AFRL

CLOSED LOOP CONTROL (CLC) OF MECHANICAL VENTILATION & REBREATHING SYSTEM

COLLABORATIVE EFFORTS: AFRL/711TH HPW RHBAM, UNIVERSITY OF CINCINNATI, (UC), ZOLL MEDICAL, CAIRE INC, SPARX ENGINEERING , UNIVERSITY OF TEXAS HEALTH SCIENCE CENTER, UNIVERSITY OF SOUTHERN CALIFORNIA,

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  - Closed Loop Control Efforts: FWR20160120X, FWR20160100X, FWO201601121X, FWR20180170X, AFOSR 2021-0007A
- Funding: Cooperative Agreements from AFRL to UC: FA8650-12-2-6B10, FA8650-12-2-6B11, FA8650-17-2-6G20, FA8650-17-2-6G22 and FA8650-19-2-6G34
- Cleared Distribution A: 2024-0824 (AFRL-2024-4473)

OVERVIEW

Background/CLC OV1

Why is CLC important for the OSCG?

Oxygen Requirements, Production and Conservation in Military Medicine

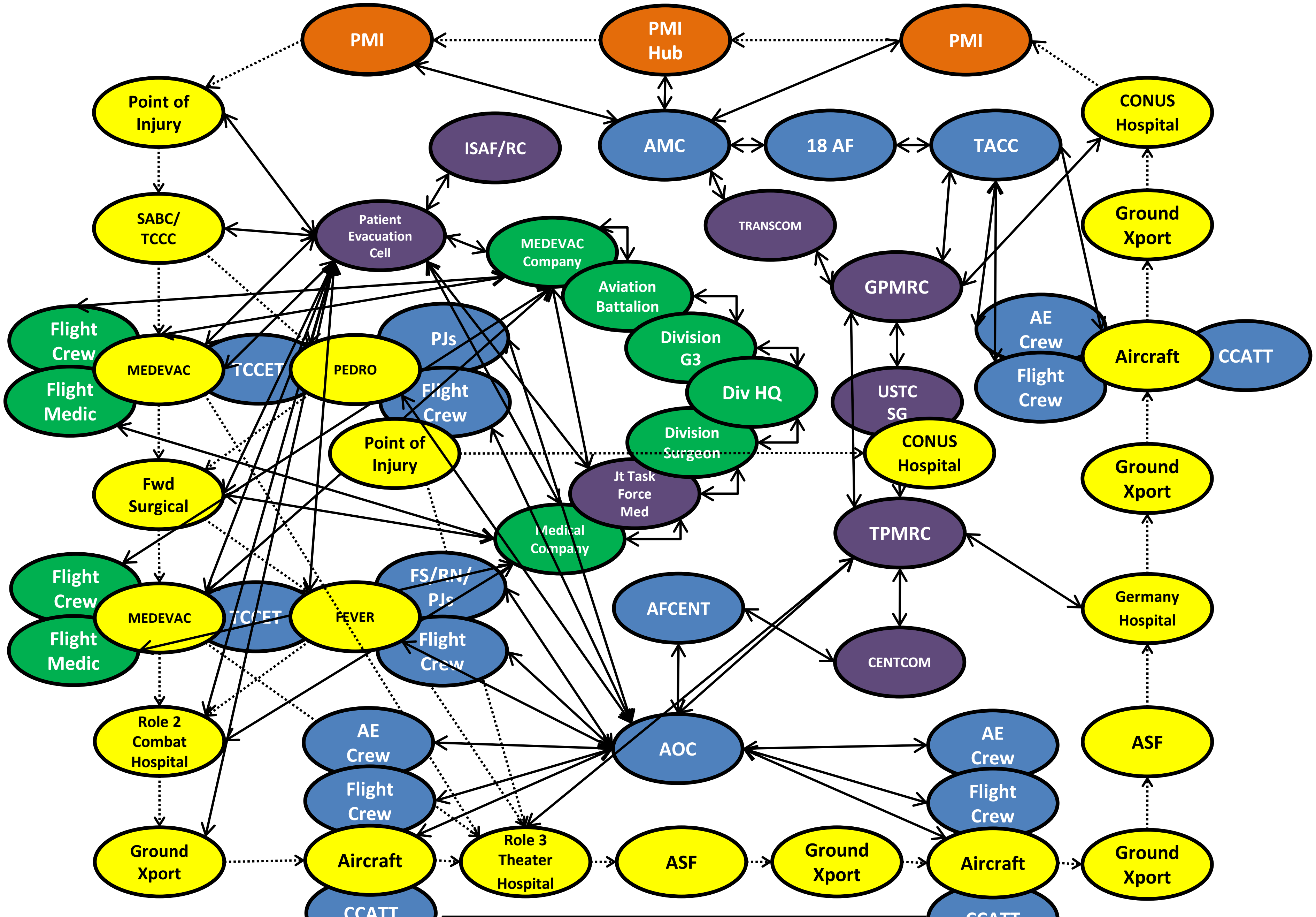
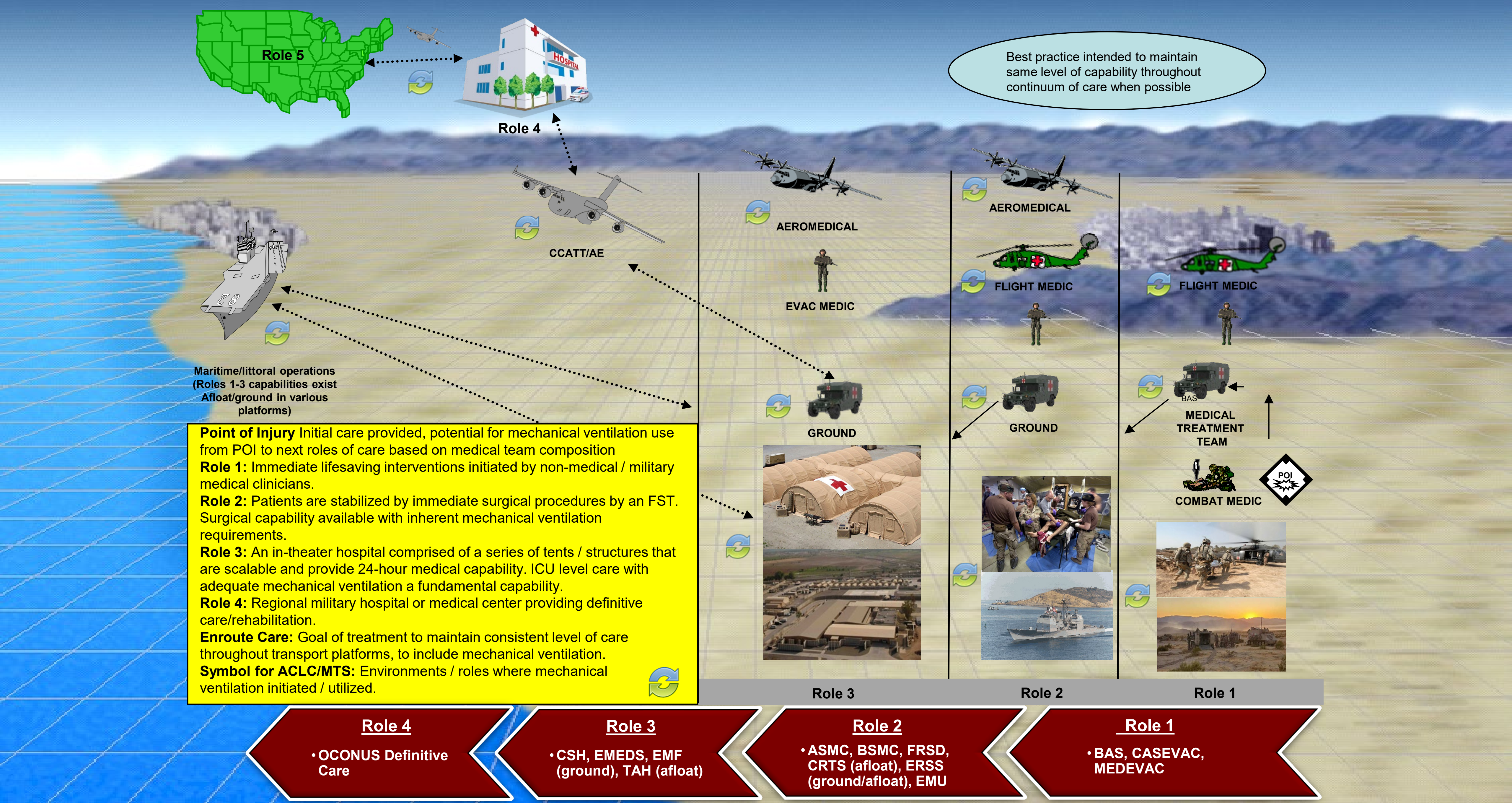


