Using Activated Charcoal to Reuse Anesthetic Gas

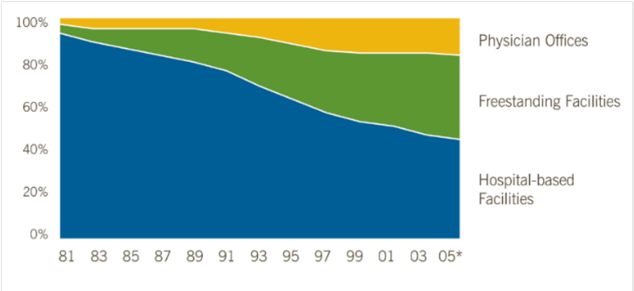
Patrick Kolbay, Joseph Orr, Kai Kück*
University of Utah

Abstract - **General anesthesia enables surgery, with anesthesia machines being the predominant tool to do so. However, these machines are hard to maintain, costly, and require significant supporting infrastructure. The current design of anesthesia machines demands the disposal of anesthetic gases at a rate equal to fresh oxygen entering the system. This causes several orders of magnitude more anesthetic vaporized than needed, yielding negative economic and environmental impact. To address this, we propose utilizing the porous surface of activated charcoal to absorb and desorb the anesthetic gases to be reused.**

I. INTRODUCTION

Anesthesia machines and systems are at the center of surgical care. Since their initial conception, the design and technology of anesthesia machines has become fine-tuned and perfected for the standard operating room. However, the demand for anesthetic care has grown tremendously in areas outside the hospital and the anesthesia machine has not been able to keep pace. Within the United States, the economic realities of health care and demands have pushed access from in-hospital to outpatient settings[1]. Globally, underdeveloped countries have been unable to match the pace of improved outcomes in anesthesia seen in the developed world[2]. These shifts in anesthesia care have led to a strikingly high incidence of preventable anesthesia-related mortality outside the hospital[3]–[5]. While there are various contributing factors to this mortality, the anesthesia machine remains a predominant factor in being unable to meet these new needs[2], [6], [7].

In outpatient clinics and small-office practices, the large migration from hospitals to office-based anesthesia has not been accompanied with the same adherence of safety standards. This lack of safety comes largely in the form of deficiencies in equipment and monitors. With the high capital costs of anesthesia machines, large size, and necessity for high pressure oxygen and scavenging lines, many clinicians turn to potent intravenous anesthetics without the presence of ventilation equipment or monitoring[8]. In the event that a patient exhibits respiratory depression or develops an airway obstruction or apnea, the likelihood of a successful resuscitation is be markedly reduced, and the effects of this have already been demonstrated. The ASA Closed Claims analysis has shown that office-based claims had more than tripled the number of deaths, 67% versus 21%, compared to their hospital counterparts. Furthermore, almost half of these claims were deemed preventable by better monitoring[9]. In a



Source: Verispan's Diagnostic Imaging Center Profiling Solution, 2004. *2005 values are estimates.

Figure 1 - Migration of anesthesia-related procedures from 1981-2005. Current statistics show that majority of outpatient procedures are now performed outside the hospital.

more controversial study, the frequency of incidence and death was found to be an order of magnitude higher in the small-office compared to the hospital[10]. With outpatient surgery rapidly migrating to non-hospital settings, this discrepancy in quality of care is becoming increasingly concerning (Figure 1)[1].

Anesthesia in low-resource areas is facing similar issues. Because the healthcare systems and the means to support complex technology in the developing world is often inadequate, many countries turn to importing their equipment despite it being often ill-suited for the environment. For many countries, there is an distinct emphasis on healthcare equipment funded by both international donors and foreign governments, with donations comprising nearly 80% of the incoming equipment[11]. However, because of sophistication of these devices, and the expertise and parts required to maintain them, anesthesia machines are particularly prone to fall by the way side, with as little as 10% of these machines ever becoming operational[12]. This makes operating facilities incredibly scare for these low resource areas with the estimated number of operating rooms per 100,000 people being more than 25 times less than high-income regions[13]. Additionally, the operating rooms that do exist in developing countries encounter significantly more adverse events and mortality. In the United States, the estimated mortality risk of anesthesia was 0.82 in 100,000 between 1999-2005[14]. Comparatively, the risk of death due to anesthesia was 3.14 in 10,000 for developing countries, nearly 40 times higher[5]. Developing anesthesia equipment that targets these issues could improve outcomes significantly.

