced by the anesthesia machine as well as the concentration of the inhalational anesthetic used in priming the machine.

It is of note that washouts from the internal and external circuits were conducted excluding the carbon dioxide absorbent from the anesthesia breathing circuit. The carbon dioxide absorbent represented a potentially large reservoir of gas and significant source of anesthetic vapor. In the operation of the KION anesthesia workstation, the carbon dioxide absorbent can be eliminated without interrupting the function or flow of gases in the machine, and fresh gas flow can be maintained at a high rate to prevent rebreathing and to avoid hypercarbia. Therefore, the final recommendations of the study for preparing this workstation were to disconnect the carbon dioxide absorber from the circuit, ventilate a new circuit and breathing bag attached to the Y-piece with a fresh

gas flow rate of 10 l/min for at least 25 min, and maintain a fresh gas flow rate of 10 l/min throughout the case. These recommendations would purge the KION workstation to 10 ppm residual anesthetic. Reducing this concentration to less than 5 ppm, however, has not been evaluated.

The effects of fresh gas flow rate and modifications to the breathing circuitry on washout characteristics of anesthetic gases were examined in Dräger Primus workstations (Dräger) in preparation for MH-susceptible patients. In the first study by Prinzhausen *et al.*,[7] they found the Primus required a maximum of 70 min to decrease the anesthetic concentration of isoflurane to 5 ppm when using a fresh gas flow rate of 10 l/min. As a comparison, an Ohmeda Excel 210 (GE Healthcare, Helsinki, Finland) attained a isoflurane gas concentration of 5 ppm in 7 min under the same conditions—as long as the ventilator bellows and ventilator tubing were replaced. It was also noted that increasing the fresh gas flow rate to 18 l/min, doubling minute ventilation, and using a less soluble gas, sevoflurane, did not significantly affect the anesthetic concentration in the system. However, reduction of fresh gas flow to 3 l/min was found to cause a significant increase in anesthetic gas concentration, which led to the proposal of maintaining a fresh gas flow rate of 10 l/min throughout the duration of anesthesia.

Given the time needed to purge this workstation, a second study was conducted by Crawford *et al.*[9] to find ways to accelerate the washout of inhalational anesthetics from the Dräger Primus workstation. Six Dräger Primus workstations were subjected to a standardized priming with 1.5% isoflurane for 2 h ventilating a model lung (Siemens, Solna, Sweden) before use in a set of six experimental configurations. All machines underwent a standardized preparation process, which included removal of the vaporizers and replacement of the carbon dioxide absorbent and canister, breathing circuit, and model lung.

The study focused on the effect of using a new or autoclaved diaphragm, an autoclaved or flushed internal breathing system, or a combination of the two components. The replacement of internal components was found to have a significant impact on the time required for purging the anesthesia machine. The most effective method was to replace the ventilator diaphragm and integrated breathing system with autoclaved components. With these replacements, anesthetic concentrations of 5 ppm were obtained in only 3.2 ± 0.4 min. This represented a 20-fold improvement in the washout time for isoflurane from a baseline of 67 ± 6.5 min in the machines prepared according to the current MHAUS guidelines. Furthermore, it was determined that there was a 3-fold increase in isoflurane concentration if the fresh gas flow rate was decreased. Therefore, the recommendations were to remove all vaporizers, replace the ventilator diaphragm and integrated breathing system with autoclaved components, and flush the workstation for 5 min at a fresh gas flow rate of 10 l/min, maintaining this flow rate throughout the case. These findings can theoretically be applied to the Apollo workstation (Dräger) because it shares the same internal breathing system as that of the Primus.