Illustration of a Patient Moving Through the Complex System:
Slide Built by Col Mark Ervin while at AMC/SG

AUTONOMOUS CLOSED LOOP CONTROL/MEDICAL TECHNOLOGY SOLUTIONS OV-1



BACKGROUND

CLC Fraction Inspired Oxygen

2010: Impact 754: research efforts to include a review of protocols and dev software prototype.
2010-2011: Impact 754 was replaced by Impact 731, which restarted research efforts in protocols, dev software, bench testing, computational modeling, and pre-clinical model testing.
2014: Impact Purchased by Zoll: Review of data and further software refinement.
2015: Zoll 731 EMV+ Submitted for FDA IDE Clinical Trial.
2016: FDA approved FDA IDE Clinical Trial: 210 patients, three clinical sites.
2021: The FDA accepted the final FDA IDE report.
2021-2023: Zoll and FDA collaborated to determine the pathway.
2023 : FDA determined that a 510(k) for the hardware and PMA for the software.

CLC Fraction Inspired Oxygen with alternate Oxygen Source (Concentrator)

2010 -2017: Research efforts w/alternate oxygen source: Ventilator controls the concentrator, bench testing, communication refinements, pre-clinical model testing. Completed research efforts. Preparing for multicenter clinical trial.
2018: Chart purchased by Caire Inc. Negotiations with Caire Inc.
2021: Caire Inc. was placed on subcontract to create a prototype and provide research support for the FDA IDE Clinical Trial.
2023: FDA determined that a multicenter clinical trial was not required/510(k) submission for the prototype is acceptable.
2023 – 2024: The prototype is not the final iteration.

BACKGROUND Cont.

CLC Decision Assist (PEEP), full autonomous system

2017-2019: Created and developed algorithms

2020-2022: Designed prototype (731 EMV+Advanced AKA PACCV)

2022-2023: Conducted research validation: bench testing, refinements, computational modeling, pre-clinical models

WHY CLC

Use less oxygen compared to manual adjustments.

Can Reduce reliance on compressed/liquid oxygen systems and logistical requirements.

Extends operational capability by conserving oxygen.

Maintains patient goal of oxygenation, ensuring positive patient outcomes.

Other considerations:

Decreases task load.

Force multiplier.

Increasing capability to provide for multiple high-acuity patients simultaneously.