Future advancements to the anesthesia machine will need to both increase device longevity and reduce capital and operational costs to encourage adoption. After surveying the components and technologies used in anesthesia machines, the infrared spectrophotometer used to monitor anesthetic gas concentrations becomes a prime target for redevelopment. The infrared spectroscopy represents a large portion of the capital costs in anesthesia machines due to the complex and fragile optics involved. Creating an alternative to this technology would greatly expand access to adequate anesthesia care. Another area of potential improvement in the anesthesia machine targets how anesthetic gases are recirculated. Currently anesthetic gases must be removed from the system at the same rate as incoming oxygen, despite anesthetics being largely unmetabolized by the patient. Because of this design choice, over the course of a 2 hour procedure, more than an order of magnitude more anesthetic is vaporized than needed. Developing a method to conserve these anesthetic gases would decrease the overall cost, and even potentially remove the need for scavenging systems installed in hospitals. Lastly, creating an automated anesthesia machine that monitors patient vital signs and adjusts the delivery of anesthesia accordingly could significantly aid clinicians who are not as highly trained in anesthesia care. While all of these aspects are being investigated, the focus on this paper will be the development of a medical device to reuse anesthetic gases.

To address the poor efficiency of anesthetic use, an understanding of current anesthesia machines is essential. Current anesthesia machines are divided into four breathing circuit types: open, semi-open, semi-closed, and closed. These circuit types refer to whether or not rebreathing occurs in the system, specifically where semi-closed and closed system do have rebreathing. Most modern anesthesia machines used in the developed world are semi-closed systems, introducing a rebreathing circuit to reuse the anesthetic gas to a partial degree.

However, anesthetic still must be removed from the system at the same rate as incoming fresh oxygen and remains non-ideal. Even worse are the anesthesia systems found in the developing world, most often being open or semi-open breathing circuits which do not incorporate any mode of rebreathing and as a result make no attempt at reusing anesthetic. Designing a system that can be used in both of these types of systems would address the largest pool of machines.

An inspiratory-expiratory loop anesthesia machine add-on capable of reflecting the anesthetic gas would fit this criteria. Conveniently, the porous surface of activated charcoal makes it a potential medium to absorb and desorb anesthetic gases, and has already been shown effective in sequestering anesthetic gases for those susceptible to malignant hyperthermia[15]. To explore the suitability of activated charcoal in reflecting anesthetic gases, we have created an anesthesia machine add-on prototype with the intended use of reducing the overall quantity of anesthetic needed in the operating room.

II. METHODS

A. Feasibility Testing

To test the feasibility of using activated charcoal as a reflecting medium, a crude prototype was created containing activated charcoal. Specifically, 5 liter per minute flow of oxygen and 5% isoflurane (Piramal Healthcare Limited, Andhra Pradesh, India) was delivered through a cylindrical vessel containing 42 grams of activated charcoal (Oxpure 1220C-75, Oxbow Activated Carbon, West Palm Beach, FL) until 0.5% isoflurane pushed through the charcoal. Flow was then reversed through the vessel at 2 liters per minute with pure oxygen and the concentration of isoflurane leaving the vessel was monitored using a standard side stream infrared gas bench (Datex-Ohmeda, Helsinki, Finland).

B. Prototype Device Design

After promising results, a more advanced two chamber housing was 3D printed using UV-cured MED-10 biocompatible plastic. The design allows for bypass of inhaled/exhaled gas to either pass freely without interference or through a cartridge containing 12 grams of activated charcoal (Oxpure 1220C-75, Oxbow Activated Carbon, West Palm Beach, FL)(Figure 2).

