Addressing the Ventilator Shortage & Solutions Discussion

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Acknowledgments:
SK Gupta (USC AME), Daniel Stemen (USC Keck), Alec Kanyuck (USC AME), Mitul Luhar (USC AME), Anita Penkova (USC AME), Boris Fritz (USC AME), Roger Ghanem (USC CEE), Hangbo Zhao (USC AME), Charles Radovich (USC AME), James A. Mertz (NASA JPL), Iliya Muzychuk (Brooks & Scarpa)

April 29, 2020

Please note

I am not an expert in:

- respiratory conditions
- mechanical ventilation

This presentation is mainly *a* compilation of information.

Outline

- Motivation
- Mechanical ventilation
- Minimal requirements
- Open-source designs
- Activities in AME at USC
- Dialogue

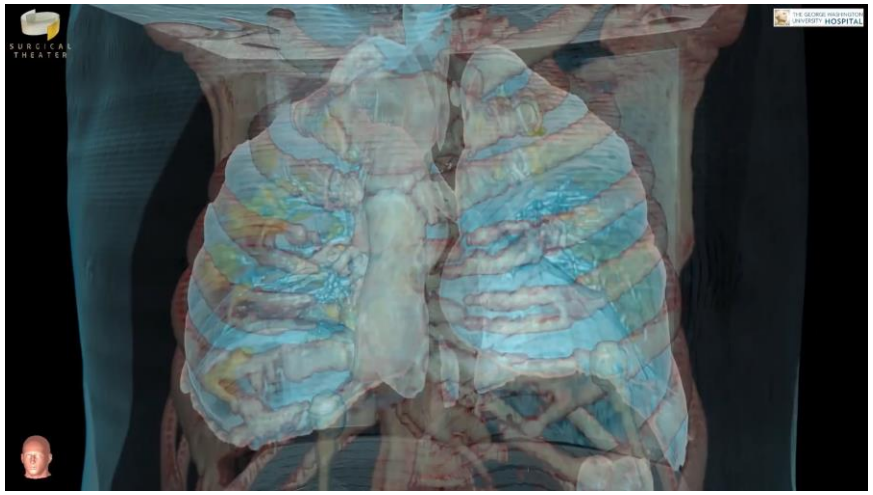
Motivation

COVID-19 can lead to Acute Respiratory Distress Syndrome (ARDS): [1]

- Rapid invasion of lung cells.
- Attack of epithelial cells lining airways.
- Airways flooding with debris and fluids.
- Pneumonia.
- Respiratory failure.

  ⇒ Mechanical ventilation *may* be required

Healthy tissue Damaged (infected) tissue



George Washington Hospital, Virtual Reality Technology
gwhospital.com/resources/podcasts/covid19-vr-technology

