

New Paradigms in
Perioperative
Anesthesia



Point-of-Care Manufacturing (& Testing)

3D Printing During the Pandemic (& Beyond!)

Toronto Anesthesia Symposium April 17, 2021

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Continuing Professional Development

The Lynn & Arnold Irwin
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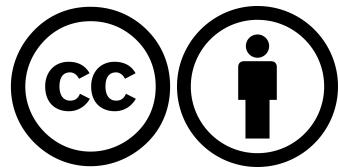
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Disclosure - Azad Mashari

Relationships with financial sponsors (APIL research group)

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- UHN Foundation
- UHN-SHS Anesthesia Association
- UHN-SHS Academic Medical Organization
- Ontario Centers of Excellence (with TME Inc)
- NSERC

Speakers Bureau/Honoraria: Nil

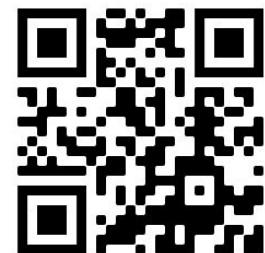
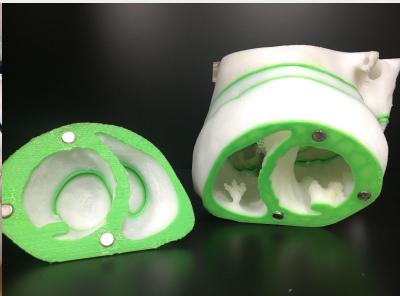
Consulting Fees: Nil

Research Collaboration:

- Glia Inc. (COVID, other)
- Thornhill Medical Inc. (COVID, other)
- Promotion Engineering (COVID)
- General Dynamics Land Systems (COVID)

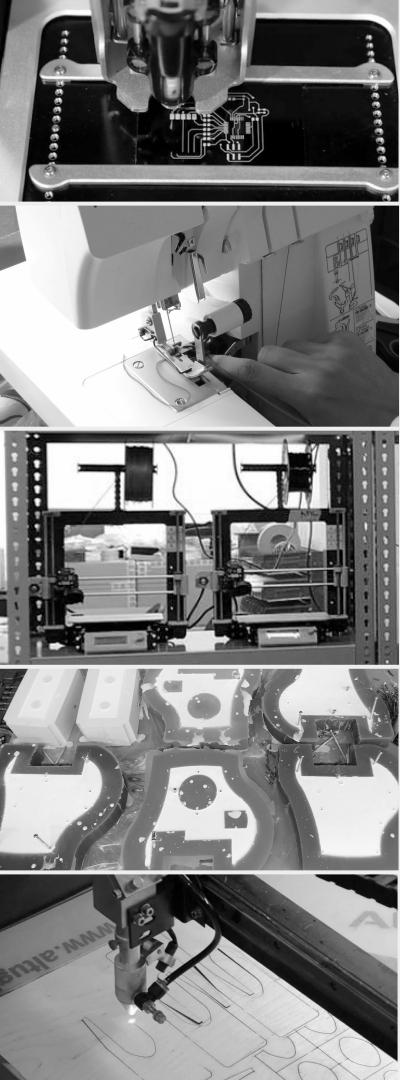
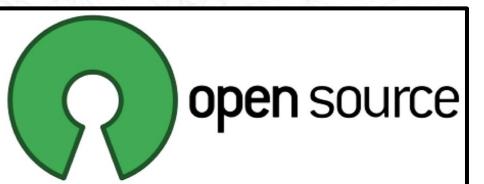
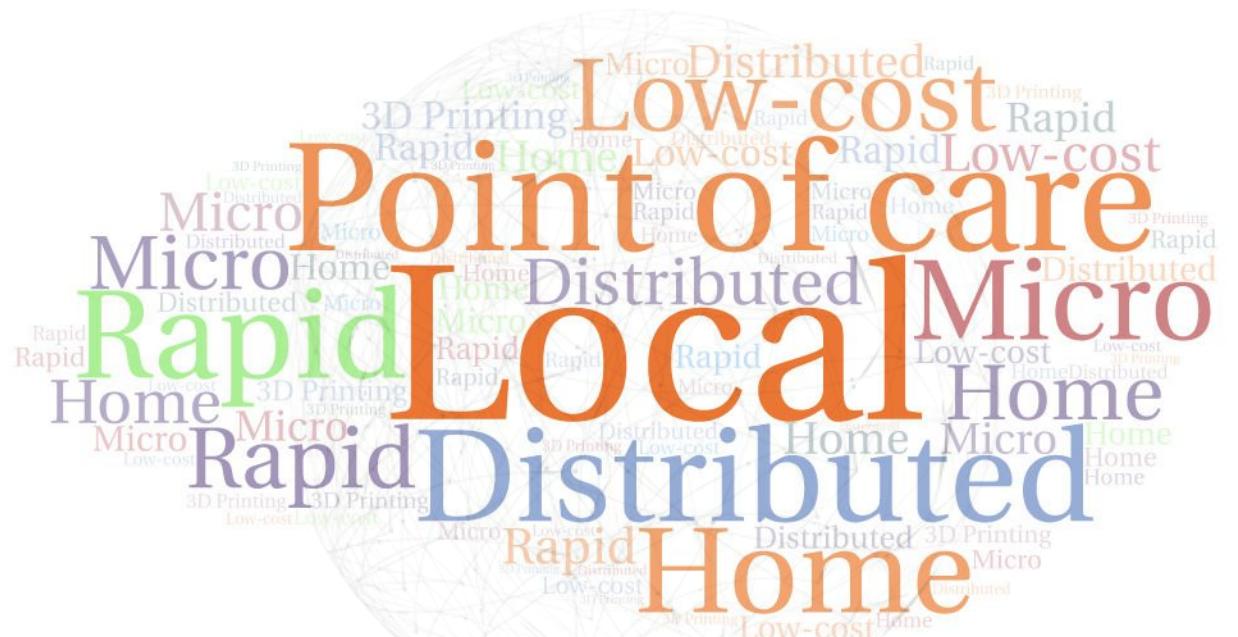
Patents: Nil

New Paradigms in
Perioperative
Anesthesia



Project repositories
<https://github.com/tgh-apil>

A family of Accessible Production Techniques (*e.g. molding*)
& Programmable Machines (*e.g. 3D printers*) for Making Health Care Products



Objectives & Outline

Learning Objectives

After the completion of this session participants will be able to

1. Describe the **current capabilities and limitations** of local and point-of-care manufacturing systems in addressing shortages of essential health care products
2. Describe the broad **contributors to health care supply chain disruptions** during the pandemic
3. Discuss the potential **role of hospital-based manufacturing and device testing laboratories** in improving the resilience of health care systems in future pandemics.

