Simulating Capnography in Software on the METI Emergency Care Simulator

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Introduction: We attempted to adapt a METI Emergency Care Simulator to support anesthesia scenarios but faced two challenges: the CO_2 gas exhaled by the mannequin does not represent the simulated patient's physical status, and the METI Waveform Display software does not support capnography monitoring.
Methods: We developed a software application that simulates a CO_2 trace that corresponds to the mannequin's ventilation. The software generated a range of CO_2 waveform shapes whereas the mannequin was either spontaneously breathing or being mechanically ventilated. We tested the software in three environments: (1) a full-scale simulator research study of advanced anesthesia monitoring displays, (2) simulator-based training courses at the Royal Adelaide Hospital, and (3) at the Sydney Medical Simulation Centre.
Results: The research study participants successfully used the simulated monitor to confirm correct intubation and detect airway events. Instructors at the Royal Adelaide Hospital reported improvement in the fidelity of simulations for anesthesia trainees. Simulation coordinators at the Sydney Medical Simulation Centre were able to use their Emergency Care Simulator for anesthesia training scenarios, which they were previously unable to run.
Conclusion: We were able to substantially increase the realism of our anesthetic scenarios for research studies and training participants with only a small increase in the fidelity of our capnography monitoring.
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Key Words: Simulator, Anesthesia, Monitoring, METI.

Capnography monitoring of patients undergoing anesthesia is well established and has many practical applications.[1] The American Society of Anesthesiologists recommends that capnography (or other quantitative CO_2 measures) be used to ensure adequate ventilation of patients during all anesthetics.[2]

Most full-scale patient simulators such as the Laerdal SimMan (Stavanger, Norway), METI Emergency Care Simulator (ECS; Sarasota, FL), and METI Human Patient Simulator (HPS) simulate capnography monitoring to various degrees (Table 1). At the high-fidelity end of the spectrum, the HPS mannequin exhales CO_2 gas that can be measured using standard capnography monitors, as in clinical environments. The amount of CO_2 gas produced automatically varies with changes in the simulated patient's physiology.

The SimMan and ECS also support capnography monitoring, albeit with lower fidelity. Both mannequins can exhale CO_2 gas to allow confirmation of correct ETT placement during intubation, but capnograms measured from their airways do not necessarily represent the simulated patient's physical status. In addition, the SimMan simulates time capnograms in software and lets instructors adjust the slope of the CO_2 rise and plateau (phase II/III) and down slope at the onset of inspiration (phase IV) on the generated CO_2 waveform.

We faced several challenges while attempting to adapt the METI ECS for use in a full-scale simulator study of anesthesia patient monitoring.[3] First, when $ETCO_2$ is measured with a standard capnography monitor its value changes with the ventilator's fresh gas flow setting and not with the simulated patient's physiology. Second, the CO_2 waveform is somewhat unrealistic when measured with standard monitors.[4] Third, the shape of the CO_2 waveform does not reflect changes in the patient's physical status, such as the onset of bronchospasm. Finally, the software-based METI Waveform Display patient monitor does not support CO_2 monitoring.

In this technical report, we describe our attempts to overcome these challenges by developing a software application that interfaces with the METI ECS. We created a software-based simulation of capnography monitoring that responds to ventilation of the mannequin while also giving the instruc-

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Table 1. Comparison of Capnography Support With Clinical Monitoring Equipment and Software-Based Simulation on the METI ECS, METI HPS, Laerdal SimMan simulators, With the METI ECS Augmented With the Capnography Simulation Software Described in This Article

Level of Capnography Monitoring Supported	METI ECS	METI HPS	Laerdal SimMan	METI ECS + Simulated Capnography
Mechanical				
Exhales CO_2 gas	Yes	Yes	Yes	Yes
Clinically appropriate waveforms	—	Yes	—	—
Software simulation				
$ETCO_2$ and $FICO_2$	—	—	Yes	Yes
Capnogram	—	—	Yes	Yes
Supported capnogram shapes	—	—	CO_2 line disconnect (trace absent); adjustment of alveolar plateau slope; adjustment of inspiration down slope	CO_2 line disconnect (trace absent); spontaneous ventilation; mechanical ventilation; bronchospasm; esophageal intubation; exhausted soda lime

tor flexibility in adjusting the $ETCO_2$ and shape of the CO_2 waveform.

