AFRL-SA-WP-SR-2019-0006

Advancing Mechanical Ventilation Management through Simulation

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March 2019

Final Report
for May 2016 to May 2018

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From – To)*
7 Mar 2019	Special Report	May 2016 – May 2018

4. TITLE AND SUBTITLE

Advancing Mechanical Ventilation Management through Simulation

5a. CONTRACT NUMBER
FA8650-16-2-6G09

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER
15-071

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Cincinnati
Sponsored Research Services
51 Goodman Drive, Suite 530
Cincinnati, OH 45221-0222

8. PERFORMING ORGANIZATION REPORT NUMBER

AFRL-SA-WP-SR-2019-0006

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
USAF School of Aerospace Medicine
Aeromedical Research Dept/FHE
2510 Fifth St., Bldg. 840
Wright-Patterson AFB, OH 45433-7913

10. SPONSORING/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited.

13. SUPPLEMENTARY NOTES
Cleared, 88PA, Case # 2019-2313, 10 May 2019.

14. ABSTRACT

A research team consisting of personnel from United States Air Force School of Aerospace Medicine, Aeromedical Research Department, En Route Care Division, Center for Sustainment of Trauma and Readiness Skills, University of Cincinnati, and IngMar Medical collaborated to develop a mechanical ventilation-training simulator. The training simulator was designed to mimic respiratory distress during mechanical ventilation. The trainer included common complications often seen with mechanically ventilated patients. A simulated torso was developed and integrated with an appropriately equipped Special Medical Emergency Evacuation Device affixed with medical equipment utilized during Critical Care Air Transport Team missions. The torso includes a lung model, upper airway, and head with reproducible computerized algorithms with the ability to simulate respiratory distress. The simulator is responsive to providers' interventions in treating conditions encountered during mechanical ventilation. While the focus for the simulator training was directed at the Critical Care Air Transport Team training platform, an additional population for inclusion is medical providers responsible for ventilator management across the spectrum of care.

15. SUBJECT TERMS
Trauma, mechanical ventilation, simulation, training, critical care, aeromedical evacuation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Dario Rodriquez Jr.
U	U	U	SAR	13	19b. TELEPHONE NUMBER *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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1.0 SUMMARY

A research team consisting of personnel from United States Air Force School of Aerospace Medicine (USAFSAM), Aeromedical Research Department, En-Route Care Division, USAFSAM, Center for Sustainment of Trauma and Readiness Skills, University of Cincinnati, and IngMar Medical collaborated to develop a mechanical ventilation-training simulator. The training simulator was designed to mimic respiratory distress during mechanical ventilation. The trainer included common complications often seen with mechanically ventilated patients. A simulated torso was developed and integrated with an appropriately equipped Special Medical Emergency Evacuation Device affixed with medical equipment utilized during Critical Care Air Transport Team missions. The torso includes a lung model, upper airway, and head with reproducible computerized algorithms with the ability to simulate respiratory distress. The simulator is responsive to providers' interventions in treating conditions encountered during mechanical ventilation. While the focus for the simulator training was directed at the Critical Care Air Transport Team training platform, an additional population for inclusion is medical providers responsible for ventilator management across the spectrum of care.

2.0 BACKGROUND

During Operations Iraqi Freedom and Enduring Freedom, the early transport of critically injured warfighters via the en route care system is often credited as one of the reasons for such a high survival rate. Mechanical ventilation of those injured remains a significant challenge for the aeromedical evacuation and medical community. Critical Care Air Transport Team (CCATT) missions maintain the responsibility for managing these patients in an austere environment. As much as 66 percent of casualties suffering traumatic injury require this life sustaining intervention while in the care of CCATT [1]. In preparation for deployment, clinicians are required to successfully pass the Advanced CCATT course or attend similar pre-deployment training prior to caring for these patients. Course curricula dedicate significant time and attention towards addressing the various maladies encountered of patients requiring mechanical ventilation, as lung injury/diseases are among the top five problems. A Capabilities Based Assessment identified as much as a 50 percent or greater failure rate of students attending these courses. This has warranted an improvement in the training platform's capabilities to meet the demands of commanders to provide a ready medical force.

