Combined Ultrasonic Sensing for Low-Cost Anesthetic Agent Detection, Concentration Measurement, and Respiratory Monitoring

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Introduction: Hospitals in austere conditions have been unable to match the reduction in anesthesia-related morbidity and mortality seen in the developed world.[1,2] Lack of healthcare resources and infrastructure has led many developing countries to import medical equipment to try and address this discrepancy, despite these devices often being ill-suited for their environment. Much of this healthcare equipment is being funded by both international donors and foreign governments, with donations comprising nearly 80% of the incoming anesthesia equipment for some developing countries.[3] Despite these donations, the expertise and parts required to maintain them leads to as little as 10% of the donations ever becoming operational. Ultimately, this resource gap contributes to a scarcity of operating facilities in low resource areas, with the estimated number of operating rooms being more than 25 times less than high-income regions, culminating in a 40-fold increase in anesthesia-related death.[1,2]

Ultrasonic sensors have long been used in anesthesia care to measure respiratory flow by measuring the time-of-flight differences between ultrasonic pulses sent both upstream and downstream.[4] However, the transmission times of these pulses can also change due to differences in the gas composition, largely due to changes in density and fluid elasticity.[5] This presents an opportunity to determine anesthetic gas concentration simultaneously to gas flow rate. As a result, we sought to develop an ultrasonic mainstream monitor capable of combined volatile agent detection, anesthetic concentration monitoring, and respiratory flow monitoring at significantly reduced cost and simplicity compared to traditional infrared spectroscopy units in an effort to provide affordable and robust anesthesia monitoring in low-resource areas.

Methods: Our initial prototype consisted of two 200 kHz transducers (Air Transducer 200 KHz, Steminc Inc., Doral, FL) driven and recorded using a development microcontroller (MSP430 Ultrasonic Gas Flow Development Board, Texas Instruments, Dallas, TX). The ultrasound transducers were externally housed perpendicular to a stream of flowing oxygen, with reflectors placed inside the housing to deflect the ultrasound pulses, causing them to run parallel to the gas stream. Isoflurane (Piramal Healthcare Limited, Andhra Pradesh, India), sevoflurane (AbbVie Inc, Chicago, IL), and desflurane (Baxter Healthcare Corporation, Deerfield, IL) were then introduced into the gas flow at concentrations of 0-3.5%, 0-4.0%, and 0-18% respectively, verified by an infrared spectroscopy monitor (Datex-Ohmeda, Helsinki, Finland). The rate of the flowing gas was additionally measured with a screened pneumotach (VT-Plus Gas Flow Analyzer, Fluke Corp., Everett, WA) and ranged from 0-55 liters/minute. Time-of-flight measurements of the ultrasound pulses both upstream and downstream were then used to determine anesthetic gas concentration and gas flow rate. The difference in time-of-flight correlated to the gas flow rate and the mean time-of-flight correlated to anesthetic gas concentration. Finally, advanced signal processing tools were used to identify which of the three anesthetic agents was present.

Results And Discussion: Flow rate measurements were accurate, with a maximum error of 1.8 liters/minute at the highest flows. Similarly, anesthetic gas concentration measurements for all gases were highly accurate, with 95% of the measurements falling between ±0.17%, ±0.11%, and ±0.20% concentration by volume for isoflurane, sevoflurane, and desflurane respectively (Figure 1). Finally, the system correctly identified which anesthetic agent was present in 96.3% of the over 300,000 samples collected, which was then increased to 98.6% accuracy when the processing was applied as a 10-second filter. Striations seen in the Bland-Altman plots for volatile anesthetic concentration measurement were caused by the changes in flow during testing. Concerning our goal of reducing the cost of anesthetic monitoring, we were able to generate these results utilizing materials that came to a total cost under $80 in single part quantities.