METHODS

We selected a range of standard and frequently encountered time capnograms by referring to an anesthesia text,[5] recording CO_2 data produced by the Advanced Simulation Corporation Body Simulation (Point Roberts, WA), and consulting with anesthesiologists running simulator-based training courses at the Royal Adelaide Hospital. We then created a library of reference shapes in a format independent of respiratory rate and $ETCO_2$.

We developed a Java software application that monitors the ECS mannequin's breathing characteristics (V_T, RR, I:E ratio) and the simulated patient's P_ACO_2, and that produces the appropriate capnogram and numerical values in real time. The application interfaces with the ECS using the METI HPS Internal Data Exchange Protocol over a Transmission Control Protocol/Internet Protocol connection, and monitors the mannequin's breathing using the values of the left lung and right lung volume variables in the METI Heads Up Display software. Together they represent the apparent volume of the mannequin's mechanical lungs and are derived from physical measurements.[6] Neither the mannequin nor its control software was modified.

Figure 1 shows the total lung volumes (left lung volume + right lung volume) measured during a typical induction on the ECS. We compared the respiratory data measured from the ECS with clinical respiratory data and while there was minimal difference under spontaneous ventilation, there were marked differences under positive pressure ventilation. Figure 2 shows the difference between data measured from the ECS and spirometry data collected from a human patient under pressure controlled ventilation during an unrelated study.[7] Because the mechanical lungs of the ECS behave differently from a human patient's lungs during the expiratory phase, we did not attempt to model the airway and CO_2 gas distribution mathematically.

We used a library of standard capnograms to create waveforms that could be synchronized to the mannequin's breathing and customizable by the instructor. Figure 3 illustrates the process of generating capnograms. The software monitors the lung volumes on the ECS (Fig. 3a) to determine the duration of each inspiratory and expiratory cycle. The instructor can either enter his/her desired waveform shape, end-tidal ($ETCO_2$) value, and inspired ($FICO_2$) value directly

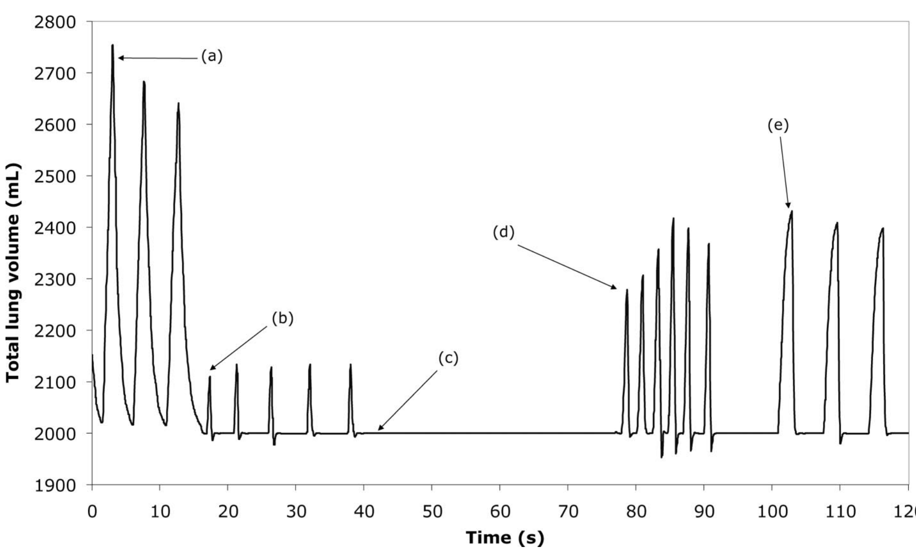

Figure 1. Total lung volume (mL) versus time (seconds) during a 2-minute induction and intubation sequence on a METI ECS mannequin. The total lung volume is calculated by left lung volume + right lung volume from the METI HUD software and represents a theoretical functional residual capacity plus measured inspired volume. The five distinct phases on the graph represent: (a) spontaneous ventilation of the mannequin, (b) bag/mask ventilation after neuromuscular blockade, (c) apnea during intubation with an ETT, (d) manual bag ventilation via ETT, and (e) positive pressure ventilation.