Current simulation technology is limited by poor lung analogs in some instances or by lack of realistic chest wall/patient form in others. Computerized test lung systems mimic lung mechanics and spontaneous breathing, but are in the form of a box or a dual chambered wedge style spirometer. Expensive high fidelity simulators use two plastic balloons to simulate the lungs and have no capacity to simulate a change in compliance, airway resistance, or rise and fall of the chest wall. Until now, no system could provide the sophisticated lung mechanics and anatomic form. As part of our effort – other industry partners have realized the limitations in their platforms/need for enhancements and are now collaborating with Ingmar to include more sophisticated lung models in their devices.

The project marked considerable advancements in developing an objective/measurable simulation-training tool that generates autonomous real-time feedback in order to provide an appropriately trained clinician in the management of mechanically ventilated patients. This technology will enable training in any environment, create synergy for the existing education

platforms, and/or afford distribution of this capability to resource-constrained locations. It will also create an exportable system that will improve on simulation training at smaller Military Training Facilities, providing an evidenced based marker of appropriate vent management, potentially mitigating the need for additional training resources.

3.0 METHODS

The research team developed algorithms, a prototype, and a material solution. The protocols for the decision matrix of the device used existing pathophysiological models from recent casualties via National Institutes of Health - National Heart, Lung, and Blood Institute NIH-NHLBI, Acute Respiratory Distress Syndrome (ARDS) data. The protocol design also integrated benchmarked clinical practice guidelines for management of mechanically ventilated patients. Pulmonary complications experienced throughout en route care was the primary focus and the system aimed to target the ability to respond to clinician interventions in treating these conditions. The model designed was to reproduce the respiratory mechanics of mechanically ventilated patients developing acute respiratory distress on the ventilator; which included the ability to adjust lung compliance and airway resistance and simulate spontaneous breathing in a range of lung values capable of simulating acute respiratory distress syndrome, mild lung injury, and chronic lung disease. The model can accommodate both mechanical ventilation and manual ventilation. During manual ventilation, the model will provide feedback – the sensation of the lung model being more difficult to ventilate and provide a realistic rise and fall of the chest. The model can simulate respiratory distress during mechanical ventilation including the most common complications:

- Pneumothorax
- Right mainstem intubation
- Bronchospasm
- Ventilator failure created by the operator not the lung model
- Airway loss requiring cricothyrotomy
- Precipitous fall in lung compliance
- Precipitous fall in oxygenation
- Precipitous increase in carbon dioxide

The model includes a realistic torso and lung model, upper airway and head (Figure 1) Changes in lung mechanics will occur through manipulation of the model using software. A commercially available Blood Oxygen Saturation (SpO_2) simulator simulated changes in oxygenation. Airway complications are simulated using physical models including complete and partial obstruction of the lumen of the tube. USAFSAM Aeromedical Research Department, En Route Care Division, Center for Sustainment of Trauma and Readiness Skills, University of Cincinnati, and research team members evaluated the model.

Figure 1. Advanced simulator (provided by IngMar Medical).

4.0 RESULTS

Generated an all-in-one patient simulator system integrating a synthetic torso manikin and Special Medical Emergency Evacuation Device on a modified litter with the following attributes (platform powered by compressed air, which is supplied externally via compressor or wall air):

- Torso manikin with anatomically correct head and airway (modified TruCorp Trauma Man) including these features:
    - Bilateral chest-rise
    - Pneumothorax pillows for realistic needle decompression
    - Chest drain (not connected to any electronics or pneumatics, but can be used for simple training)
    - Ability to perform cricothyrotomy and trach intubations
    - Tongue edema
    - Sensibility to carina touch (when intubating), resulting in a cough
    - Endotracheal (ET) Tube position sensing that discriminates between right-main stem and normal placement as well as no intubation (bag-mask)
    - Chest compression assessment
    - Sensing of metered dose inhaler (MDI) application