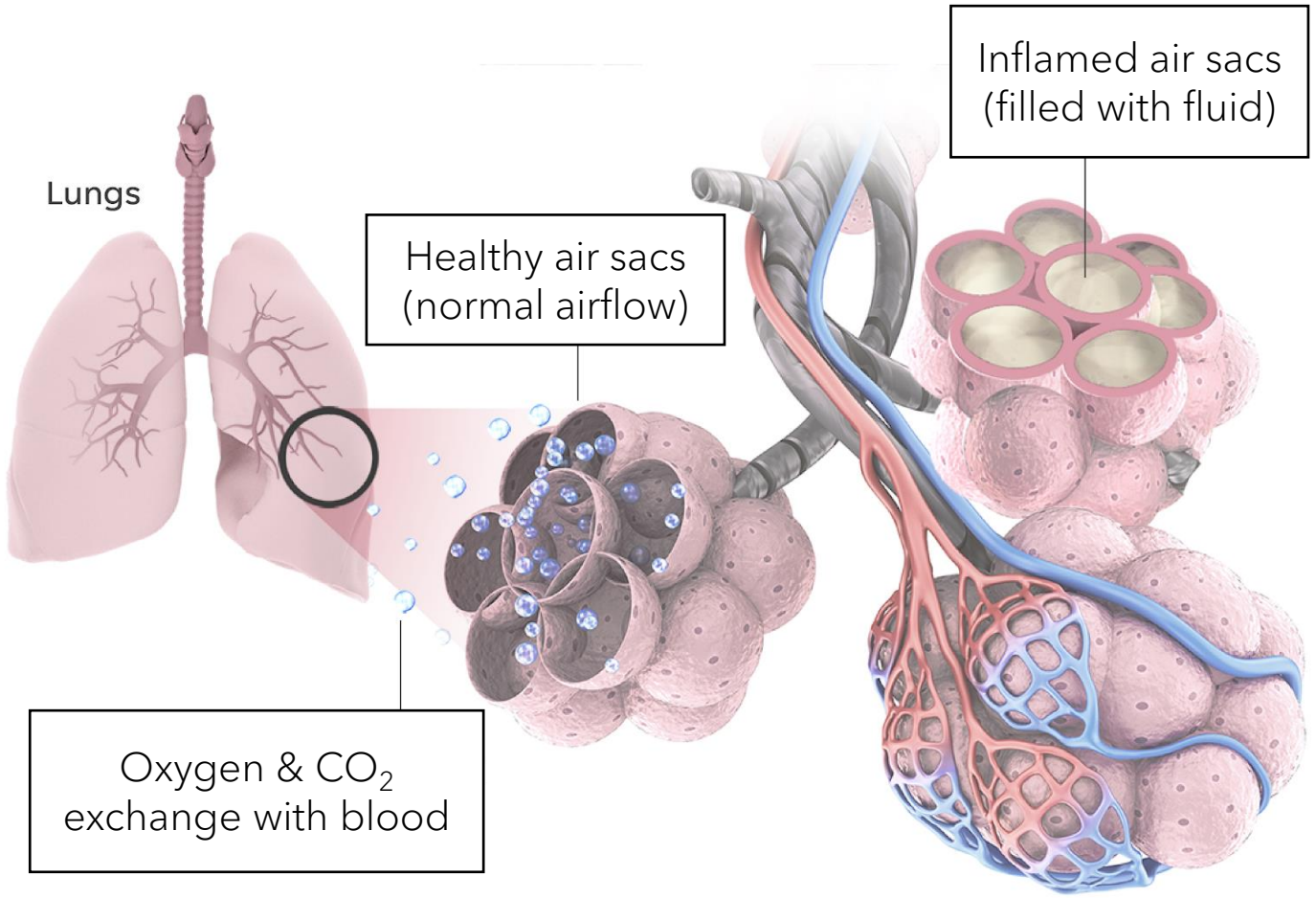
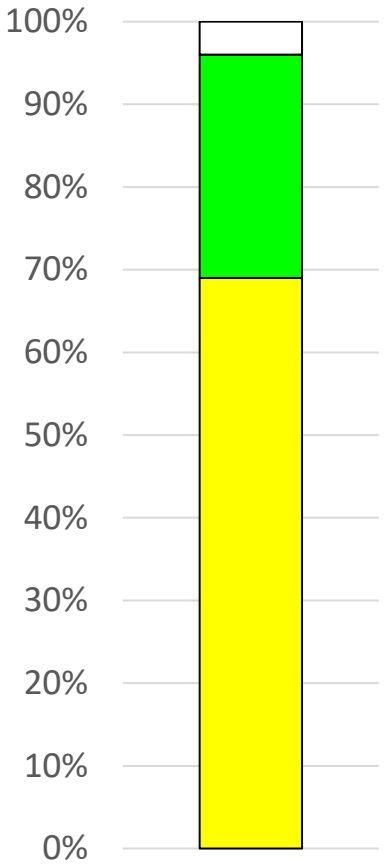


Image adapted from:
usatoday.com/in-depth/news/2020/04/10/coronavirus-ventilator-how-works-why-covid-19-patients-need/2942996001/

(1) American Lung Association (lung.org)