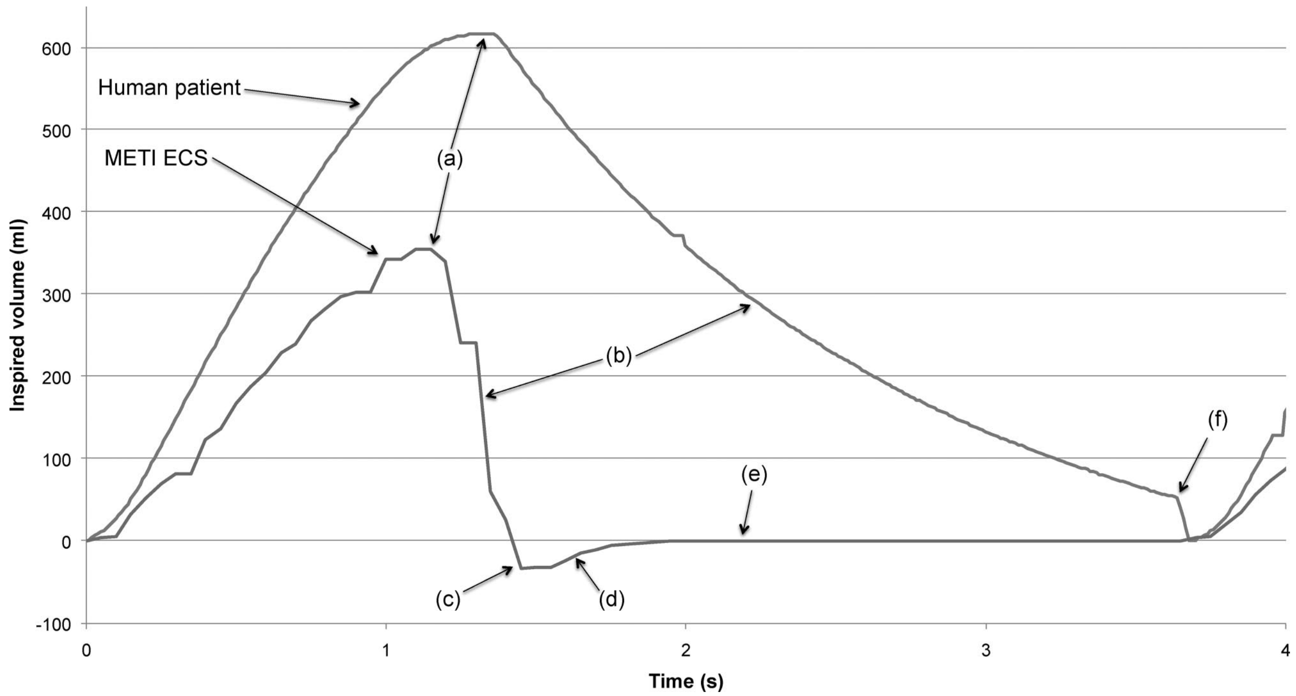

Figure 2. Inspired volume (mL) versus time (seconds) for a human patient and a METI ECS mannequin under positive pressure ventilation with the ventilator adjusted to 600 mL tidal volume. Notable differences with the simulator are (a) a reduced tidal volume, (b) an extremely rapid expiratory phase, (c) "overshoot" of expiration into the "expiratory reserve volume," (d) a small period of inspiration to the baseline lung volume, and (e) a prolonged postexpiration pause due to the rapid expiratory phase. Inspired volumes measured on the human patient were reset to 0 mL upon the start of inhalation (f).

into our software, or they can integrate the parameters into preprogrammed METI simulator scenarios by adjusting user-defined variables, eg, Option 1 (user defined).