Hands-free care.

Clinicians set targets.

Status

CLC FIO2: It has transitioned to 6.4 (Advanced Development), and funding has been authorized (DHA). Contracting is in progress.

Expected IOC FY26, FOC: FY28.

CLC Decision Assist (PEEP), full autonomous system:

Completed pre-clinical model.

FDA Q-subs in progress. Expect FDA IDE requirements with multiple sites.

Under consideration by DHA for advanced development funding.

CLC Fraction Inspired Oxygen with alternate Oxygen Source (Concentrator):

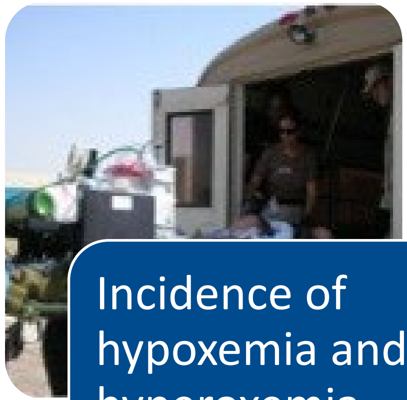
The prototype proved feasibility via pre-clinical models.

Oxygen Requirements, Production and Conservation in Military Medicine

- The oxygen story 2008- present

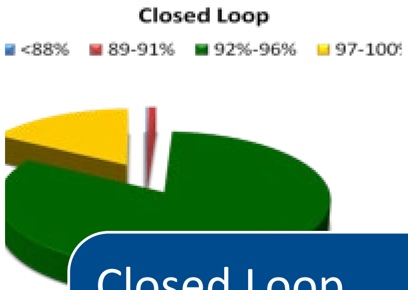
Oxygen Requirements

- CCATT MV study
- Pre-hospital oxygen use



Incidence of hypoxemia and hyperoxemia

- AE monitoring
- Oximeter accuracy

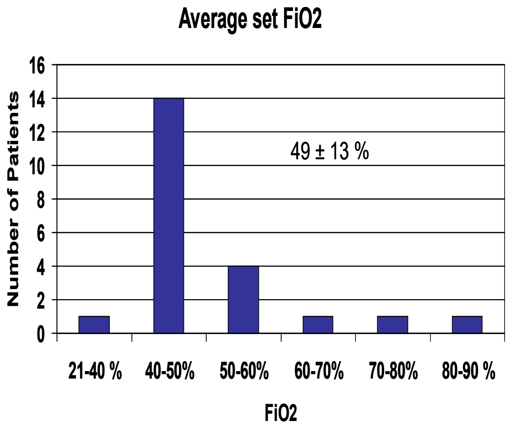


Closed Loop Control

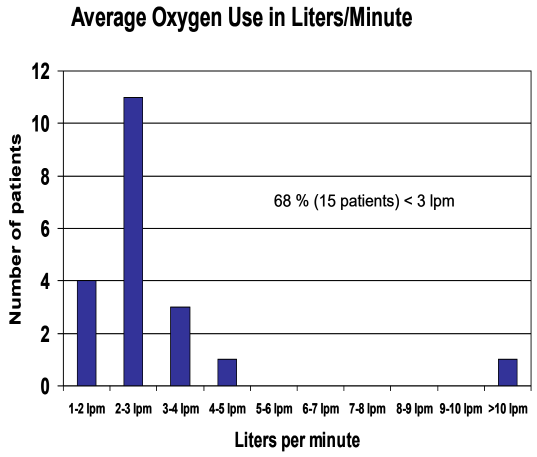
- Closed loop control of inspired oxygen
- Two clinical trials
- FDA acceptance

Oxygen Requirements

- What are the oxygen requirements for mechanically ventilated patients?
- What are the oxygen requirements for trauma patients?



- Most CCATT patients need < 3 L/min of oxygen
- Half of civilian trauma patients do not require any oxygen



Oxygen represents up to 30% of the weight and cube of medical transports

TABLE II. Frequency of Indications for Supplemental Oxygen Administration

			95% CI	
	N	%	Lower	Upper
Pulse Oximeter Oxygen Saturation ≤90% (Hypoxemia)	86	38.4	32.2	44.9
TBI	22	9.8	6.5	14.3
Hemorrhagic Shock	20	9.0	5.7	13.2
Intubated	0	0.0	0	1.1
Documented Oxygen Indication (Any of the Above)	107	47.8	41.3	54.3

Barnes et al. J Trauma 2008;64:S129-34.