New Paradigms in Perioperative Anesthesia

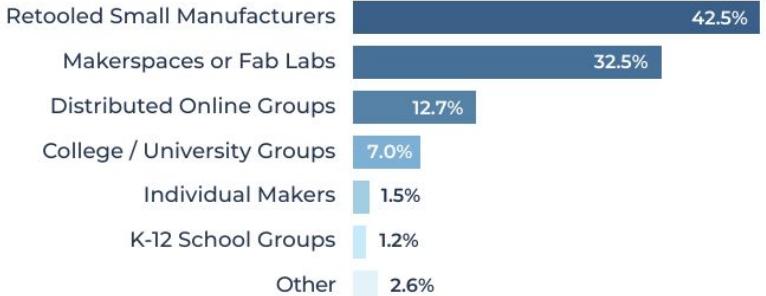
Outline

1. Who made how much of what?
2. Local efforts
3. What has been achieved?
4. What has not (yet) been achieved?
Why?
5. Where to now? How these approaches may contribute to more robust health care infrastructure



Bird's Eye View

Production Per Organization Type



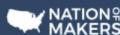
International survey by **Open Source Medical Supplies & Nation of Makers**

- 6 months March - Sept 1 CE (2020)
- 1800 respondents from 86 countries
- 42,000 people involved, 93% volunteers

DESIGN | MAKE | PROTECT

A report on the open source maker and manufacturer response to the COVID-19 PPE crisis

Download the full report at: osms.li/impact



OSMS and NoM collected data from **1800 respondents** from **March to September 2020**. Below are the **key report findings**.

WHO

Maker organizations, re-tooled manufacturers, and networks of volunteers

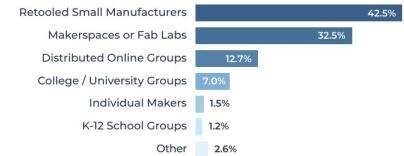
42,000+ Citizen Responders

86 Countries with Local Response Efforts

93% Volunteers

50 US States, Washington DC, and Puerto Rico

Production Per Organization Type



WHAT

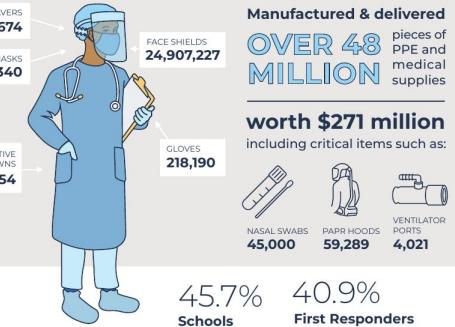
Created hundreds of new open source designs for medical supplies

200+ DESIGNS

available in the OSMS Library for 35 categories of PPE & supplies

6,000% Increase in unique visitors to the NIH 3D Print Exchange within 24 hours of engaging the maker community.

Numerous medical inventions



WHERE

Serving their entire communities, from major hospital networks to underserved populations

Schools, non-profits, senior housing and hospitals all received PPE and medical supplies. The following percentages of makers reported distributing supplies to these recipients:

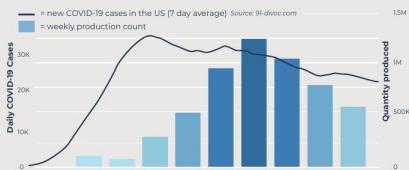
45.7% Schools 40.9% First Responders

80.4% Hospitals and medical clinics 56.5% Senior Housing 43.6% Non-profit agencies serving low income populations

WHEN

Swiftly pivoting to address critical shortages

Makers were toolled for rapid prototyping — and they were indeed fast. Maximum production capacity was achieved in only six weeks; whereas traditional manufacturing took several months to reach its full production potential.



What was made

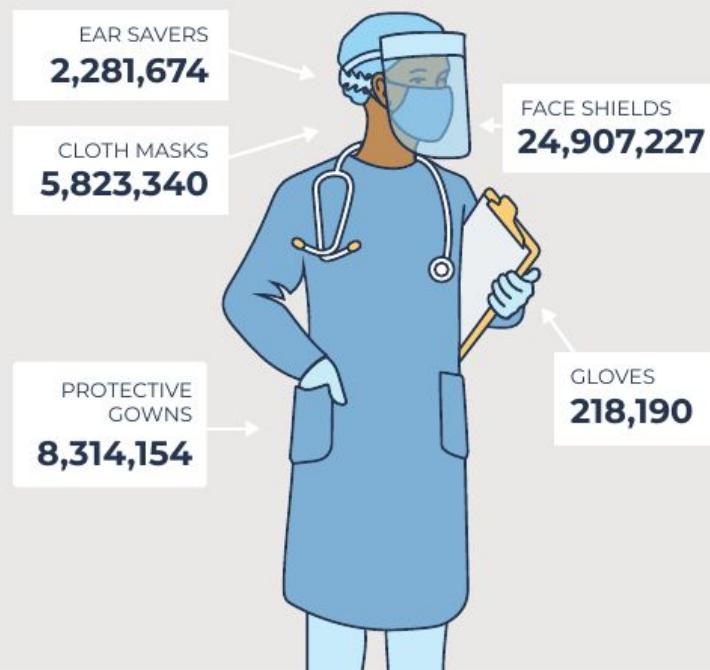
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Numerous medical inventions



Manufactured & delivered **OVER 48 MILLION** pieces of PPE and medical supplies

worth **\$271 million** including critical items such as:

	NASAL SWABS 45,000		PAPR HOODS 59,289		VENTILATOR PORTS 4,021
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<https://OSMS.li/impact>

Enabling Network Infrastructure



OPEN SOURCE INFORMATION

We were able to prepare and organize **weeks before the virus reached our country** due to the experiences, resources, procedures, source files, etc. shared by the maker community as a whole.

*Andres Hermes
TecLab, Guatemala*



COMMUNITY NETWORKS

71%

of respondents depended on networks, community platforms and personal introductions

It's been fantastic **not only to share but compare and review** what people have been doing.