Gunter *et al.*[10] examined the kinetics of sevoflurane clearance in the Dräger Fabius anesthesia machine (Dräger Medical, Telford, PA). A comparison was first conducted between the Dräger Fabius and Dräger Narkomed GS (Dräger Medical), which served as the control for later studies of the Dräger Fabius. Both machines were primed with 3% sevoflurane in oxygen 3 l/min for 2 h, while ventilating a 2-l breathing bag as an artificial lung. Before the study, vaporizers were removed, the carbon dioxide absorbent (Amsorb® Plus, Keomed, Minnetonka, MN) was replaced, and a clean breathing circuit, breathing bag, and artificial lung were installed. When compared with the Dräger Narkomed GS, the Fabius required nearly a 6-fold longer flush time. Modifications to the Fabius machine included adding an additional 10 l/min of oxygen to increase circuit flow, flow to the ventilator, and flow to the ventilator piston in a retrograde fashion in separate experiments. To isolate the contribution of the ventilator piston as a reservoir of anesthetic gas, a bellows ventilator was placed between the piston ventilator and the breathing system. The effects of the alterations were modest and only lasted as long as the duration of additional oxygen flow. The interposition of a bellows ventilator demonstrated that the piston ventilator may act as a modest reservoir of anesthetic gases.

The last modification to the Dräger Fabius anesthesia machine was designed to scavenge trace anesthetics from the patient circuit. Given the constraints with flushing anesthesia machines for protracted amounts of time, these authors sought a novel approach for eliminating anesthetic gases rapidly at the end of the case by placing an activated charcoal filter (QED® or Quick Emergence Device; Anecare Laboratories, Salt Lake City, UT) on the inspiratory limb of the breathing circuit. The activated charcoal scrubs the gases from the circuit when the filter is turned on for use. To test this hypothesis, the Fabius machine was prepared by flushing the machine with a fresh gas flow rate of 10 l/min for 5 min with the device turned off, and then for 5 min with the device turned on. The fresh gas flow rate was maintained at 10 l/min for an additional 5 min, and was then decreased to at least 2 l/min. Under these experimental conditions, anesthetic concentration was reduced to less than 5 ppm in fewer than 10 min. The effectiveness of activated charcoal in removing environmental toxic gas is well known, and an early adaptation of a charcoal filter to an anesthesia machine was described by Jantzen *et al.*[11,12] The previously cited study by Reber *et al.*[3] utilized an older generation anesthesia machine which had a simple internal design and not the complex internal circuitry of the modern ones.

The feasibility of utilizing autoclaved components to replace parts of the breathing circuit readily accessible to anesthesia providers was examined by Whitty *et al.*[13] using a Dräger Fabius GS anesthesia machines (Dräger). The study focused on reducing the preparation time of an anesthesia

machine by replacing the workstation's exchangeable and autoclavable components: the ventilator diaphragm, ventilator hose, and the compact breathing system, components where uptake of anesthetic gases has been well documented. Six Dräger Fabius GS machines were utilized in four different modifications. Each machine was primed for 2 h with 1.5% isoflurane in air using a fresh gas flow rate of 3 l/min while ventilating a model lung. Next, each machine had its vaporizer removed and the carbon dioxide absorber canister, Amsorb (Armstrong Medical, Coleraine, Northern Ireland), circle breathing circuit, model lung, and reservoir bag replaced.

Six experiments were then conducted in each of four groups evaluating the effect of no replacement (control group), replacement with autoclaved ventilator diaphragm and ventilator hose (group 2), flushed ventilator diaphragm and ventilator hose (group 3), and autoclaved compact breathing system (group 4). The replacement components were autoclaved at 132°C for 10 min to release any retained gases. The results showed that the washout of isoflurane to a concentration of 5 ppm in a Dräger Fabius GS was twice that of the Dräger Primus. In addition, the results of the study showed that the time required to washout trace isoflurane gas to 5 ppm was significantly faster in group 2 (42 ± 6 min), relative to groups 1 (151 ± 17 min), 3 (137 ± 7 min), and 4 (122 ± 11 min). However, it was noted that group 2 had the highest isoflurane concentration, 46 ± 6 ppm (double the concentration of gas compared with the other groups), during the late washout phase when the flow rate was reduced to 3 l/min. This result was thought to reflect the shorter time period to flush anesthetic gases from other nonreplaceable components of the anesthesia machine. However, all groups had concentrations above 10 ppm when fresh gas flow rates were adjusted from 10 l/min to 3 l/min.