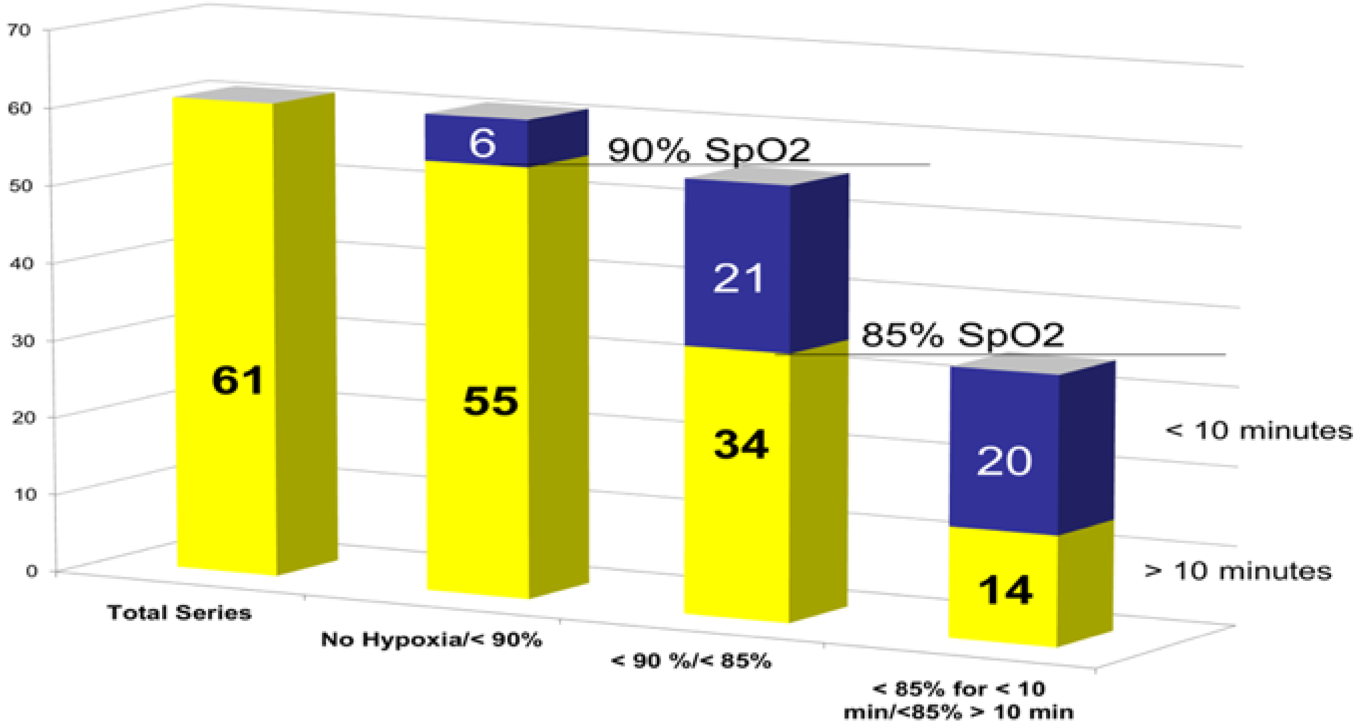
McMullan et al Mil Med 2013;178:1121.
McMullan Mil Med. 2016;181(8):767-72.

Hypoxemia during aeromedical evacuation of the walking wounded

Jay Johannigman, MD, Travis Gerlach, MD, Daniel Cox, MD, Jon Juhasz, MD, Tyler Britton, RRT, Joel Elterman, MD, Dario Rodriquez, Jr., MSc, RRT, Thomas Blakeman, MSc, RRT, *and* Richard Branson, MSc, RRT, *Cincinnati, Ohio*

TABLE 1. Demographic Data of Subjects Enrolled in the Study

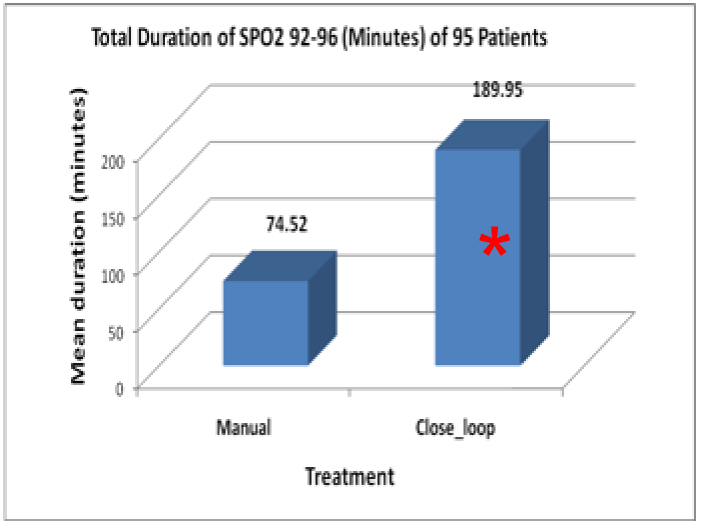
Patient Demographics	
Patients enrolled	61
Age, mean (SD), y	26.2 (6)
Service	
US Army	44
US Marines	11
US Air Force	4
US Navy	1
Injury pattern	
Battle injury	48
Improvised explosive device	27
Gunshot wound	14
Rocket-propelled grenade	4
Grenade	2
Environmental	1
Nonbattle injury	13

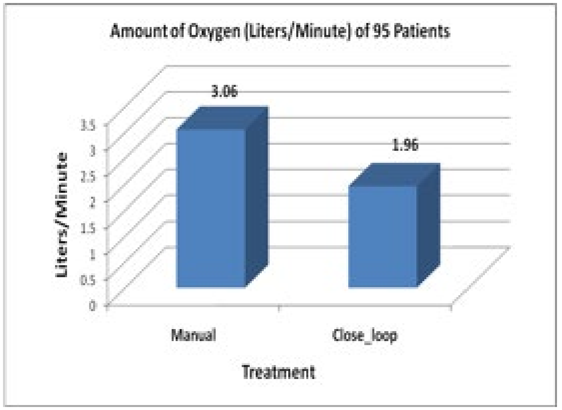


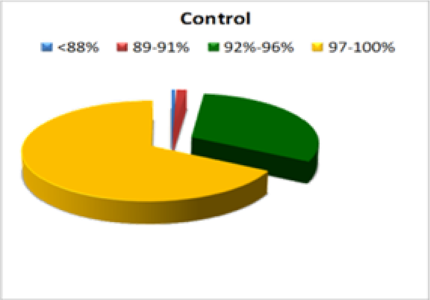
J Trauma Acute Care Surg
Volume 79, Number 4, Supplement 1

