A New Era of Anesthetic Equipment

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***Abstract* - Long duration space missions are becoming highly probable, and with them arise new challenges. Maintaining the long term health of astronauts and developing the appropriate equipment for advanced medical interventions suitable for space becomes incredibly important. Surgical interventions especially are a problematic scene given the complexity and size of the required equipment for general anesthesia. As a result, creating advanced inhalational anesthetic devices that are small and light weight is needed for these long duration space missions. The past decade has brought a host of advances that would allow the development of smarter, smaller, lighter, and more efficient machines. These include pharmacokinetic and pharmaco-dynamic models to create feedback delivery systems, better sensing technologies to meter precise gas delivery, and closed breathing circuits that conserve anesthetic agents. However, despite these advances, anesthetic machines and devices still remain incredibly heavy and bulky, and ill-suited for space travel. A brief summary of technological advances will be discussed as well as preliminary results in measuring the concentration of volatile anesthetics using convective heat transfer principles.**

I. INTRODUCTION

Modern inhalational anesthetic machines are designed to provide a variety of functions in the administration of anesthesia – delivery of fresh gas flow of oxygen and anesthetic vapor to a patient through a breathing circuit, sensing and monitoring of these gas concentrations, and ventilating the patient either though spontaneous, manual, or mechanical means. An ideal anesthesia machine would allow for instantaneous control and manipulation of these parameters, with little to no risk to the patient. Sensing and delivery of anesthetic agents has greatly improved, allowing for highly controllable systems. Still, anesthetic equipment remains cost and resource prohibitive for many applications. The next steps in improving anesthetic machines will come from creating compact, efficient, and low cost technologies while retaining the precision and accuracy of current methods. Realizing the key components of anesthetic machines and their respective recent advancements is crucial for innovation.

Accurately dosing of anesthetic vapors is the central function of any anesthetic machine and fundamental to the practice of anesthesia. When anesthetics are delivered inaccurately or inappropriately, adverse side effects can lead to inadequate sedation, postoperative complications, or even mortality. Most modern anesthetics are liquid at room temperature but are highly volatile, allowing for easy vaporization and subsequent inhalation. Delivery of these anesthetics is achieved via controlled vaporization into a carrier gas, most often oxygen (Figure 1). Because different anesthetic agents have varying physiological and physical characteristics, controlled dosing is challenging. To address the issues of varying physiological effects of each anesthetic agent, the notion of minimum alveolar concentration (MAC) was introduced in 1965 to standardize anesthetic potency [1].

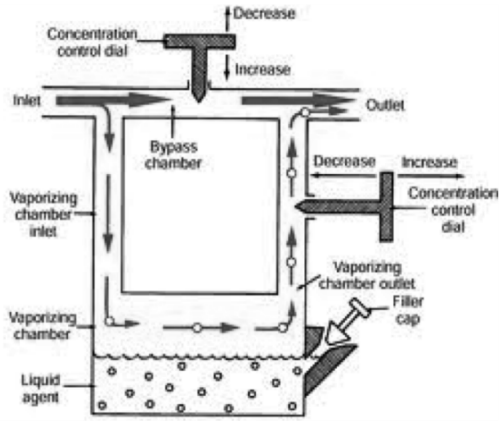

Figure 1. Schematic of a traditional volatile anesthetic vaporizer. The carrier gas is diverted across the surface of the fluid where the anesthetic then vaporized and carried to the patient. (Sandberg 2011)

Specifically, MAC is the exhaled concentration of anesthetic gas needed to prevent patient movement in response to a skin incision on 50% of the population.

Expired concentration of anesthetic is one of the best measurable indicators of how deeply a patient is anesthetized as it directly correlates to the concentration in the body [2]. However, this still leaves the challenge of varying physical properties of each anesthetic, notably the differing vapor pressure. As a result of this, anesthetic machines typically contain multiple vaporizers that are calibrated and designed for the different properties of each gas, allowing for the specific titration of each individual anesthetic. This in of itself causes a large amount of redundancy in anesthetic machines making them incredibly large and bulky.

Despite the fact that specialized anesthetic vaporizers are needed for every unique agent, changes in pressure, flow rates, and temperature can still affect vaporization. This results in discrepancies of set delivered concentrations and actual delivered concentrations. Monitoring the inspiratory concentration of anesthetic is critical to ensure an appropriate and safe amount of anesthetic is being delivered to the patient. Measuring the expiratory concentration also helps to determine the current depth of anesthesia. Monitoring oxygen and carbon dioxide levels is also required during anesthetic maintenance [3]. Oxygen concentration needs to be sustained above a certain level and monitored to avoid delivering hypoxic mixtures to the patient[4]. Carbon dioxide must also be measured to determine pulmonary perfusion, alveolar ventilation, respiratory patterns, and appropriate elimination of carbon dioxide from the breathing circuit [5]. The current technology uses side stream infrared analysis to determine anesthetic agent and carbon dioxide concentration with high accuracy as each anesthetic gas absorbs different wavelengths of infrared light [6].