An MCU monitors and controls a variety of sensors and components associated with the device based off a custom PCB (Figure 3). A gear controlled by a 12V small reduction stepper motor controls what proportion of the gas flow is directed through each chamber. To determine inspiratory or expiratory flows, multiple differential pressure sensors (MPXV7002DP Integrated Silicon Pressure Sensor On-Chip Signal Conditions, Temperature Compensated and Calibrated, NXP Semiconductors, Austin, TC; DLVR-L01D Low Voltage Digital Pressure Sensor, All Sensors, Morgan Hill, CA) in conjunction with Respironics NICO capnograph flow module. The MCU also received oxygen, carbon dioxide, and anesthetic

Figure 2 - 3D rendering of the prototype housing. The design includes a main body with two chambers, one of which contains a charcoal cartridge. This is contained with an end cap. Internally, a gear with a semicircle opening directs flow.

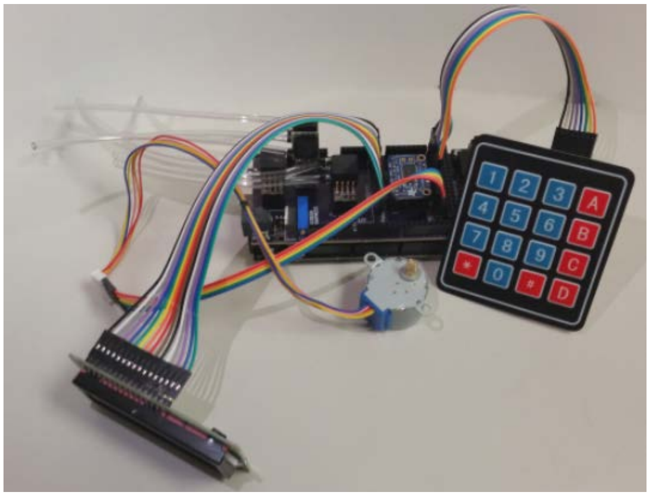


Figure 3 - MCU controller for the anesthetic reflector. Consists of a keypad, LCD screen, stepper motor and driver, and various differential pressure sensors.

agent concentrations from a standard infrared gas bench (Datex-Ohmeda, Helsinki, Finland). Using the anesthetic concentration measured from the infrared gas bench and a set concentration input by the user, a basic feedback loop changed the position of the gear to meet the anesthetic requirements. Additionally, alarms were included and displayed on an LCD screen in the event of high or low anesthetic agent concentration, low oxygen concentration, and low carbon dioxide concentration (possible apnea). The MCU was programmed to saturate the charcoal during anesthesia induction, and run primarily on the reflected gas during maintenance (Figure 4).

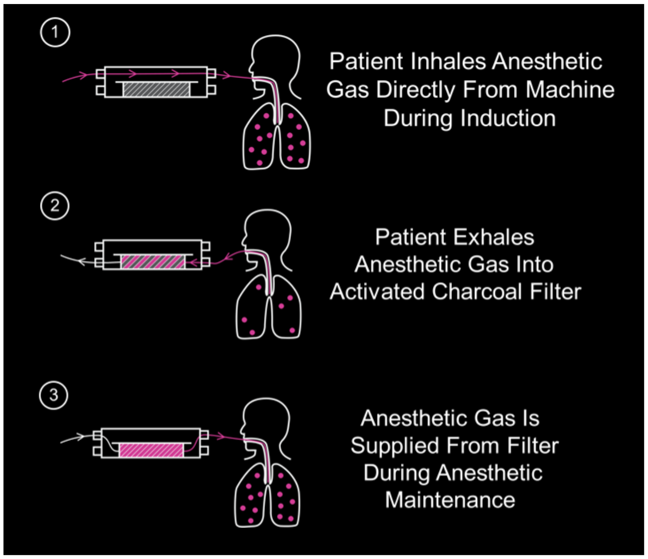


Figure 4 - Schematic of device during use. During induction, the device will alternate between open and filter chamber during inspiration and expiration respectively (Phases 1-2). Once the filter is saturated, all inspiratory and expiratory gas will be passed through that chamber (Phase 3).