Capnograms are generated by interpolating a reference template for the current waveform shape (PCO_2 vs. time graph) to the required parameters (Fig. 3b). Respiratory rate changes are handled by scaling the *x*-axis (time). The expiratory (Fig. 3e) and inspiratory (Fig. 3f) phases are interpolated independently which allows for different *I*:*E* ratios to be supported automatically. The interpolated CO_2 waveform includes the short period of apnea after the mechanical lungs' expiratory phase (Fig. 2e) in the alveolar plateau to offset the lungs' short expiratory phase (Fig. 2b). Changes in the desired $ETCO_2$ and $FICO_2$ are made by scaling the *y*-axis (PCO_2; Fig. 3b and 3c).

The generated capnogram and numerical values (Fig. 3f) are displayed in a window superimposed over a blank panel configured in the METI Waveform Display simulated patient monitor (Fig. 4), which in turn is displayed on a standard video graphics array (VGA) monitor located on the anesthesia machine. The outcome gives partici-

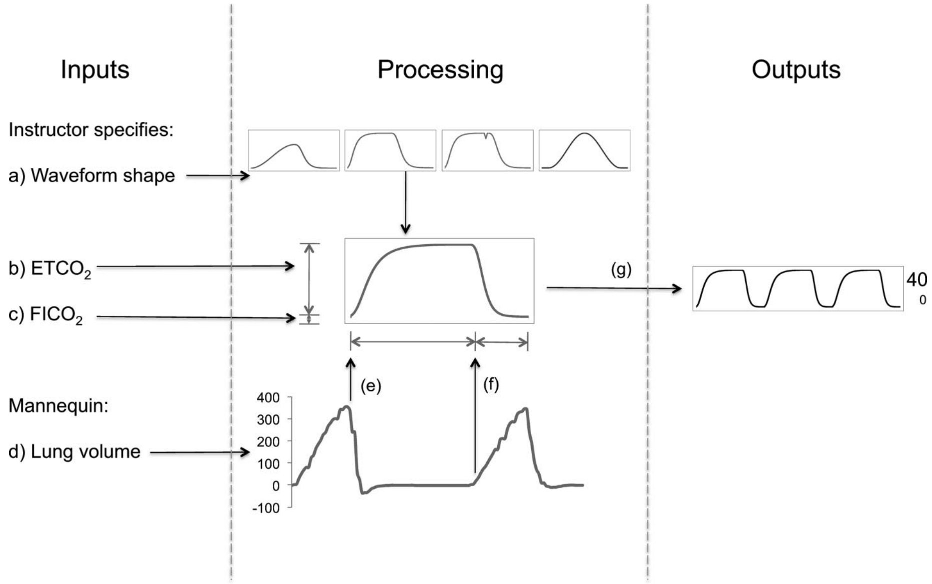

Figure 3. Data flow diagram showing the inputs into the capnography simulation, the interpolation process, and the outputs. The instructor specifies (a) their desired waveform from a library of templates, (b) desired $ETCO_2$, and (c) desired $FICO_2$. Flow sensors on the mannequin continuously update left lung volume and right lung volume on the METI HUD software, reported as (d) lung volume. Directional changes in the lung volume are detected as the starting points of the (e) expiratory and (f) inspiratory phases. The inputs of $ETCO_2$ and $FICO_2$ adjust the template shape along the *y*-axis (PCO_2), with lung volumes adjusting the template along the *x*-axis (time). The resultant waveform (g) is displayed on the monitor.