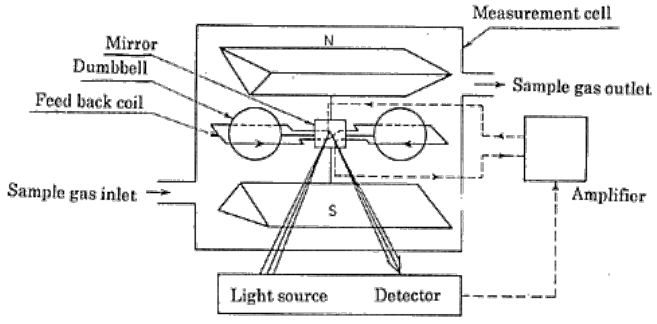

Figure 2. Schematic of a dumbbell type oxygen analyzer. When a sample gas is containing oxygen is introduced, the dumbbell twists and causes a light to move across a detector. (White 2016)

Oxygen is sensed using either galvanic, polarographic, or paramagnetic techniques. The paramagnetic method is most commonly used in modern anesthesia devices, and takes advantage of interactions between the free electron pair in oxygen and magnetic fields to determine concentration [7] [8] (Figure 2).

Another side effect of anesthetic drugs is depressing the patient's respiratory drive and ultimately causing apnea, a fatal condition if left untreated. Ventilators are required to mechanically move gases, including oxygen and anesthetic vapors, into the lungs and remove carbon dioxide from the lungs [9]. Most anesthetic machines contain automatic ventilators to relieve the anesthesiologist from having to physically squeezing manual ventilators. Gases are forced into the lungs by bellows, pistons, or blowers creating changes in pressure. Various parameters can be controlled in these ventilator systems including tidal volume, positive end-expiratory pressure (PEEP), and respiratory rate [10]. These parameters are adjusted and controlled through a combination of pressure and flow sensors. Smart technologies in these ventilators allow for detection in attempted spontaneous breathing in patients who are not fully apneic. Ventilators are designed to support patients' spontaneous breathing efforts and to match patient's natural physiological respiratory drive.

II. RECENT TECHNOLOGICAL ADVANCES

The past decade has brought a variety of major technological advances to anesthesia care. Understanding these advances is fundamental for innovation in the field.

A. Direct Injection of Volatile Anesthetics

Recent attempts have been made to reduce and remove influences of pressure and temperature on anesthetic agent concentration by direct injection of volatile anesthetics [11]. Because the anesthetic agents are metered while still in liquid phase, this method allows for highly controlled titration of anesthetic agent regardless of the chosen carrier gas. It also results in rapid concentration changes in closed loop breathing systems. This technology has recently been realized in the PhysioFlex and Zeus anesthesia machines, both manufactured by Dräger. These machines store the

anesthetic liquid bulk in a reservoir unit where it then travels to a dosing chamber to be pressurized accordingly. Finally, a specific dose of agent is released into a heated vaporizing chamber for vaporization and delivery into the breathing system. This direct injection of anesthetics not only allows for higher precision in set gas concentrations, but also achieves the stability needed for automatic closed-loop feedback control. A target expiratory gas concentration is set by the user, then pharmacokinetic and pharmacodynamics models are used to calculate the necessary inspiratory concentration to achieve the target expiratory concentration. Gas sensors at both the inspiratory and expiratory limb ensure appropriate and safe dosing from the injection as well as help in controlling anesthetic dosing.

B. Anesthetic Agent Conserving Device

Extremely low metabolism of anesthetic agents creates an opportunity to reuse exhaled anesthetic gases during the course of an operation [12]. An anesthetic conserving device (ACD) has been introduced to achieve precisely this function [13]. This system administers liquid anesthetic using a syringe pump connected to a porous rod where, due to the large surface area, the anesthetic instantaneously vaporizes. Elsewhere in the breathing circuit, activated carbon fibers are exposed to the expired anesthetic gas where the vapor is absorbed (Figure 3). During the next inspiration, the anesthetic desorbs from the carbon and is reused to maintain anesthesia [14]. This conserves anesthetic agent and reduces waste.