*Sam Haynor
Something Labs,
San Francisco, CA*



VETTED DESIGNS

50%

of respondents made use of open source design repositories

Without the **pre-vetted designs AND production instructions** we would have spent too much time reinventing the wheel and not enough time producing.

*Nathaniel Fairbanks
Makelt Labs, Nashua, NH*

<https://OSMS.li/impact>

Local Projects

Face shields

Reusable Silicone Stop-Gap Respirator

Reusable Snorkel Mask-Based PAPR

Ventilator Sharing System

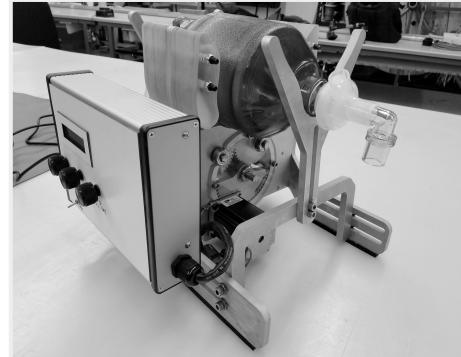
Aerosol Reducing NIV Mask

BVM-Based Emergency Use Ventilator

Evaluation of BVMs for Pre-oxygenation

Open Ventilator Evaluation Framework (NSERC, UT MIE)

Open Ventilator Controller Platform (NSERC, UT MIE)



Stop-gap Silicone Respirator Mask (William Ng)

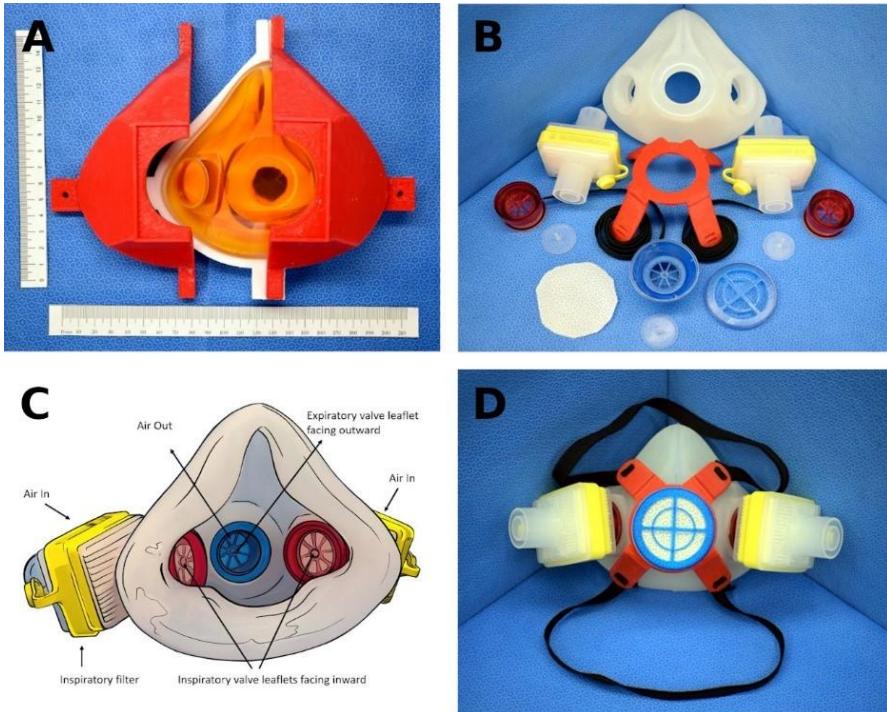
Goal: Develop a locally manufacturable, reusable respirator meeting or exceeding N95 protection

Progress:

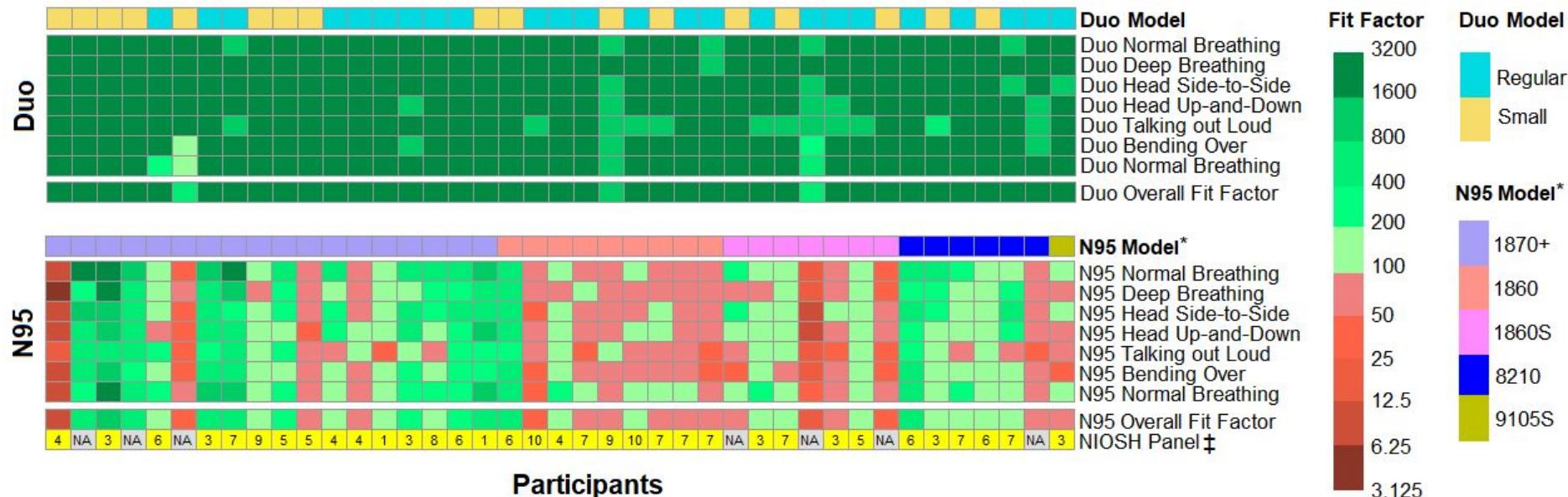
- Second generation design. Exceeds N95 filtration performance. Validated in 40 HCW.
- Undergoing testing and refinement to meet technical standards for resistance and CO₂ retention.
- Planned application for HC.