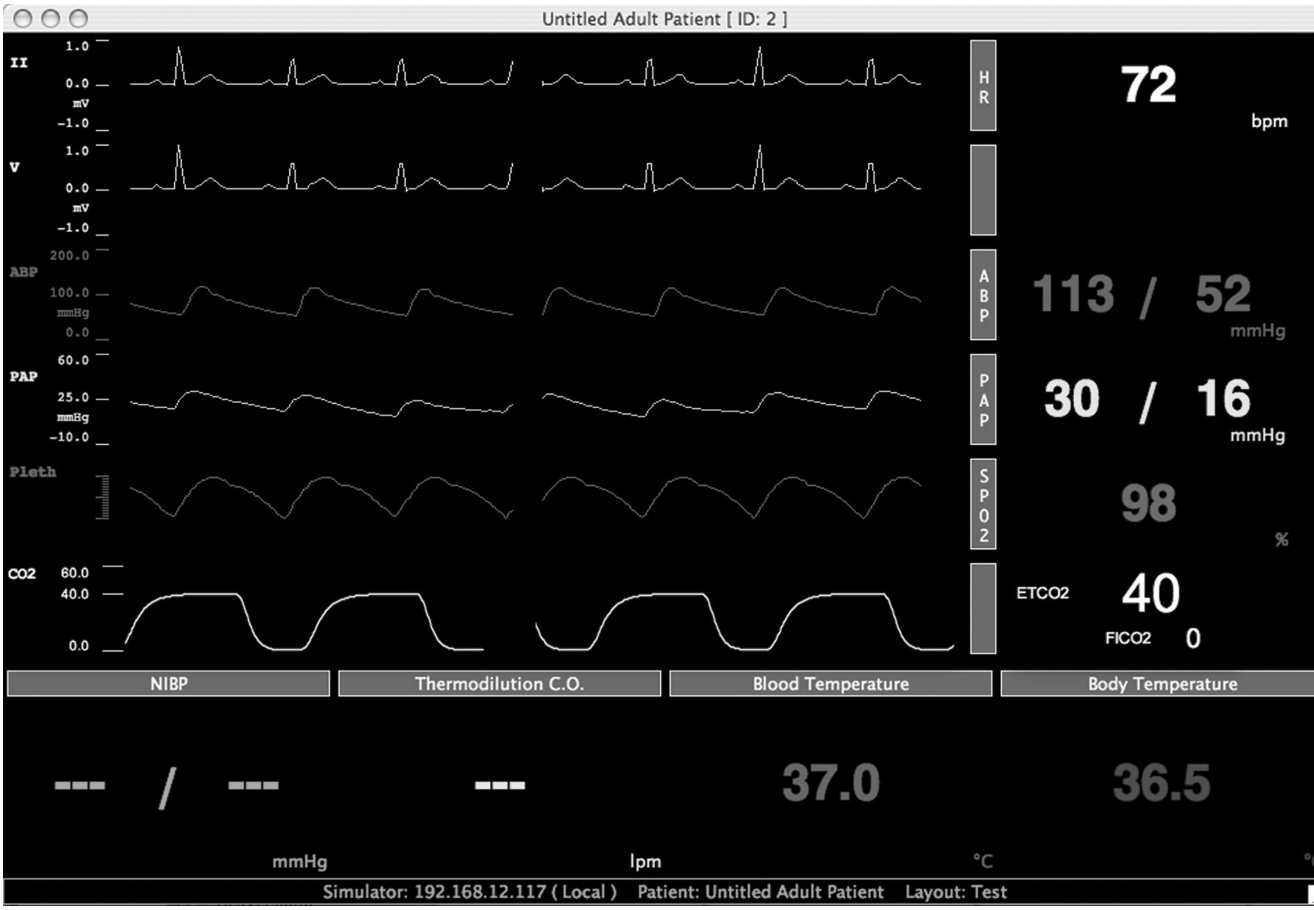

Figure 4. The METI Waveform Display software patient monitor with the simulated capnogram (lowermost wave) and numerics superimposed. This combined display was presented to simulation participants using a VGA monitor mounted within an anesthesia machine.

pants the illusion of native capnography support by the METI simulator.