Motivation

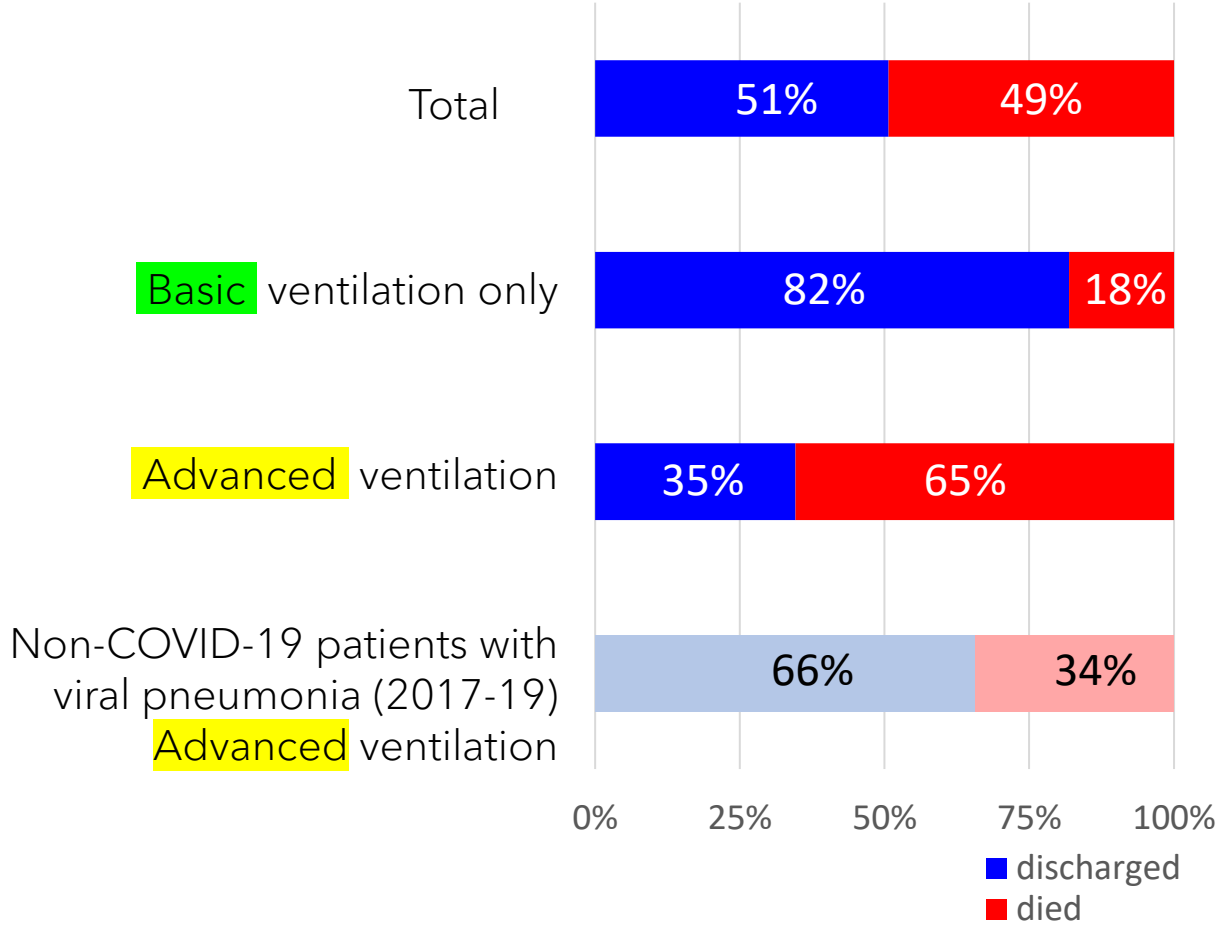
Data from 4,072 patients with confirmed COVID-19 admitted for critical care in the U.K. that have been discharged or died