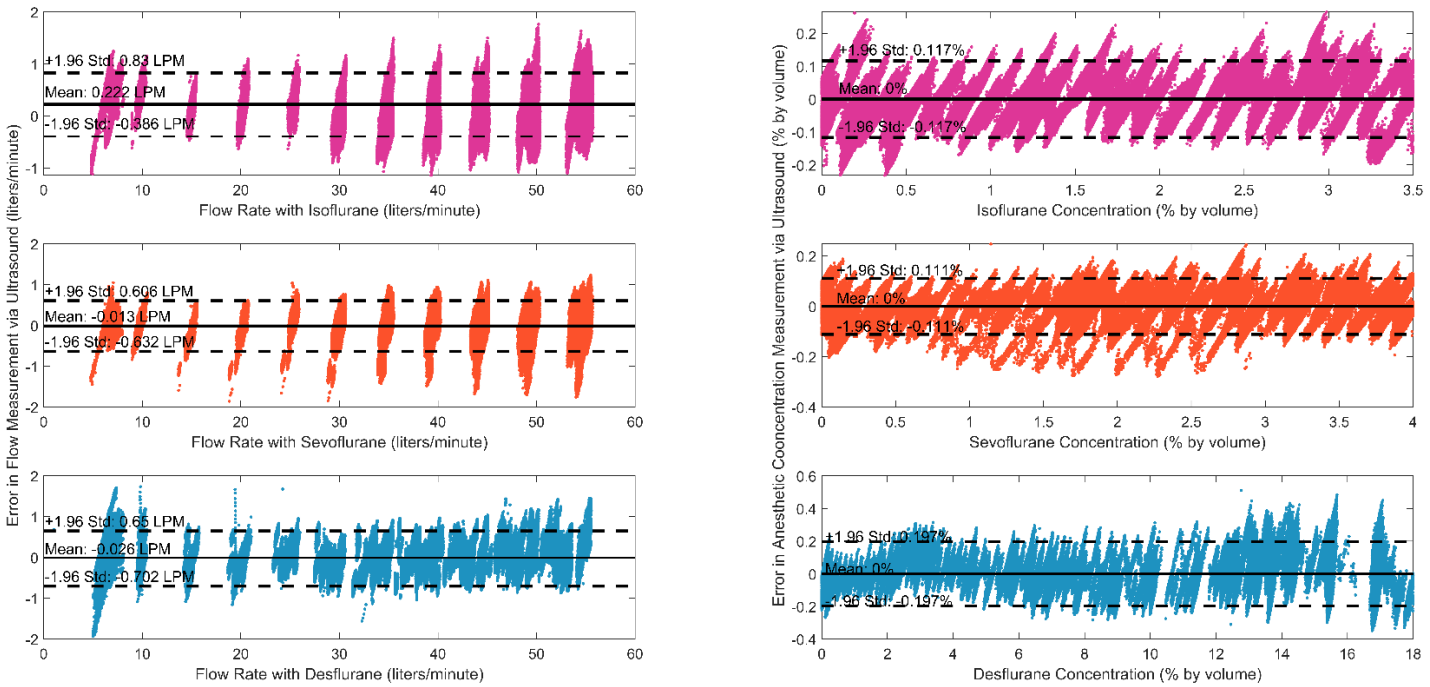

Figure 1 – (Left) Error in flow rate measurement utilizing difference in time-of-flight measurements compared to a screened pneumotach in isoflurane (top), sevoflurane (middle), and desflurane (bottom). (Right) Error in volatile anesthetic gas concentration measurement compared to infrared spectroscopy for isoflurane (top), sevoflurane (middle), and desflurane (bottom).

References:

[1] Bainbridge et al. Lancet 380, 1075–1081 (2012)
[2] Funk et al. Lancet 376, 1055–1061 (2010)
[3] Gatrad et al. Anaesthesia 62, 90–95 (2007)
[4] Jewitt et al. Anaesthesia and Intensive Care Medicine (2012)
[5] Douheret et al. Chemphyschem 2, 148-161 (2001)