References:

1. <https://github.com/tgh-apil/Reusable-N95-Respirator>
2. Ng et al. PLoS ONE. 2020; 15(11):e0242304.
3. Anwari et al. PLoS ONE. 2021;16(3):e0247575.
4. Version 2 MS in preparation



Stop-Gap Respirator (Duo) vs N95: Quantitative Fit Testing in 40 HCW



Overall Pass Rate:

- **N95: 58.5%** (most failures in dynamic maneuvers; difference across models)
- **Reusable SGR: 100%**

Positive-Pressure Air Purifying Respirator (PAPR) - Mod. Snorkel Mask

(L. Fedorko)

Goal: Develop a locally manufacturable, reusable PAPR

Progress:

- Designed, tested, and validated in 40 HCW.
- 50 units manufactured for UHN. Not deployed.
- Difficulty communicating (like other PAPRs)
- Planned application for HC.

References:

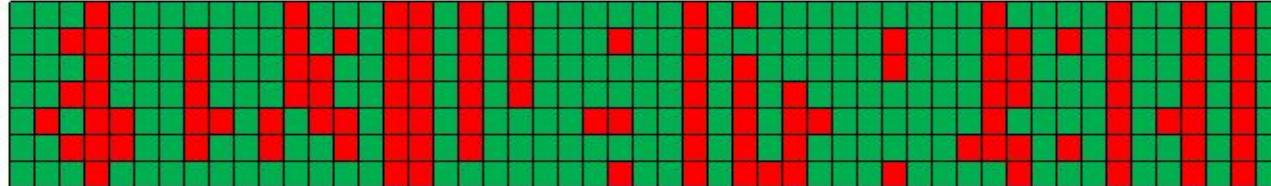
1. <https://github.com/tgh-apil/PAPR>
2. Clinkard et al. Anaesthesia. 2021;76(5):617–22.



N95 vs. Filtered Snorkel Mask vs. PAPR: Quantitative Fit Testing in 40 HCW

N95

Quiet Breathing
Deep Breathing
Side-to-side
Nodding
Talking
Bending
Quiet Breathing

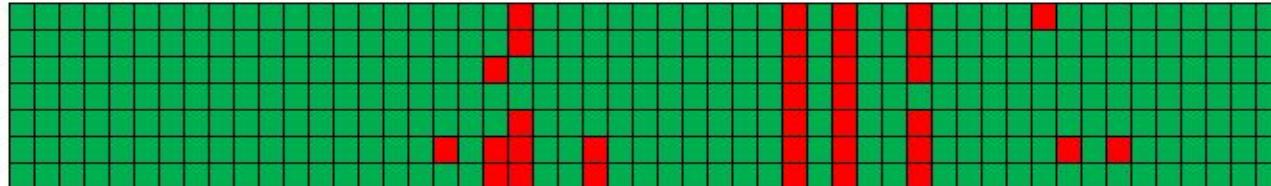


SWPF



SM

Quiet Breathing
Deep Breathing
Side-to-side
Nodding
Talking
Bending
Quiet Breathing

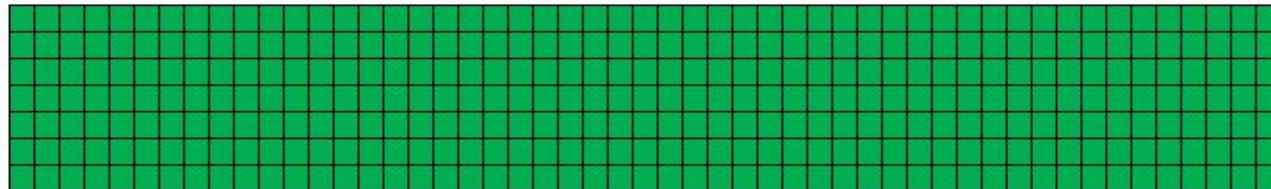


SWPF



PSM

Quiet Breathing
Deep Breathing
Side-to-side
Nodding
Talking
Bending
Quiet Breathing



SWPF



Respirator Feature Summary

	Face Seal	Filtration Performance	Filtered Exhalation	Comfort	Voice
Disposable N95	+/-	+/-	+	+	+/-
3M Elastomeric	++	++	-	+/-	-
Duo Stop-Gap Silicone	++	++	+	+/-	-
Snorkel PAPR	+	++	-	+	-

Ventilation

Emergency Use Device Development

- Aerosol Reducing NIV Mask
- Ventilator Splitter
- BVM Based Emergency Ventilator

Device Evaluation

- Evaluation of BVM Models for Pre-Oxygenation
- Open-Source Ventilator Evaluation Framework
- Use of BVM for Pre-oxygenation

Aerosol-Reducing NIV Mask

Goal: Develop a locally manufacturable NIV mask that minimized aerosol generation. For use in transport, hospitals and northern health stations

Progress:

- Developed rapidly in collaboration with Glia & General Dynamics Land Systems-Canada
- May 2020 Health Canada granted Interim Order for clinical use in pandemic
- Subsequent evaluation (clinical trial, user feedback, bench testing) suggested significant problems. Device voluntarily held from sale. Second version in development.

References:

1. <https://github.com/GliaX/Aerosol-Reducing-Mask>
2. [Final Report of Device Testing and Clinical Trial Data ARM v1.0](#)



Aerosol-Reducing NIV Mask: Clinical Trial (N = 6+8)

Clinical Trial at London Health Sciences Center

Western University HSREB

Pts. prescribed NIV in ED randomized to ARM or control mask.