Basic ventilation only

Advanced ventilation

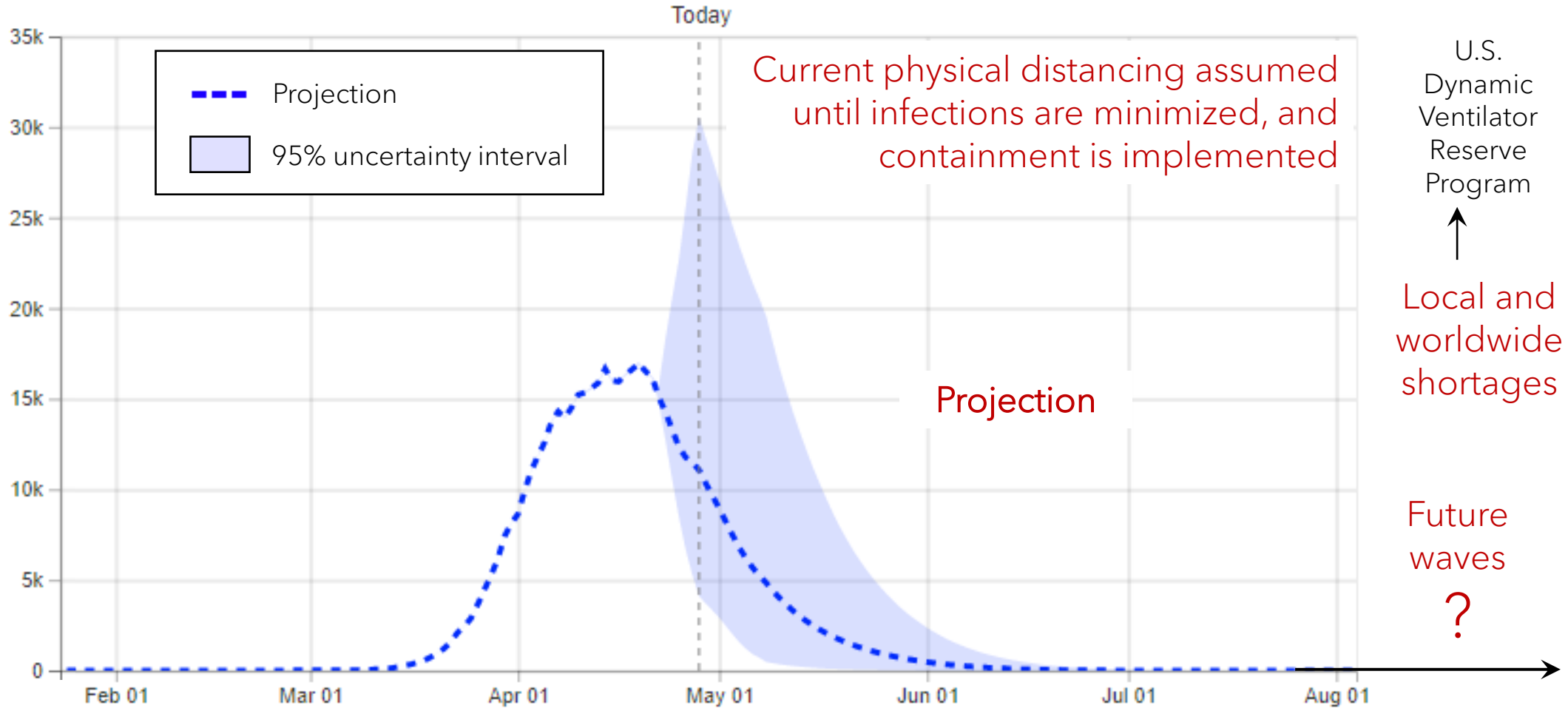
- Invasive ventilation
- BPAP via trans-laryngeal tube or tracheostomy
- CPAP via trans-laryngeal tube
- Extracorporeal respiratory support



"These data derive from the ICNARC Case Mix Programme Database. The Case Mix Programme is the national clinical audit of patient outcomes from adult critical care coordinated by the Intensive Care National Audit & Research Centre (ICNARC). For more information on the representativeness and quality of these data, please contact ICNARC." icnarc.org/Our-Audit/Audits/Cmp/Reports (figures generated from data downloaded on April 24, 2020)

Motivation

Invasive Ventilators Needed for COVID-19 in the U.S.



U.S. Dynamic Ventilator Reserve Program

↑

Local and worldwide shortages

Future waves

?

U.S. national supply: 105,000 = 95,000 in hospitals + 10,000 in Federal Strategic National Stockpile.
Private industry to produce ~32,000 by the end of May and 150,000 by the end of the year.

Demand: Up to now, invasive ventilators needed peaked at 16,620 on April 14, 2020.