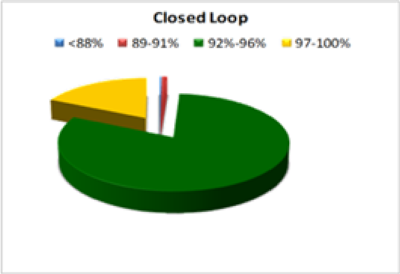
Closed Loop Control of Inspired Oxygen

- FiO_2 automatically adjusted based on SpO_2, SpO_2-target difference and trends in SpO_2.
- SpO_2 target is 94% (adjustable).
- If $SpO_2 \leq 88\%$, FiO_2 increases to 1.0.
- A combination of fine and coarse control.
- If SpO_2 signal is lost, FiO_2 remains constant.
- If FiO_2 increases > 10%, an alert is provided.
- 95 Subjects









Closed Loop Control of Inspired Oxygen

AFRL

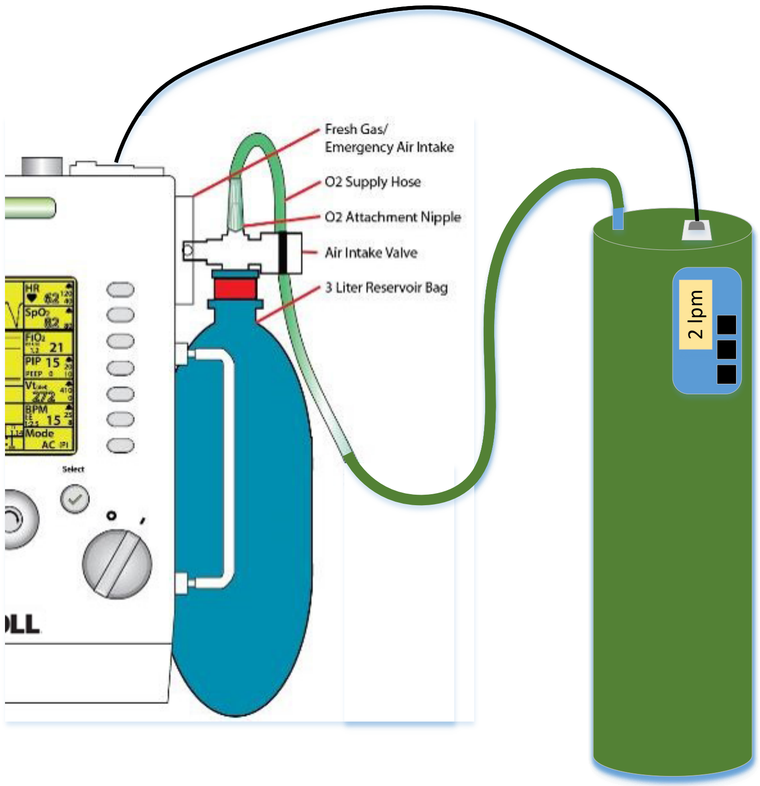
- FiO_2 automatically adjusted based on SpO_2, SpO_2-target difference and trends in SpO_2.
- SpO_2 target is 94% (adjustable).
- If $SpO_2 \leq 88\%$, FiO_2 increases to 1.0.
- If SpO_2 signal is lost, FiO_2 remains constant.
- If FiO_2 increases > 10%, an alert is provided.
- Randomized controlled trial of manual vs automated control of FIO2 (n=208)

SpO_2 92-96%
N
Mean (SD)
Median (Q1, Q
Min-Max
Missing
Wilcoxon Rank

	Total	CLC	MC
Oxygen Use (min/L)			
N	203	103	102
Mean (SD)	1.2 (1.36)	0.9 (1.15)	1.5 (1.50)
Median (Q1, Q3)	0.6 (0.2, 1.8)	0.4 (0.1, 1.2)	0.9 (0.3, 2.3)
Min-Max	0.0-6.3	0.0-5.1	0.0-6.3
Wilcoxon Rank Sum P Value		0.001	
FIO_2 Changes			
N	203	103	100
Mean (SD)	199.4 (263.01)	380.8 (263.38)	12.5 (12.81)
Median (Q1, Q3)	47.0 (10.0, 314.0)	306.0 (185.0, 517.0)	10.0 (5.0, 16.0)
Min-Max	0.0-1408.0	21.0-1408.0	0.0-107.0
Wilcoxon Rank Sum P Value		<0.001	

Materiel Solutions for Oxygen Conservation

- Use of an oxygen concentrator
- Combined use of an oxygen concentrator and D cylinder
- Addition of rebreathing



Future Directions

POGS/Ventilator:

Small, lightweight

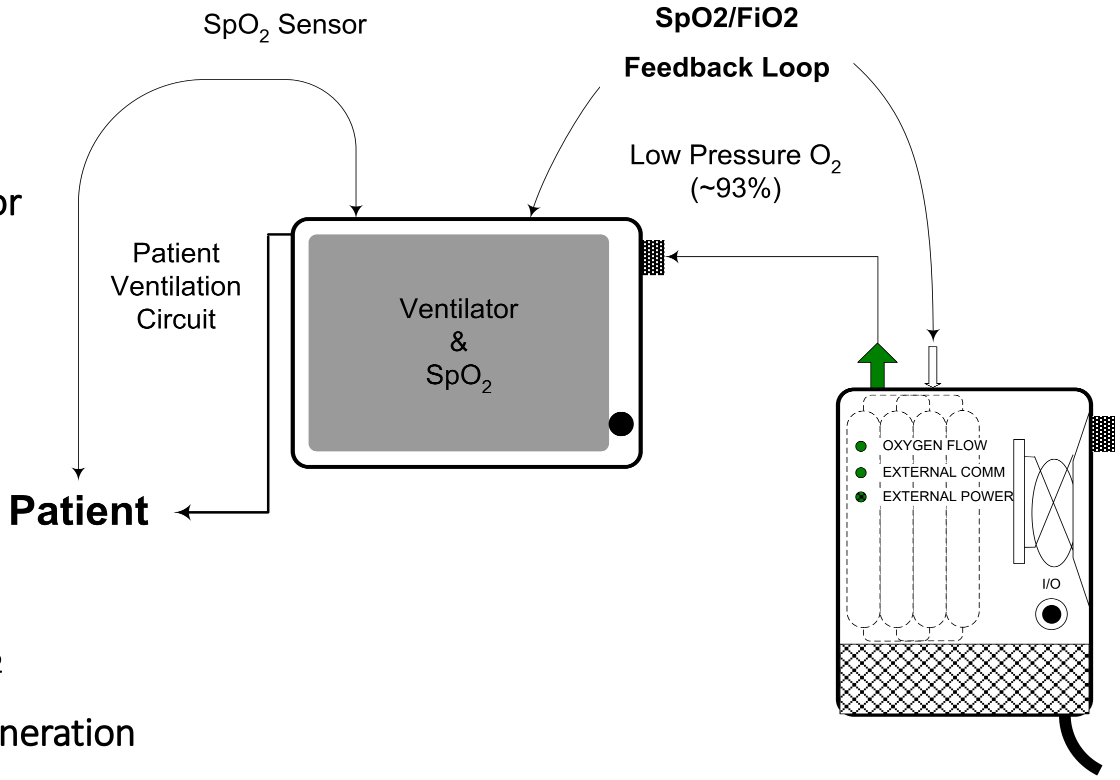
Integrated with a ventilator

Comprehensive modes of ventilation

Supplemental O_2 administration

Closed-loop control of oxygenation using SpO_2

Feedback control of O_2 generation



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Materiel Solutions for Oxygen Conservation

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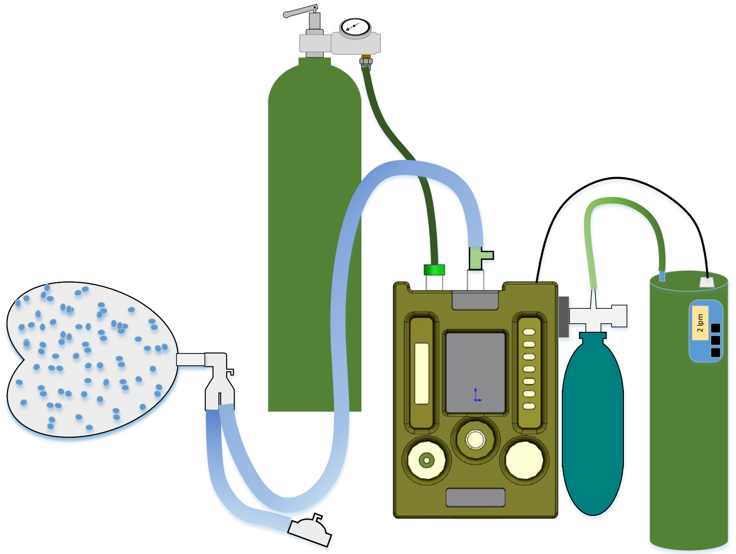
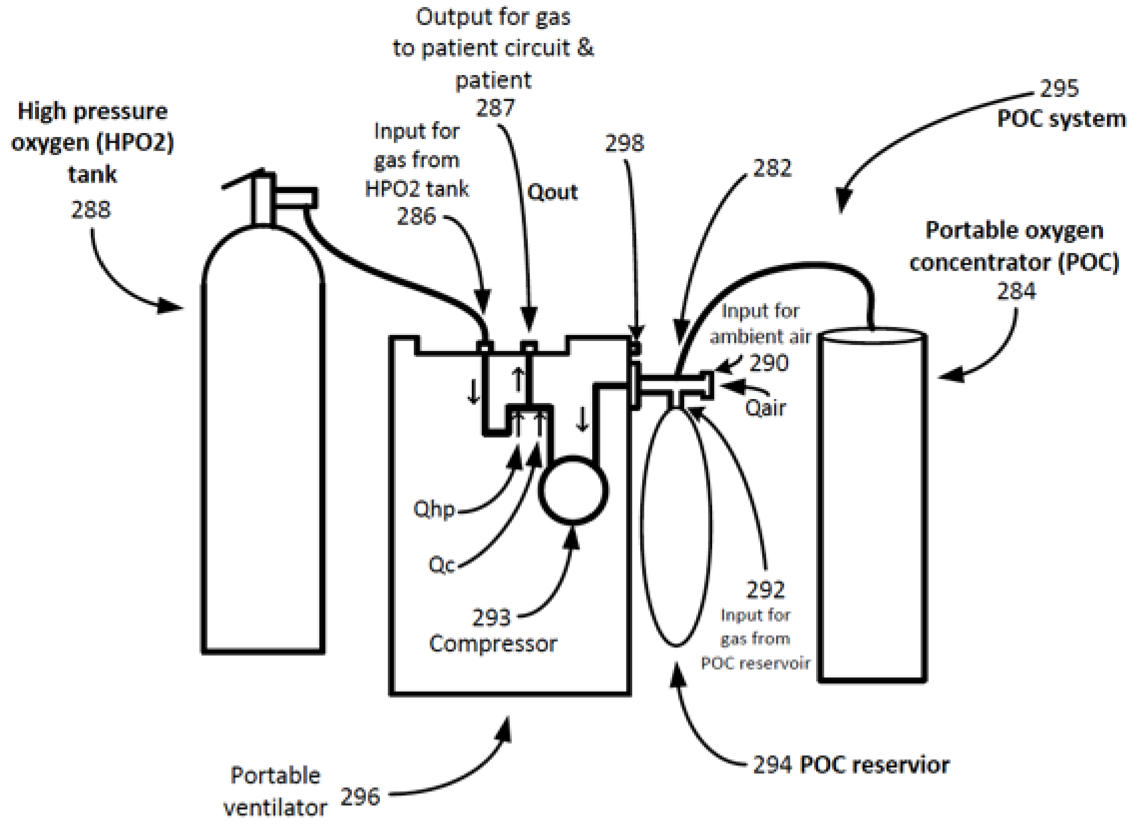
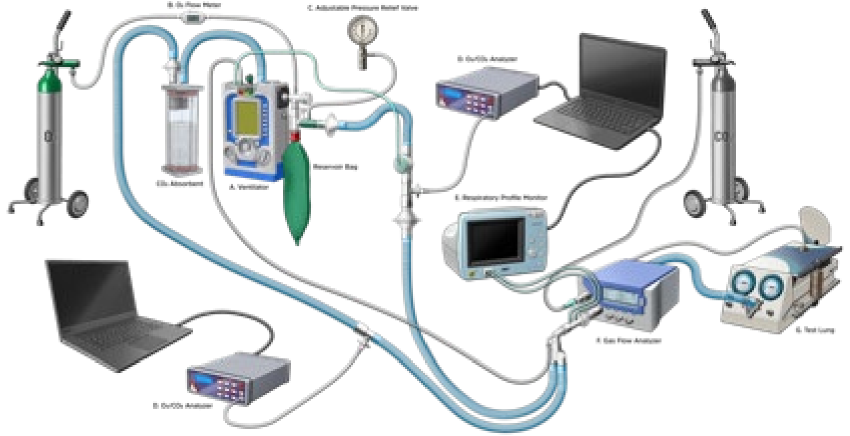