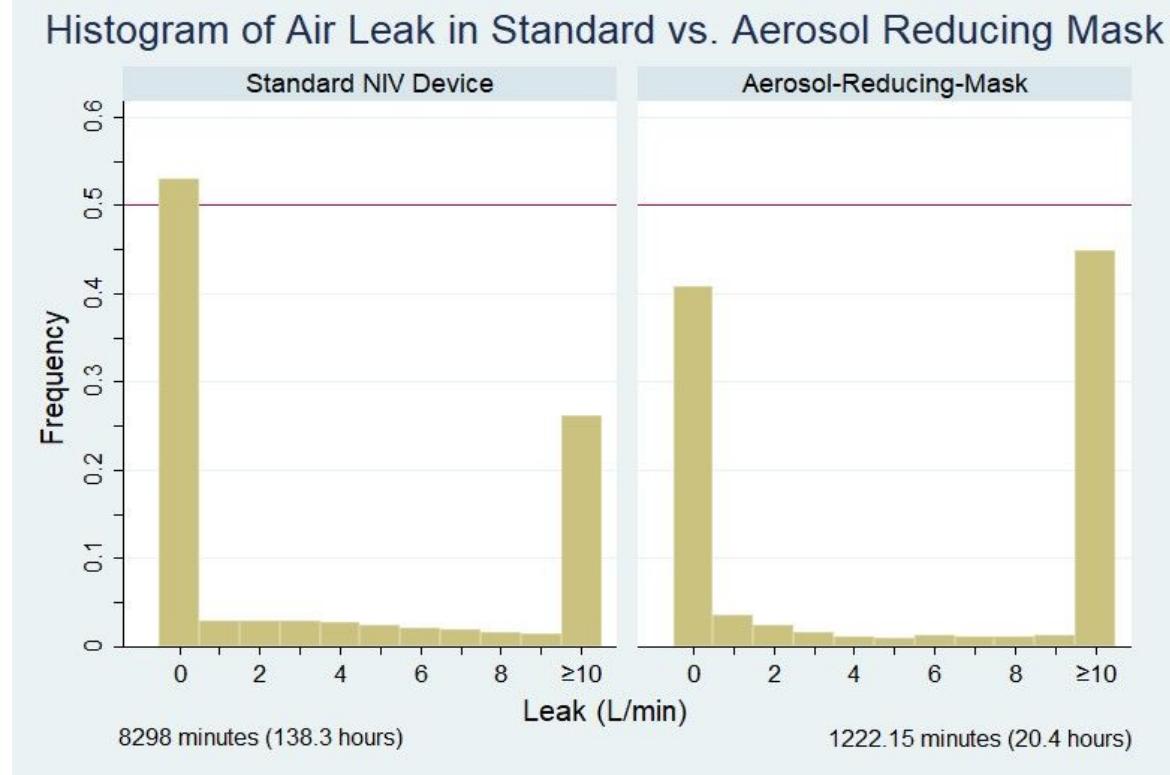
Upto 24 hours.

Outcome: Leak L/min.

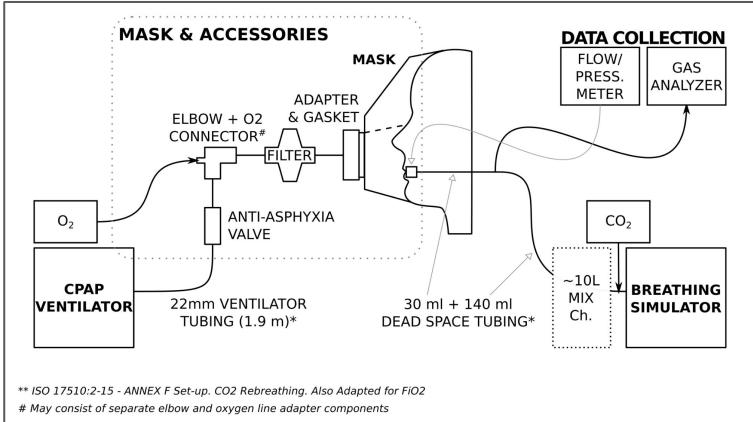
Stopped early after 14 participants
(6 ARM; 8 control) due to loss of equipoise

Device did not reduce leaks

No adverse events



Aerosol Reducing Mask CO₂ Re-breathing Test (ISO 17150:2)



Test Condition	End-Tidal CO ₂ %	End-Tidal CO ₂ (mmHg)	Increase from baseline (%)	Acceptable Increase (%)
Baseline: No mask/CPAP	5.04	40	-	-
CPAP 5 cm H ₂ O	5.70	46	13.1	20
CPAP 10 cm H ₂ O	4.31	35	-14.4	20
CPAP 20 cm H ₂ O	2.30	18	-54.3	20
Fault: Patient connection port occluded	8.35	67	65.7	60
Fault: CPAP connected with no flow	8.36	67	65.8	60

- Risk of significant CO₂ rebreathing in event of ventilator failure or disconnection.
- Only appropriate for supervised use.
- Not practical with current staffing shortages.

Aerosol-Reducing NIV Mask - Quality Control

Health Canada Interim Order Authorization for Clinical Use **May 2020**.

- IO did not require any trial data, bench testing or user/human factors testing

Undertook additional evaluation after IO authorization (no requirement from Health Canada)

- Clinical Trial: **no reduction in mask leak** overall.
- User feedback (RT, RN): several **significant usability limitations**:
 - Opaque face-piece concealing vomiting; No NGT fitting;
 - Heavy;
 - No emergency release;
- CO2 rebreathing testing showed **failure to meet ISO requirements for rebreathing** in the event of a ventilator failure.

Device sales suspended **Nov 2020**. No units sold. Back to the drawing board. ARM 2.

- At the time device was under consideration by ORNGE & Indigenous Services Canada

Ventilator Splitting System



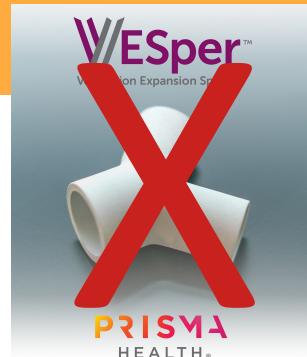
ABOUT SCCM + COMMUNICATIONS + EDUCATION CENTER + FUNDAMENTALS + MEMBER CENTER + PROFESSIONAL DEVELOPMENT +

SCCM > Emergency Resources: COVID-19 > Advocacy

Consensus Statement on Multiple Patients Per Ventilator

Issued: March 26, 2020, 12:00 p.m.