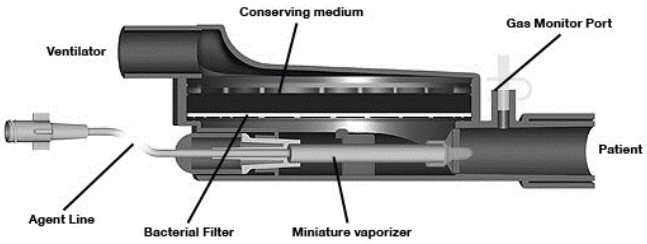

Figure 3. Schematic of an anesthetic conserving device used to recycle exhaled anesthetic. As anesthetic agent travels across the conserving medium, or activated carbon, it is absorbed. Following the next inspiration from the patient, the anesthetic agent is desorbed to be reused. (Sedana Medical 2016)

C. Infrared Low-Cost Analyzer

Using infrared absorption to determine anesthetic agent and carbon dioxide remains the primary method in modern anesthetic equipment. However, significant headway has been made in creating compact integrated gas benches. Dräger Medical has introduced the Infrared Low-Cost Analyzer (ILCA) that utilizers solid-state technology and integrated design yielding a highly compact device that is capable of measuring all current anesthetic agents, carbon dioxide, and nitrous oxide. The device functions by splitting infrared light into four directions and then passing it through narrow-band filters that fit the peak absorption rates of the gases to be analyzed. This light finally reaches a pyroelectric detector chip where the level of absorbance corresponds to the gas concentration (Figure 4). Due to the narrow-band filters, the ILCA is also resistant to error due to absorption of other gases or water.

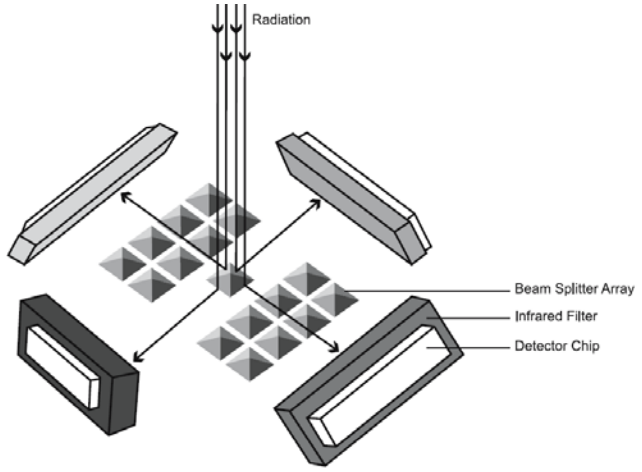

Figure 4. Schematic of the detection method used in the ILCA gas analyzer. (ProMed Strategies 2009)

D. Closed-Circuit Anesthesia

Closed-circuit systems have become the newest improvement to anesthesia delivery systems. These systems function by matching both the oxygen and anesthetic agent consumption of the patient, as opposed to previous methods of having a constant low fresh gas flow and scavenging system for wasted gas (Figure 3). Similar to the anesthetic conserving device, this results in less anesthetic waste and release into the environment through the scavenging system. This closed-breathing

circuit also allows for additional monitoring of oxygen and anesthetic agent consumption. As oxygen and anesthetic agent levels decrease, the machine automatically replenish the gases accordingly. Additionally, this method ensures that the total amount of gas remains constant within the system. This results in quantitative and autonomous anesthesia delivery systems that adjust and maintain expiratory anesthetic concentrations, inspiratory oxygen levels, and total breathing circuit volume.

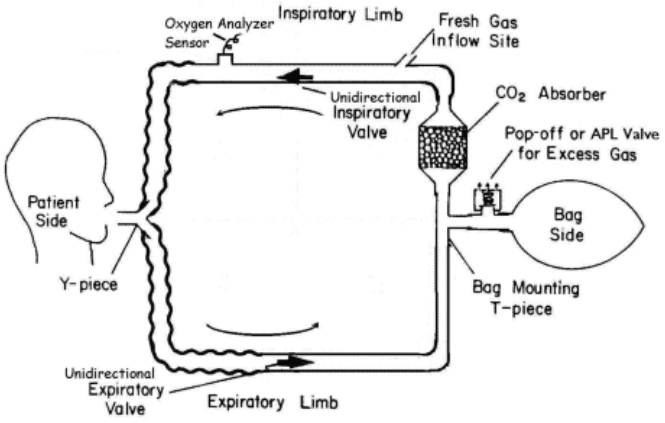

Figure 5. Schematic of a closed-circuit anesthesia system. As anesthetic agent is absorbed, oxygen consumed, and carbon dioxide remove, fresh gas is introduced at the inflow site to maintain volume and concentrations. (OSHA 2016)