Future Directions

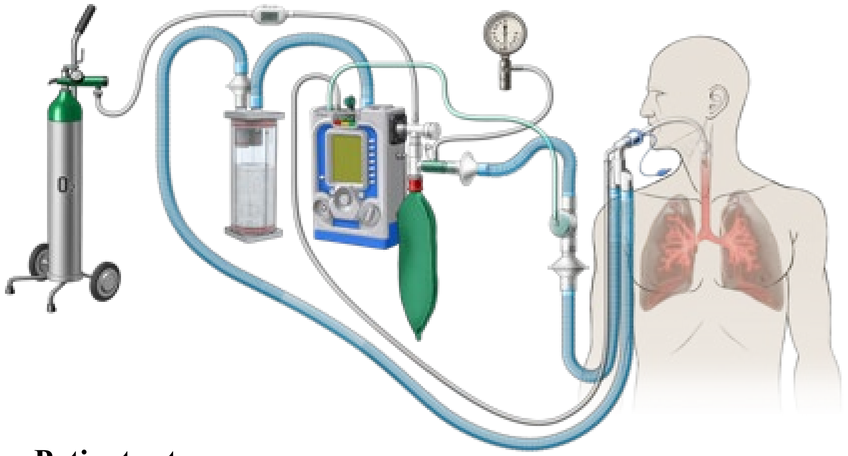


Integration Capabilities

Adding a rebreathing system.