The above-named organizations advise clinicians that sharing mechanical ventilators should not be attempted because it cannot be done safely with current equipment. The physiology of patients with COVID-19-onset acute



High risk of

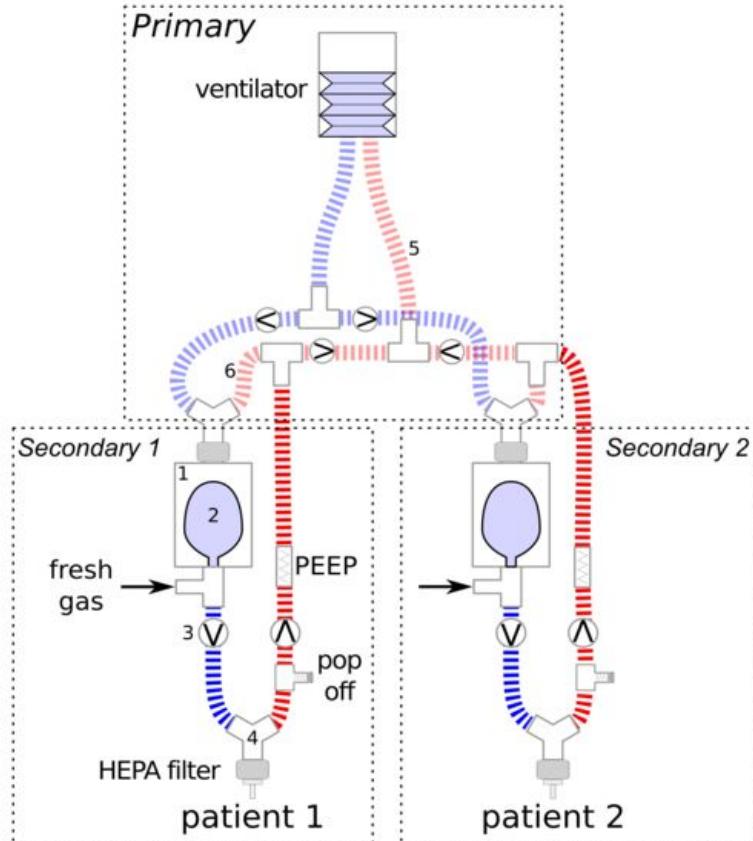
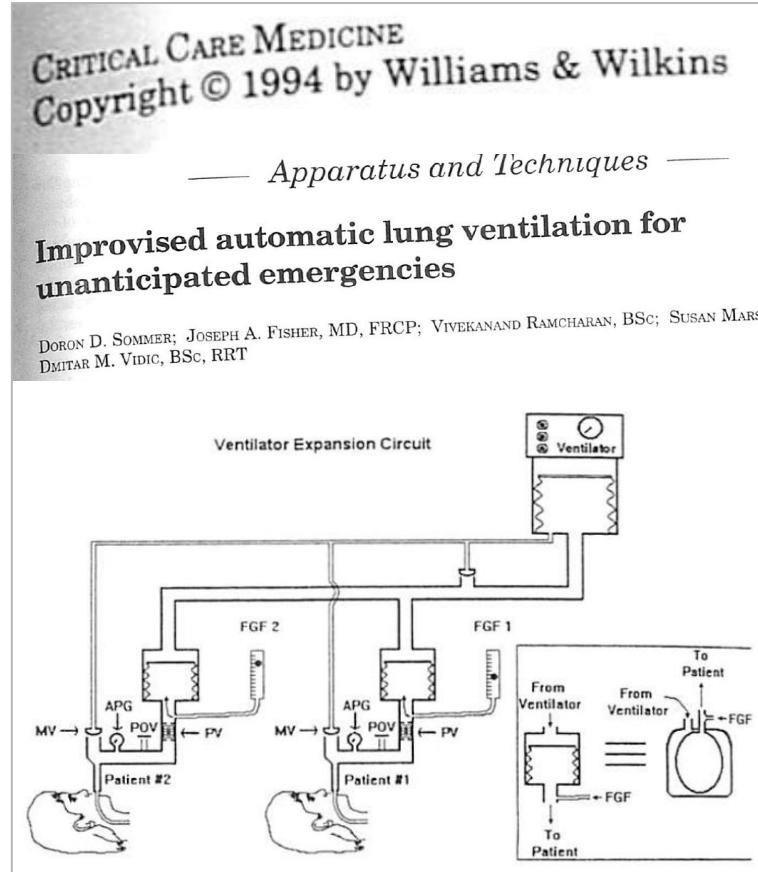
- **Barotrauma:** Inability to control distribution of shared tidal volume
- **Hypoventilation** in patient with higher lung compliance
- **Disconnection or blockage** of one circuit affecting both co-ventilated patients
- **Cross Infection**

Ventilator Splitting: Cerberus

J. Han, D. Singh, J. Fisher



Joe Fisher



Ventilator Splitting: Cerberus

J. Han, D. Singh, J. Fisher

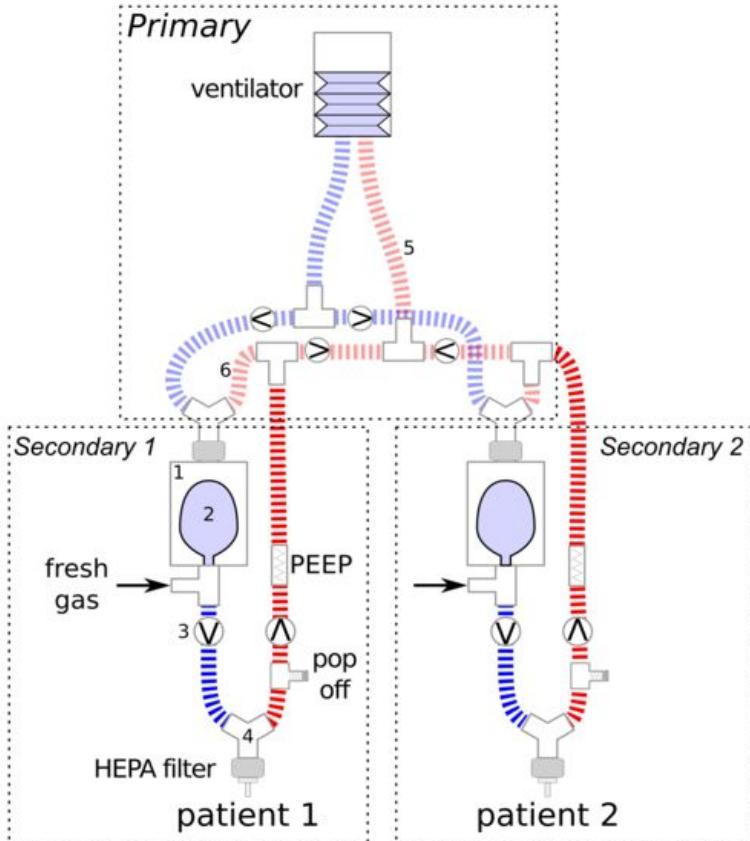
Goal: To build and test an emergency use splitter system that addresses these limitations.