III. RESULTS

A. *Feasibility Testing*

Isoflurane was released at concentrations suitable for anesthesia maintenance for a significant amount of time, approximately 10 minutes (Figure 5).

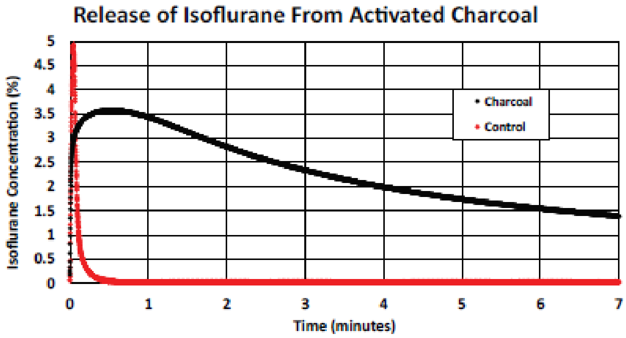


Figure 5 - The observed concentration of isoflurane leaving the vessel containing 40 grams of saturated activated charcoal as the flow was reversed at 2 liters per minute. The activated charcoal (black) allowed for the gradual released of isoflurane compared to the control (red) containing no activated charcoal.

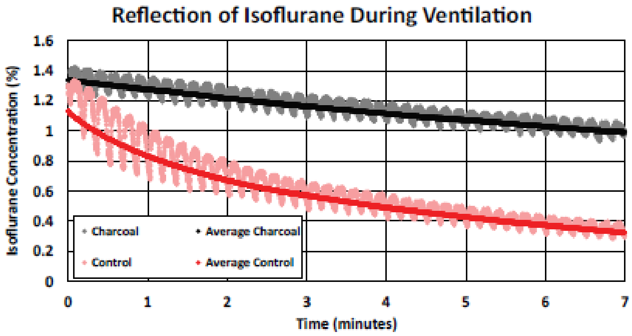


Figure 6 - The observed concentration of isoflurane during ventilation between the vessel of 10 grams of activated charcoal and the test lung. Similar to Figure 5, the activated charcoal (grey) allowed for the gradual released of isoflurane compared to the control (pink) containing no activated charcoal. A running average is shown for both the activated charcoal (black) and control (red).

Ventilation was also tested to investigate more dynamic conditions where the device was ventilated with a test lung (Figure 6). Once saturated, the activated charcoal had absorbed approximately 60% of its total weight in isoflurane, and was capable of repeatedly reflecting 10% of its total weight in isoflurane or about 3.2 mL of liquid isoflurane. This volume of isoflurane capable of being reflected is the equivalent of anesthesia maintenance at 1 MAC for 1 hour at a fresh gas flow rate of 1 liter per minute.

B. Prototype Device Design

A prototype was successfully created and was capable of performing the basic desired functions. Specifically, inspiratory and expiratory flows were detected and a basic “bang-bang” feedback control was implemented to achieve the desired concentration. Future iterations will focus on increasing the speed of the valve control as well as more controllable PID feedback control.

IV. DISCUSSION

Activated carbon has been shown to readily absorb and release anesthetic gases. Creating a system using this material would allow for the implementation of an activated carbon reflector that absorbs, holds, and releases anesthetic gases back to the patient. Not only would this remove the need for an anesthetic scavenging system, but it would also significantly decrease the cost of anesthetic maintenance by reducing the amount of gas vaporized. Preliminary data has shown that 40-mesh activated carbon can capture anesthetic gases and release them with reversed flow at a concentration high enough for sedation. By combining this material with a novel breathing circuit design, we will remove the need for a scavenging system and expand the environments in which anesthesia can be used. Success in this research will ultimately reduce the cost, infrastructure, and expertise needed to deliver general anesthesia. By doing this, the global access to anesthesia and surgical will be greatly increased, reducing the suffering in the world.