We tested the software in three situations. First, we used the software in a research study at the Royal Adelaide Hospital with 12 anesthesiologists, each providing anesthesia to four simulated patients.[3,8] Second, instructors at the Royal Adelaide Hospital's Simulation Unit have incorporated the software into several of their simulation training courses, including crisis management in anesthesia, trauma training, and physiology for medical students. Finally, the Sydney Medical Simulation Centre trialed the software on their ECS to evaluate whether our software application could complement their existing METI HPS, and so allow them to increase the number of physicians participating in their training courses.

RESULTS

Figure 4 shows the capnogram, end-tidal and inspired CO_2 values overlaid on top of the METI Waveform Display monitor. Our software was able to generate various CO_2 waveform shapes under spontaneous and positive pressure ventilation of the mannequin: "normal" waveform, breathing against the ventilator, bronchospasm, circuit disconnection, CO_2 rebreathing, and esophageal intubation.

The research study participants were able to confirm correct placement of the ETT after intubation; detect and diagnose a bronchospasm event; and detect disconnection of the circuit. For example, one advantage of this approach is that it allows an actor to surreptitiously disconnect the circuit without immediately affecting the monitor. Thus, the controllers can later trigger the event on the monitor when the actor has moved to a different location, thereby not providing a visible cue to the event's onset.

The Royal Adelaide Hospital's Simulation Unit has been using the simulated capnography for 2 years. Instructors reported a great improvement in the fidelity of their simulations for trainees in anesthesia. Before this software, the instructors used two separate monitors (a VGA display and a separate capnometer) for all anesthetic scenarios. Subsequent to its introduction, a single VGA monitor displayed both the METI Waveform Display and our capnography (as per the OR workstation) and the capnograms more accurately reflected the clinical state of the simulated patient.

Simulation coordinators at the Sydney Medical Simulation Centre concluded, after a 1-day training course involving 40 physicians each participating in four scenarios, that the simulated capnography solution on the ECS was quite adequate for their anesthesia training.

During the evaluations, we received reports from instructors of three types of problems with the capnography software. First, occasionally the instructor would see no capnogram, when they believed they should. We attribute this to airway leaks around the mask or ETT cuff leading the simulator to fail to register breathing. Second, the exhaled CO_2 wave occasionally did not return to zero when the instructors believe it ought to. This was due to prolonged expiration of the mannequin at a low flow rate at the onset of neuromuscular blockade. Finally, instructors reported that having to manually enable and disable the CO_2 trace (when participants applied the mask or switched on the ventilator after intubation) was a laborious process.

DISCUSSION

Our simple software-based simulation of capnography on the METI ECS enabled us perform a research study and run training scenarios that would not otherwise have been possible.

The realism of simulation is often discussed with respect to its physical, semantic, and phenomenal fidelity.[9] In this case, we were able to substantially increase the level of semantic fidelity in our research study and training courses with a small increase in physical fidelity. Complex and expensive equipment, such as the METI HPS's simulated lungs,[10] is required to create a level of physical fidelity that is sufficiently high for clinical capnography monitors to be used with a simulator. In contrast, here a high level of semantic fidelity was achieved by showing participants capnograms on the simulated monitor—a simpler task to achieve.

Interestingly, the reduced physical fidelity of our software capnography solution provided unexpected benefits for our research study. It was easier for the actors (operating room staff) to surreptitiously disconnect the CO_2 sample line than it would have been if we had used a clinical capnography monitor. Furthermore, we could guarantee that a regular mechanical ventilation capnogram would be displayed so that participants were not distracted by potentially misleading artifacts when measured by a clinical monitor (eg, $ETCO_2$ value affected by fresh gas flow; capnogram falsely diagnosed as bronchospasm).

In future work, we aim to extend the interpolation algorithm to support the small tidal volumes encountered with mask and ETT leaks, and automatically zero the CO_2 with very low flow rates. Automatic detection of when the mask is applied or the ETT inserted will reduce the workload on instructors. Ultimately, we aim to provide instructors with visualization of shape changes over multiple breaths, and the ability to display the capnogram directly on a clinical monitor using a digital data interface such as the Philips VueLink Open Interface Protocol.

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