Review of the cited literature led to a common finding in all the anesthesia machine washout studies: the rebound effect. This observation was made under conditions when low (5–10 ppm) anesthetic concentrations were established and maintained at high fresh gas flow rates; however, reducing the fresh gas flow rate resulted in an increase in anesthetic concentration beyond this acceptable limit. This rebound effect was thought to occur because of several factors. The internal components of anesthesia machines contain more plastic, rubber, and silicone material, which, as noted previously, absorb and release anesthetic gases.[6] The configuration of the internal breathing circuitry also creates dead zones or poorly ventilated compartments resulting in pockets of trapped gas.[7,8] Such pockets contain potentially high concentrations of gas that wash out slowly over time. The introduction of fresh gas decoupling as a means to ensure accurate and precise delivery of tidal volumes during mechanical ventilation interrupts purging of the anesthesia machine during the preparation period.[14] The fresh gas decoupling device directs "extra" fresh gas to the rebreathing bag during inspiration, thereby ensuring accurate tidal volume delivery by the ventilator; but this extra fresh gas will not leave the rebreathing bag and enter the breathing circuit until expiration. As such, fresh gas decoupling prevents newer generation machines from being purged during all phases of the respiratory cycle. Incomplete flushing of the anesthesia system per ventilator cycle therefore requires more time than older models, which did not have a fresh gas decoupling device. Anesthesia machines equipped with compliance/tidal volume compensation to ensure accurate delivery of tidal volume are not restricted to a particular cycle of ventilation; however, a microprocessor over the course of six breaths compensates for changes in fresh gas flow by reducing the oxygen flow driving the ventilator bellows, which will slow anesthetic egress from this compartment.[14]

The complexity of the modern anesthesia workstation makes it difficult to reduce the concentration of residual gas in a simple and timely manner. One study suggested that it may be more prudent to maintain an anesthesia machine specifically for MH-susceptible patients. However, the costs involved in purchasing, maintaining, and routinely inspecting a spare anesthesia machine and having it on standby specifically for these patients in the current economic healthcare environment seem impractical. As a spare machine for use as a replacement during an MH crisis, the time and personnel involved in replacing an anesthesia machine during an MH event would have to be weighed against the time and personnel needed to flush the anesthesia machine and care for the patient.[3]

Utilizing an intensive care unit ventilator in conjunction with an intravenous technique for MH-susceptible patients is another possibility, especially as a replacement for the anesthesia ventilator during a MH crisis. This alternative may reduce the risk of exposure to anesthetic vapors, but it would only be applicable to institutions where such equipment is readily available and would add the inherent risk of employing equipment unfamiliar to anesthesia providers. This option must also be exercised with caution because intensive care unit ventilators may have been used to deliver potent anesthetic gases for the management of status asthmaticus in adults and children, and the purge times necessary for these machines are unknown. In addition, the same concerns for maintaining a clean anesthesia machine apply for a designated intensive care unit ventilator for operating room use and cannot be recommended as a standard of care. Hand ventilation or spontaneous ventilation with a Mapleson circuit and an uncontaminated oxygen source represents more a familiar alternative and may be more suitable for emergencies, but each may not be applicable for certain surgeries. A novel approach to quickly reduce the concentration of anesthetic gas delivered to the patient was the installation of an activated charcoal filter on the inspiratory limb of the patient breathing circuit. Such a technique may balance safety and efficiency but requires further testing.[10,11]

A major impediment to validating guidelines for purging anesthesia machines is that a maximum "safe" concentration

to which a MH-susceptible patient can be exposed is not known. Moreover, such a limit may never be known because of the high morbidity and mortality of MH, the restrictions placed on human studies involving significant health risks, and the incomplete penetrance and variable expressivity of MH—up to 50% of MH-susceptible patients have documented prior, uneventful anesthetics where triggering agents were used.[15] In the absence of comprehensive patient data, many studies utilize swine models of MH, where 5 ppm of anesthetic gas is reported not to trigger MH.[9] The MHAUS recommendations for purging anesthesia machines attempt to decrease residual anesthetic vapors to concentrations that are as low as possible, targeting levels within the anesthesia breathing circuit to less than 5 ppm.