III. CURRENT WORK

With the incorporation of feedback control into anesthesia machines, the limiting factor is most often the accuracy and precision of the gas sensor. The gas analysis also constitutes one of the more expensive features in anesthetic machines. However, a multitude of physical and chemical property differences between anesthetic gases, oxygen, and carbon dioxide presents new opportunities to measure gas concentration beyond what is currently used. Hot wire anemometry is a common method to measure gas flow by utilizing convective heat transfer. As fluid flows across a heated resistive wire, the filament is cooled. Higher fluid velocities yield increased cooling, and therefore measuring the required voltage to maintain a constant temperature in the filament is directly proportional to the fluid velocity (Figure 6). Given a known flow rate, this method can also be used to determine the concentration of fluids with different heat

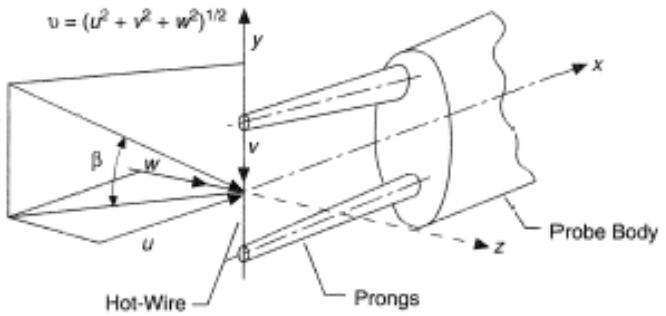

Figure 6. Working principle of hot-wire anemometry. As fluid flows across a suspended hot-wire, the resulting decrease in temperature will be proportional to the increased voltage required to maintain the temperature. (Thermopedia 2016)

capacities [15]. Using this concept to measure anesthetic agent concentrations inline would yield an inexpensive, simple, and compact alternative to infrared analysis of gases. A preliminary study was performed to determine the real world feasibility of such a system.

IV. METHODS

A hot wire anemometer (AWM700 Series Airflow Sensor, Honeywell, Golden Valley, MN) was placed inline of a fresh gas flow outlet at known flow rates ranging from 2-12 liters per minute (measured using VT-Plus Gas Flow Analyzer, Fluke Corp., Everett, WA). This gas flow contained 0-3.25% isoflurane (measured using an infrared gas bench, Datex-Ohmeda, Helsinki, Finland) and a balance of oxygen. Baseline measurements were used to calibrate the hot wire anemometer voltage at 0% isoflurane. When isoflurane was introduced into the system, deviations from this baseline voltage were attributed to changes in the isoflurane concentration.

V. RESULTS

A total of forty-two isoflurane estimations were obtained. The estimated isoflurane concentration was highly correlative with the measured Datex-Ohmeda Gas Analyzer isoflurane concentration with an average error of 0% isoflurane and standard deviation of 0.04% isoflurane (Figure 7).

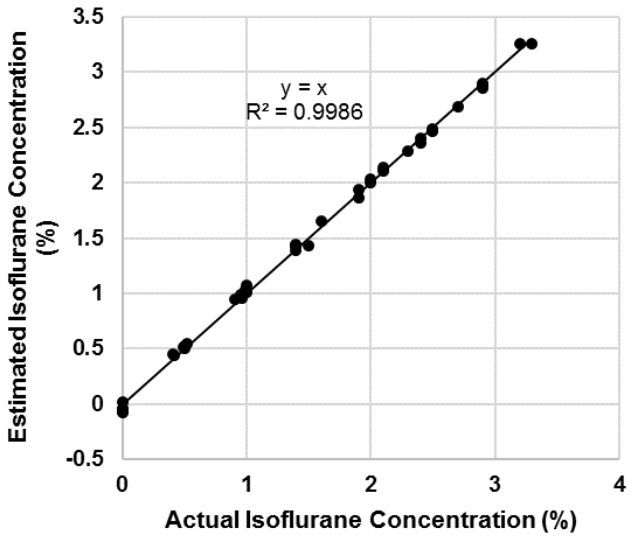

Figure 7. Estimated isoflurane concentration using hot wire anemometer versus actual isoflurane concentration.

VI. CONCLUSION

Anesthesia technology has improved significantly within the last decade. However, there is still considerable potential for innovation. Preliminary results suggest that hot wire anemometry may be an effective mainstream method to measure volatile anesthetic gas concentration. This would allow the creation of a cheaper anesthetic machine with improved feedback control properties. Further studies will be performed to confirm these results in conditions that include pressure variations and the presence of humidity and carbon dioxide.

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