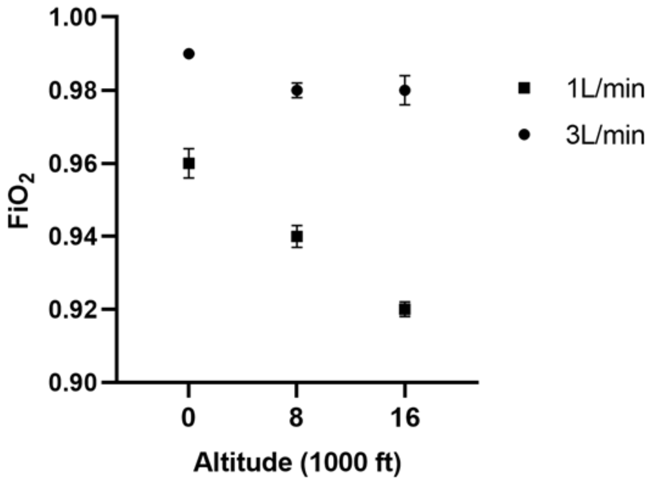


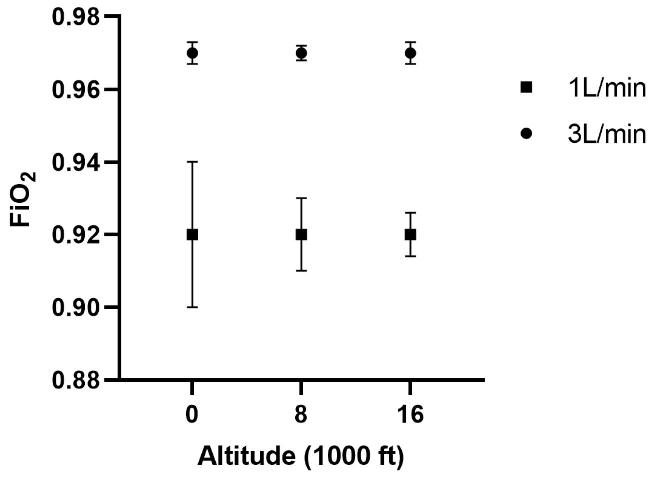
Experiment setup



Patient setup

Blakeman T et alJ Spec Oper Med. 2024 Jun 25;24(2):34-38



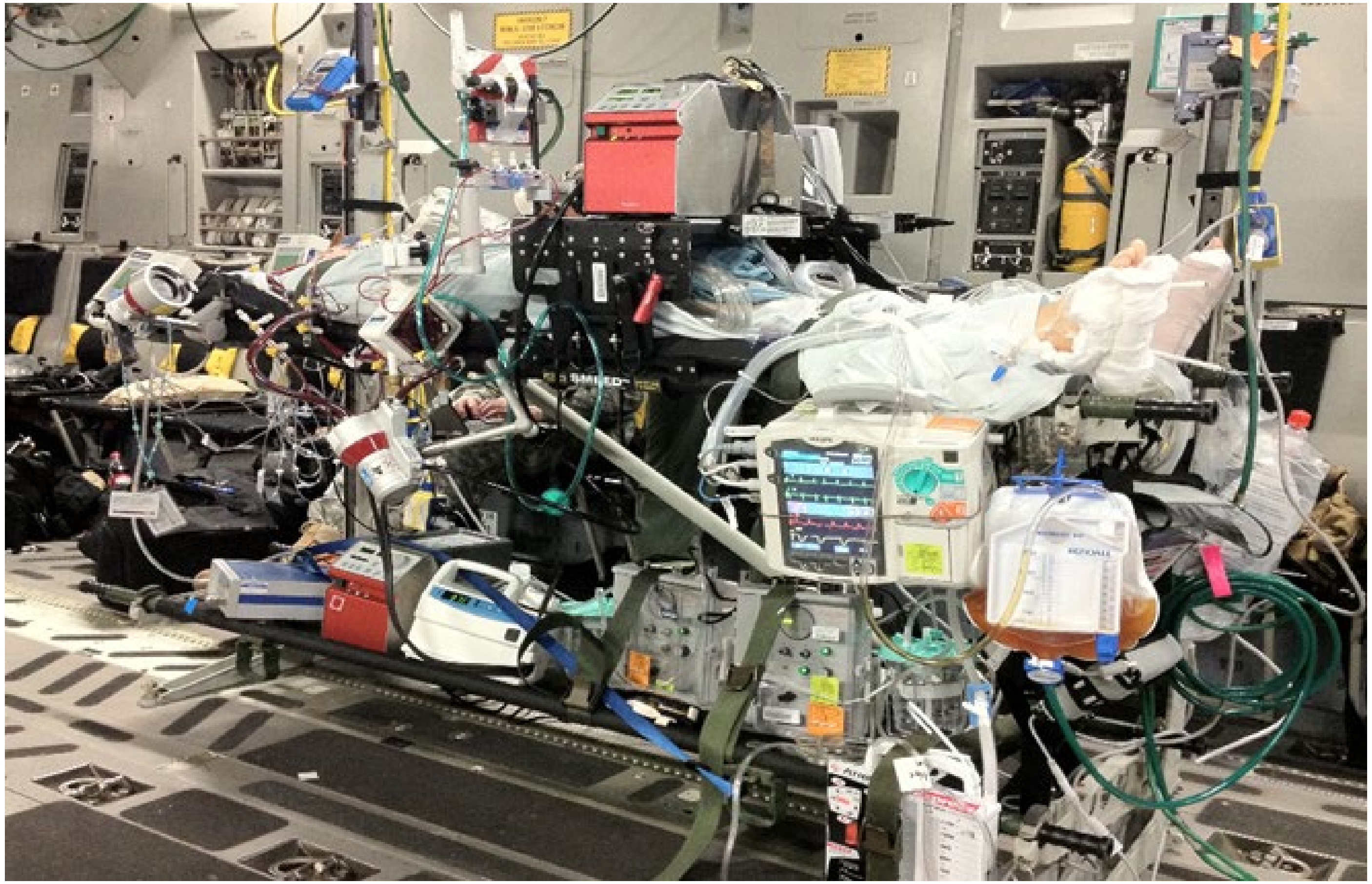


The study results show that using low oxygen flow ≤ 3 L/min with a rebreathing system attached to a portable ventilator can provide $FiO_2 \geq 90\%$ across a range of ventilator settings, lung models, and altitudes. Use of a rebreathing system has the potential for oxygen conservation but requires diligent monitoring of inspired FiO_2 and CO_2 to avoid untoward consequences.

- Currently pre-clinical model research is in progress to determine if CLC integrated with a rebreathing systems can safely and effectively manage subjects.
- Rebreathing results in oxygen conservation but poses other concerns
  - Excess humidity
  - Loss of oxygen can result in delivery of hypoxic gas mixtures
  - Adds the new consumable – CO_2 absorbent
  - Cleaning concerns
  - FDA approval

Clinical Perspective

- Care of the critically ill and injured casualty is complicated
- Technology solutions must meet the standard of care
- The regulatory pathway is perilous
- Joint decisions are needed.



Clinical Perspective

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Acknowledgements

Chief Master Sergeant Dario Rodriquez, Jr
Air Force Research Laboratory, Human Effectiveness Directorate, Air and Space Biosciences Division, ERC Section
University of Cincinnati
Zoll Medical
Caire Inc
Sparx Engineering
University of Southern California
University of Texas Health Science Branch
Regions Hospital
St Anthony Hospital
Cincinnati Children's Hospital
United States Air Force School of Aerospace Medicine/CSTARS (UC)

QUESTIONS?