Progress:

- Massive collaborative effort involving over 100 people across U of T and academic hospitals
- System refined and bench validated
- Validated in two pigs (34 and 80 Kg)
- 40 units (80 patient circuits) ordered for UHN in June 2020
- **Still unable to obtain some “off-the-shelf” parts**

References:

1. <https://github.com/tgh-apil/Cerberus-Multivent>
2. [Han et al. Critical Care Explorations. 2020 May;2\(5\):e0118.](#)
3. Porcine validation paper in preparation.



Ventilator Splitting: Cerberus

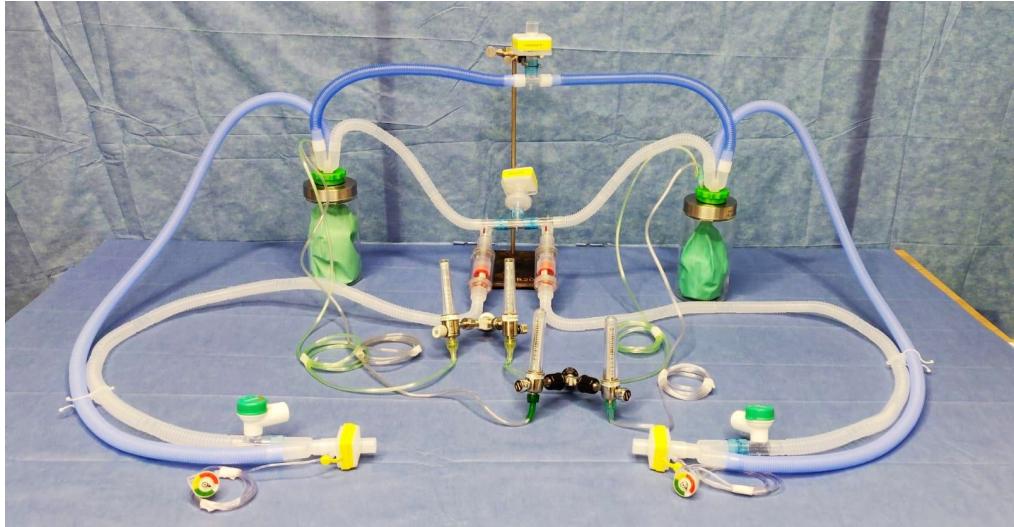
J. Han, D. Singh, J. Fisher

Strengths

- Independent control of TV, FiO₂, PEEP
- Catastrophe on one side (disconnection, obstruction) does not affect other side
- Isolated gas paths to each patient

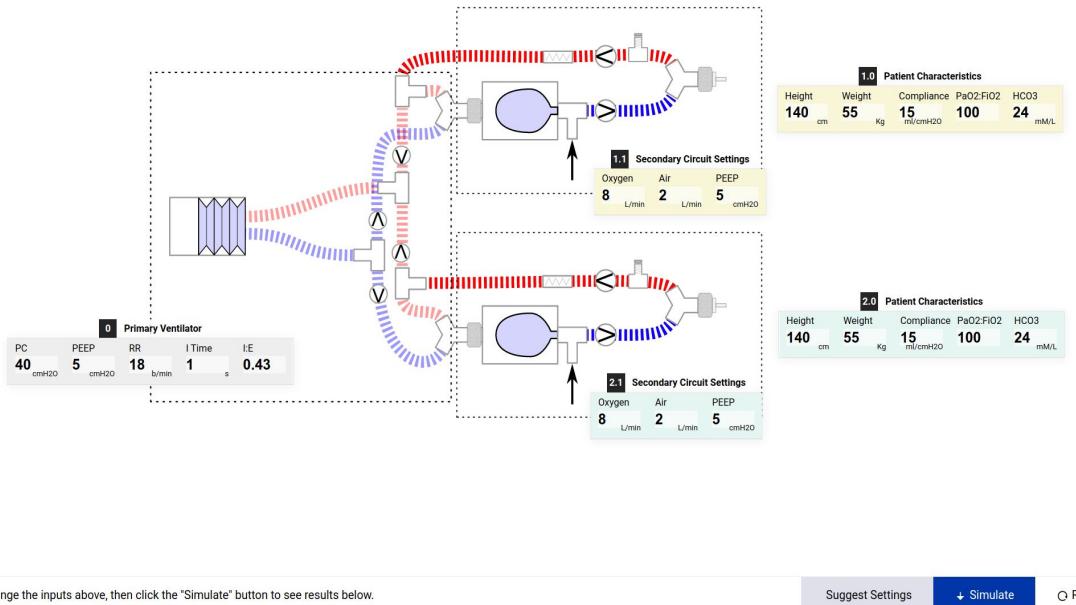
Challenges

- Volume control only
- Deep sedation
- No weaning
- < 48 hours of emergency use
- Close monitoring (1 provider to max 2 patients)
- **Adjustment is not intuitive ...**

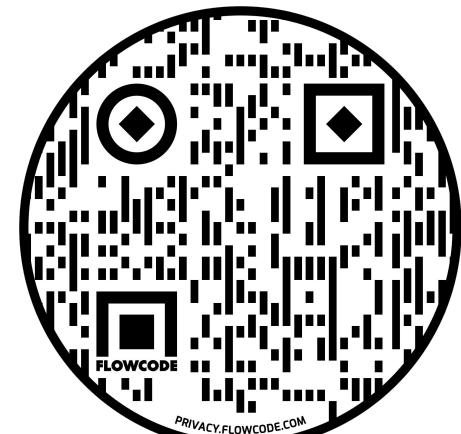


Ventilator Splitting: Cerberus Model & Simulator

Eitan Grinspan, Isaac Waller, Bai Li, James Duffin



<https://ventilator-simulator.now.sh>



Change the inputs above, then click the "Simulate" button to see results below.