Although extending toxicology data from animals to humans is fraught with difficulties secondary to pharmacodynamic, pharmacokinetic, and developmental differences among species, these limitations are intrinsic to all animal studies and are the benchmark for preclinical safety assessments for all drugs. Vapor anesthetics nevertheless possess similar pharmacodynamic variables in swine and humans and the swine model of MH faithfully reproduces the clinical aspects of MH. At present, there are insufficient data on humans to affirm or refute 5 ppm as a level that is safe for human exposure. It is of note, however, that there are no case reports of triggered MH events in susceptible operating room personnel during their daily work, suggesting that such individuals are able to tolerate low concentrations of anesthetic vapor without adverse consequences.

The National Institute of Occupational Safety and Health has created an even more stringent standard for occupational exposure for operating room personnel. In 1977, recommendations were made by the National Institute of Occupational Safety and Health** to limit exposure to waste anesthetic gases. The limits of exposure were established as 2 ppm of halogenated anesthetic agent used alone and 0.5 ppm when used in combination with nitrous oxide. These limits are measured using a time-weighted average of samplings of operating room air; however, it has not been established that this level of exposure is safe (or unsafe). These standards were created not in relation to a defined toxic limit of exposure, but largely on what concentrations could be detected using the sampling and analysis techniques recommended by the National Institute of Occupational Safety and Health at the time. This limit therefore would have questionable applicability to anesthesia machine preparation for MH. More importantly, the limits of exposure established in 1977 were based on studies of halothane, enflurane, methoxyflurane, and other gases used before this time period. "The levels of risk for isoflurane, desflurane, and sevoflurane have not been established," and therefore occupational exposure limits have not been determined.††

In the absence of new directives and based on our review, we suggest purging anesthetic gases from modern anesthesia delivery systems by following some basic steps. The most important step is to allow sufficient time to flush the internal components of gases. This can be achieved with as little as 5 min in the Dräger Primus/Apollo or as much as 104 min in the Dräger Fabius. The second most important step would be to utilize a high fresh gas flow rate, typically 10 l/min, throughout the case to avoid the rebound phenomenon. Autoclaving or replacement of exchangeable internal components may be necessary to expedite degassing as suggested by studies and the two main suppliers of anesthesia machines, Dräger Medical AG & Co. KG (Drägerwerk AG) and Datex-Ohmeda (GE Healthcare). Finally, the solubility of anesthetic gases in the internal components of the anesthesia machine vary; agents with higher blood solubility possess greater solubility in plastic and rubber, with halothane > isoflurane > sevoflurane > desflurane.[10] Therefore, the purge time may in part be dictated by the most soluble anesthetic gas available on the anesthesia machine. For example, in one study looking at Ohio Modulus I anesthesia machines, it was found that isoflurane washed out three to four times faster than halothane given the same conditions of priming of the anesthesia machine.[4]

We were unable to find any studies on purging anesthetic gases from the latest GE anesthesia workstations. These machines continue to maintain the basic internal flow circuitry as previous models, with the addition of compliance/tidal volume compensation feedback. The latest models also allow for a quick exchange of the external breathing circuit or advanced breathing system, potentially removing a significant reservoir of anesthetic gases.