    - Special Medical Emergency Evacuation Device (SMEED) used for attaching all equipment (mechanical ventilator, patient monitor)
- Remote vent control (Zoll Impact with special firmware) for setting initial parameters
- Patient monitor link via VitalsBridge.
- Autonomous cardiopulmonary physiological model (enhanced Pulse by Kitware -developed from the BioGears physiological model also used in the Advanced Modular Manikin project by the Department of Defense). It autonomously drives all patient responses, including those to treatments from:
    - Mechanical ventilation, including the application of positive end-expiratory pressure (PEEP)
    - MDI inhaler
    - Chest compressions
    - Right-stem intubation
    - Ventilator changes
    - Needle decompression
    - Occluded airway
    - Enhanced Pulse model responding realistically in scenarios for:
        - Asthma
        - ARDS
        - Head trauma
        - Pneumothorax
        - Sepsis
        - Pulse model enhancements include:
            - Spontaneous driver:
                - Unstressed volume = Flow RATE (FR)
                - Breath cycle fractions, (new equation to produce pressure waveform, and adjusting based on frequency)
                - New way of doing conscious respiration with fractions
        - Sigmoidal compliances from pressure-volume curve
        - Improved piecewise-linear resistances
        - Reduced peak driver pressure due to fatigue - results in lower tidal volume (TV) and higher respiratory rate (RR)
        - Improved diffusion surface area equation based on severity
        - Pneumothorax: introduced displacement in the mediastinal structures, which can interfere with venous return to the heart (by way of a mechanistic model that takes the volume/pressure increase in the pleural space and maps it to a resistance increase in the vena cava)
        - Dead space modification
        - Directly driving respiratory mechanics through a ventilator (overriding flow, etc.)
        - Stabilizing with ventilator

- Newly designed Graphic User Interface for tetherless instructor tablet personal computer includes:
    - Instructor panel for simulation control
    - Instructor assistance notes sections

    - Task completion logging, both instructor-driven and automated
    - Debrief window, showing simulation state changes, task implementation, respiratory waveforms
    - Save/replay feature for debriefing
    - Basic performance scoring system
- Student touch-screen for viewing x-rays, labs, and arterial blood gas (ABGs) (also linked to tasks)
- Networking capabilities:
    - Built-in Wi-Fi to drive system as ad-hoc / stand-alone
    - Ability to connect to facility network to drive system remotely

An evaluation tool utilizing a Likert scale 1 -10 was generated to provide assessment from students/cadre as to ease of use, realism, and "suspension of disbelief". Evaluators provided feedback for enhancements to potentially be incorporated in next phase of development.

5.0 CONCLUSIONS

The results of this study are positive and demonstrate that with today's technological advances specifically with the ability to design algorithms with real time end user feedback loops and combining with life like mannequins medical training can take several leaps forward. Utilizing this technology can assist with mitigating skill decline, resource constrained budgets for training, and decrease in attrition rate for initial and advanced training. The system would be useful for all medical provider skillsets with the requisite clinical competency of managing critically ill/injured casualties requiring mechanical ventilation.

6.0 TRANSITION PLANNING/RECOMMENDATIONS

Utilizing the Technology Readiness Level (TRL) guidelines. The TRL level assigned currently is a level 8, "Actual system completed and qualified through test and demonstration". The TRL level is indicative of the total platform ability. In order to gain a TRL of 9, "Actual system proven through successful mission operations." The simulator will be utilized in the CCATT course as supplemental training for the Respiratory Therapist and other providers as needed. In order to fully transition from the design and development phase into acquisitions, the study results will be shared with key decision makers to assist in creating a process for possible end users to purchase as a commercial off-the-shelf item.

While this research and development project resulted in an advanced training simulator, the scenarios only scratch the surface of the complications regarding mechanical ventilation. In order to further this technology a follow-on effort is needed to create additional scenarios.

The major limitation of the current project has been an attempt to integrate a background physiologic model upon which scenarios run. As an example, in most simulators the instructor who implements the change in physiology based on the action verifies the correct action by the caregiver. Such as, the endotracheal tube is withdrawn from the right mainstem and that action results in a fall in peak airway pressure and improved lung compliance. The goal of this project has been to develop scenarios where this occurs. As the correct action is taken, the simulator responds as a patient would, without input by the instructor. This has been more complex than

either our corporate partner or we anticipated. Some simulations will always require instructor interaction. However, removal of secretions, alleviating pneumothorax and right mainstem intubation should allow the model to respond without instructor intervention. This allows for a smoother simulation and less anticipation of students, that something was modified unrealistically.

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LIST OF ABBREVIATIONS AND ACRONYMS

CCATT Critical Care Air Transport Team

TRL Technology Readiness Level