Primary Vent	Patient 1				Secondary 1				Patient 2				Secondary 2												
PC	PEEP	RR	I:R	I:E	H	W	Cr	P/F	VT	FIO ₂	PaO ₂	PaCO ₂	HCO ₃	pH	FGTot	PEEP	APEEP								
40	5	18	1	0.43	140	55	15	100	555.56	0.84	84.2	25.93	7.59	10	5	14.8	140	55	15	100	555.56	0.84	84.2	25.93	7.59

Click on a row to reset input values to those values. Current values are bold

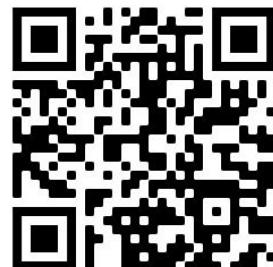
Expert mode (show all variables)

Some BVM Manual Resuscitators are NOT Safe for Preoxygenation

- Incidental finding of BVM valve incompetence during testing of ARM NIV Mask.
- New model at UHN & CAMH due to shortage of regular model
- Assumed equivalence since HC approved
- Large leak through expiratory port during spontaneous inspiration in new model.
- **Effective delivered FiO_2 35-60% during negative pressure inspiration.**
- Relevant international standard CSA/ISO 10651-4:2002 only requires 35%. Does not require competence of patient valve.
- Models used before voluntarily exceeded the standard.

References:

1. <https://github.com/tgh-apil/BVM-Evaluation>
2. MS in preparation.



<https://github.com/tgh-apil/BVM-Evaluation>



Point-of-Care Manufacturing & Testing: What has been achieved?

Class I devices - Tens of millions of face shields, stethoscopes, cloth masks made & reached frontlines, many following standard regularly pathways (relatively simple for Class I)

Class II & III - Vast number of collaborations developing open source Class II and III devices

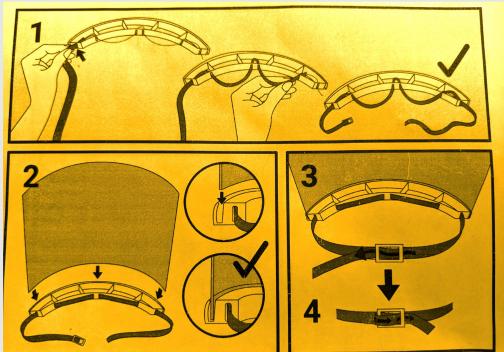
N95 Respirators, Swabs, Ventilation Masks, Ventilator components, Ventilators...

- **Massive investment** of volunteer resources; significant public funding (swabs, ventilators)
- A few devices received **emergency use approval** (e.g. HC IO, FDA EUA)

Dramatic **growth in networks** and communities of open source developers, small-medium scale manufacturers, academics, health care providers

Increasing awareness of the **potential of local point of care manufacturing**

Increasing awareness of the **limits of current regulatory processes**



What has not (yet) been achieved

Few class II-III devices were clinically deployed

- Significant safety concerns about some device with accelerated approval

The [open medical device development model](#) is still a work in progress

- Quality management administrative systems
- **Open technical standards**

[Regulatory pathways](#) needs to adapt to accommodate and adequately regulate the open devices.

Lack of institutional integration

Open Device Development Process Elements	
Quality Management Administrative System	+
Risk Management Framework	+
Problem Identification	++
Specifications	+/-
Iterative Design	+++
Prototyping, Formative Testing	+++
Formal testing & Validation	+
Supply Chain & Manufacturing Process Design	+/-
Formal Evaluation (bench, clinical, standards conformance)	+/-
Regulatory Approval	+/-
Manufacturing	+
Distribution	+
Post-marketing surveillance	+/-

Supply Chain Failure

Sparks:

- Rapid increase in global demand
- Closures, worker illness, hoarding, export controls

Tinder:

- **Just-in-time** systems - low stockpiles
- High reliance on **disposable** products and components
- **No advanced emergency planning** in most jurisdictions: e.g. N95s
- **Decentralized supply chain management:** stock information, purchasing; hospitals and LTC fending for themselves on open market
- **Centralized sourcing:** often single supplier with access to relevant **IP** (drugs, devices, vaccines)
- **Limited local manufacturing capacity:** 90% of health products in NA from China. 73% of Mouth/nose protection devices.
- Inability to **identify appropriate replacements** - no product coding system: Eg. Bag-Valve-Masks
- Inability to **evaluate new or alternative products** rapidly



[Snowdon A. \(2021\) Key Characteristics of a Fragile Healthcare Supply Chain. CanCOVID Speaker Series](#)
<https://www.youtube.com/watch?v=hrooLCxsCRY>

Safety & Quality Control Failure

Damage control & Fallout:

- Accelerated regulatory approval pathways >>> **Quality control failure**
- Rapid retooling, accelerated manufacturing >>> **Quality control failures**
- Market competition >>> skyrocketing prices (1000% increase N95s, Swabs ...) >>> Incentive for unscrupulous production

Digital Stockpile?

Separate development from manufacturing

- **Open-source stockpile of essential devices**
 - device design & manufacturing plans
 - Testing procedures and data
 - QC plans
- **Emergency manufacturing networks** - local manufacturers, academic centers, community groups etc.
 - **Hospital based manufacturing & testing facilities**



Merlo S. (2020) Building Medical Supply Chain Resilience through a U.S. Manufacturing Reserve and Digital Stockpile. Day One Project; <https://www.dayoneproject.org/post/u-s-prototyping-manufacturing-reserve-u-s-digital-stockpile>

Acknowledgements

S. Ajami, E. Al-Azazi, K. Behdinan, M. Al-Mandhari, S. Ansari, N. Ayach, V. Anwari, J. Carroll, R. Caragata, D. Clinkard, M. Dinsmore, S. Doshi, J. Duffin, D. Duncan, L. Fedorko, J. Fisher, D. Gucciardo, E. Grinspun, J. Han, J. Qua Hiansen, K. Kazlovich, B. Li, T. Loubani, J. May, A. Mbadjeu Hondjeu, W. Ng, S. Plimmer, S. Russell, D. Singh, L. Venkatraghavan, C. Wakem, I. Waller, M. Xiao, T. Yan ...

University of Toronto: Computer Science, Mechanical & Industrial Engineering

UHN: Peter Munk Cardiac Center, Med Eng, JDMI, RT, OR, MDRD, Techna Inst, IPAC, Animal Lab ...

Interdepartmental Division of Critical Care Medicine

Glia Inc. UHN-SHS Anesthesia Associates, Thornhill Medical, London Health Sciences Center, General Dynamics Land Systems-Canada, University of Toronto, Lakehead University, TME Inc., Promation Engineering



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