In conclusion, the development of modern anesthesia workstations has not been accompanied by new guidelines for their preparation in MH-susceptible patients. The current recommendations are based on studies of older generation machines and are thus inadequate for modern workstations. The latest studies of modern anesthesia machines propose a very time-consuming and often cumbersome washout process. Alternative solutions appear impractical or require further investigation. We note the absence of a known safe exposure level for MH-susceptible patients. An extension of animal data to humans is a process that is inherently questionable but remains representative of the best available data and the source for the current MHAUS guidelines. We encourage a comprehensive study of all anesthesia machines currently in use and the development of guidelines for their proper preparation through a collaborative effort of the different anesthesia machine manufacturers, the Ameri-

** National Institute for Occupational Safety and Health. March, 1977. *Criteria for a Recommended Standard: Occupational Exposure to Waste Anesthetic Gases and Vapors*. Cincinnati, Ohio: U.S. Department of Health, Education, and Welfare. Public Health Service. Center for Disease Control. National Institute for Occupational Safety and Health. DHEW (NIOSH) Publication No. 77-140. Accessed June 1, 2010

†† http://www.osha.gov/dts/osta/anestheticgases/index.html#C2. Accessed June 1, 2010..

Table 1. Study Recommendations for Preparing Anesthesia Machines for Malignant Hyperthermia–susceptible Patients

Recommendation	Ohmeda Modulus I[4]	Ohmeda Modulus II[5]	Ohmeda Excel 210[7]	Datex-Ohmeda AS/3[8]	Narkomed GS[10]	Drager Primus/ Apollo[9]	Drager Primus[7]	Drager Fabius[10]	Drager Fabius GS[13]	Siemens KION[6]
Preparation time, min	5	15	7	30	20	5	70	10 min, filter*; 104 min, no filter	50	≥ 25 min for 10 ppm
Fresh gas flow, l/min	10	12	10	10	10	10	10	10	10	10
Vaporizer	Remove	Remove	Remove	Remove	Remove	Remove	Remove	Remove	Remove	Remove/Off
Breathing circuit	New	New	New	New	New	New	New	New	New	New
Fresh gas hose	New	New	New	NA	NA	NA	NA	NA	NA	NA
Carbon dioxide canister, absorbent	No change	New absorbent	New absorbent	New absorbent	New absorbent	New absorbent	New absorbent	New absorbent	New canister, absorbent	Exclude
Special instructions	Avoid previously used ventilator	No reference to ventilator	Replace ventilator bellows, tubing	Ventilator V_T 1 l RR 10/min I:E 1:2 FGF 10 l/min during case T-piece circuit only FGF 10 min	Ventilator V_T 600 ml RR 10/min I:E 1:2 FGF 10 l/min	FGF 10 l/min during case Replace with autoclaved ventilator diaphragm and integrated breathing system	FGF 10 l/min during case	Ventilator V_T 600 ml RR 10/min I:E 1:2 FGF 10 l/min	Ventilator V_T 500 ml RR 15/min FGF 10 l/min Replace with autoclaved ventilator diaphragm and tubing Rebound in gas level at FGF 3 l/min	Ventilator V_T 500 ml RR 15/min PEEP 0 FGF 10 l/min during case

* Charcoal filter (QED® or Quick Emergence Device; Anecare Laboratories, Salt Lake City, UT) on inspiratory limb; FGF ≥ 10 l/min for 5 min with filter off, then 5 min with filter on and FGF ≥ 10 l/min for first 5 min of case, then FGF ≥ 2 l/min for at least 6 h.

FGF = fresh gas flow; I:E = inspiratory to expiratory ratio; NA = not available (no reference); PEEP = positive end-expiratory pressure; ppm = parts per million; RR = respiratory rate; V_T = tidal volume.

can Society of Anesthesiologists, the Anesthesia Patient Safety Foundation, and MHAUS. In the interim, we recommend modifying the MHAUS guidelines for specific anesthesia workstations and summarize the procedures for preparing the different anesthesia machines discussed in this paper (table 1).

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