Future work will include further development and tuning of this technology, and incorporating it with other advances in the field of anesthesiology to create a novel anesthesia machine that addresses the needs in both the developing world and the emerging small-office anesthesia. These will include better patient monitoring, reduced machine footprint, and patient-included feedback control.

REFERENCES

[1] “The Migration of Care to Non-hospital Settings: Have Regulatory Structures Kept Pace with Changes in Care Delivery,” *Am. Hosp. Assoc.*, 2006.

[2] S. J. Bharati, T. Chowdury, N. Gupta, B. Schaller, R. B. Cappellani, and D. Maguire, “Anaesthesia in underdeveloped world: Present scenario and future challenges,” *Niger. Med. J.*, vol. 55, no. 1, pp. 1–8, 2014.

[3] K. B. Domino, “Office-Based Anesthesia: Lessons Learned from the Closed Claims Project,” *ASA Newsl.*, vol. 65, no. 6, 2001.

[4] D. Bainbridge, J. Martin, M. Arango, and D. Cheng, “Perioperative and anaesthetic-related mortality in developed and developing countries: A systematic review and meta-analysis,” *Lancet*, vol. 380, no. 9847, pp. 1075–1081, Sep. 2012.

[5] M. Khan and F. A. Khan, “Anesthetic deaths in a developing country,” *Middle East J. Anaesthesiol.*, vol. 19, no. 1, pp. 159–72, Feb. 2007.

[6] R. D. Urman and F. E. Shapiro, “Improving Patient Safety in the Office: The Institute for Safety in Office-Based Surgery,” *APSF Newsl.*, pp. 3–4, 2011.

[7] P. Saksena, A. F. Antunes, K. Xu, L. Musango, and G. Carrin, “Impact of mutual health insurance on access to health

care and financial risk protection in Rwanda,” *World Heal. Rep. Backgr. Pap.*, vol. 6, p. 14, 2010.

[8] D. Rex, “Propofol can be used safely by trained registered nurse/endoscopy teams,” 2005. [Online]. Available: http://www.gastro.org/user-assets/Documents/AGAPerspetives_FebMar_2005.pdf. [Accessed: 24-Mar-2016].

[9] S. M. Bhananker, K. L. Posner, C. W. Frederick, R. A. Caplan, L. A. Lee, and K. B. Domino, “Injury and Liability Associated with Monitored Anesthesia,” *Anesthesiology*, vol. 104, no. 2, pp. 228–234, 2006.

[10] H. Vila, Jr, de J. RH, S. W, C. P, and S. R, “Comparative Outcomes Analysis of Procedures Performed in Physician Offices and Ambulatory Surgery Centers,” *Arch. Surg.*, vol. 138, no. 9, p. 991, Sep. 2003.

[11] A. R. Gatrad, S. Gatrad, and A. Gatrad, “Equipment donation to developing countries,” *Anaesthesia*, vol. 62, no. s1, pp. 90–95, Dec. 2007.

[12] “Guidelines For Health Care Equiptment Donations,” *World Heath Organ.*, no. March, 2000.

[13] L. M. Funk *et al.*, “Global operating theatre distribution and pulse oximetry supply: An estimation from reported data,” *Lancet*, vol. 376, no. 9746, pp. 1055–1061, 2010.

[14] G. Li, M. Warner, B. H. Lang, L. Huang, and L. S. Sun, “Epidemiology of Anesthesia-related Mortality in the United States,” *Anesthesiology*, vol. 110, no. 4, pp. 759–765, 2009.

[15] N. Birgenheier, R. Stoker, D. Westenskow, and J. Orr, “Activated Charcoal Effectively Removes Inhaled Anesthetics from Modern Anesthesia Machines,” *Anesth. Analg.*, vol. 112, no. 6, pp. 1363–1370, Jun. 2011.