Institute for Health Metrics and Evaluation (IHME). COVID-19 Hospital Needs and Death Projections, University of Washington, 2020 (covid19.healthdata.org)

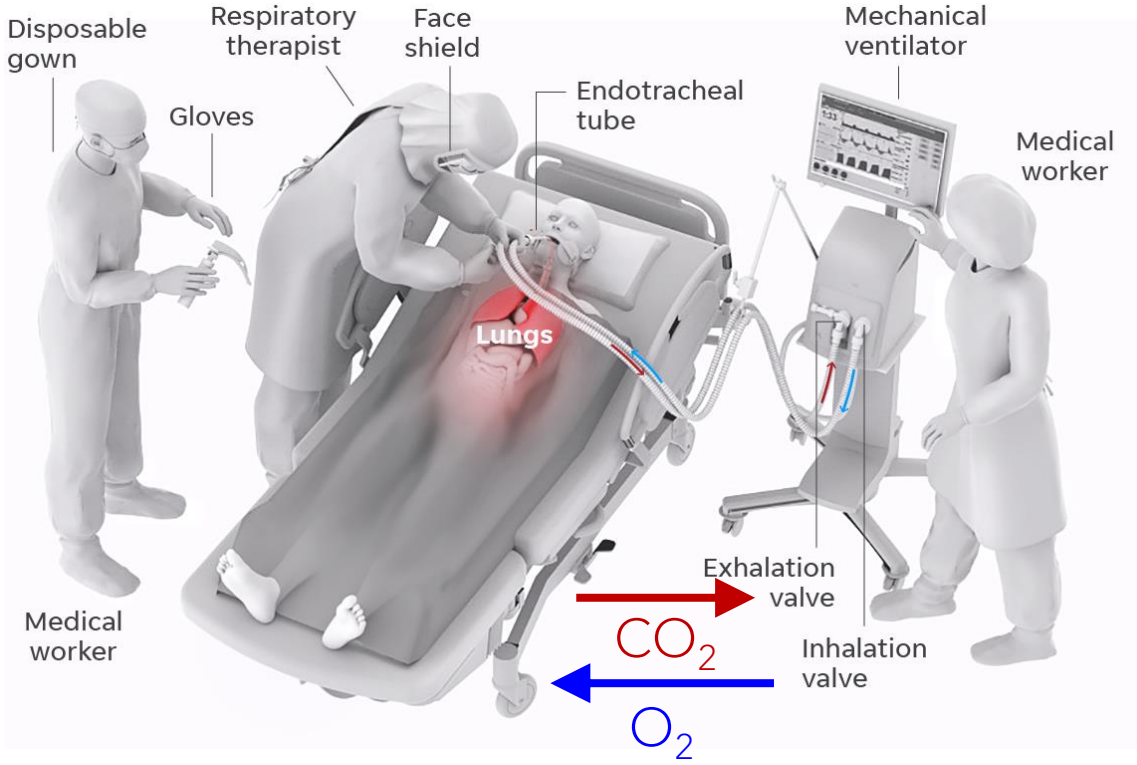
Mechanical Ventilation

Non-invasive

Mask (face/nasal) and helmet

Invasive

Intubation
(endotracheal and tracheostomy)



Both require ventilator circuit supplies (tubing, parts, adaptors, valves, filters, etc.):

- Urgent calls are in effect for small, non-traditional sectors of advanced manufacturing to replenish inventories [3].

Risks:

- alveolar damage and lung collapse from overpressure.
- ventilator-associated pneumonia, if ventilator circuit unclean.
- diaphragm atrophy from prolonged assistance; may require *weaning* (gradual ventilator support withdrawal)

Image sources:
teleflex.com/usa/en/product-areas/respiratory/active-humidification-and-breathing-circuits/non-invasive-ventilation-masks/MC-003320_FIN_HR-1-end_use_mask2.jpg
i1.wp.com/coreem.net/content/uploads/2016/07/Screen-Shot-2016-07-17-at-2.38.29-AM.png?fit=663%2C542&ssl=1
usatoday.com/in-depth/news/2020/04/10/coronavirus-ventilator-how-works-why-covid-19-patients-need/2942996001/

(3) Joint Acquisition Task Force, Request for Proposals for Critically-Needed Ventilator Consumables, 2020, americamakes.us/wp-content/uploads/sites/2/2020/04/CSO_COVID-19-AOI_ventilator.pdf

Mechanical Ventilation

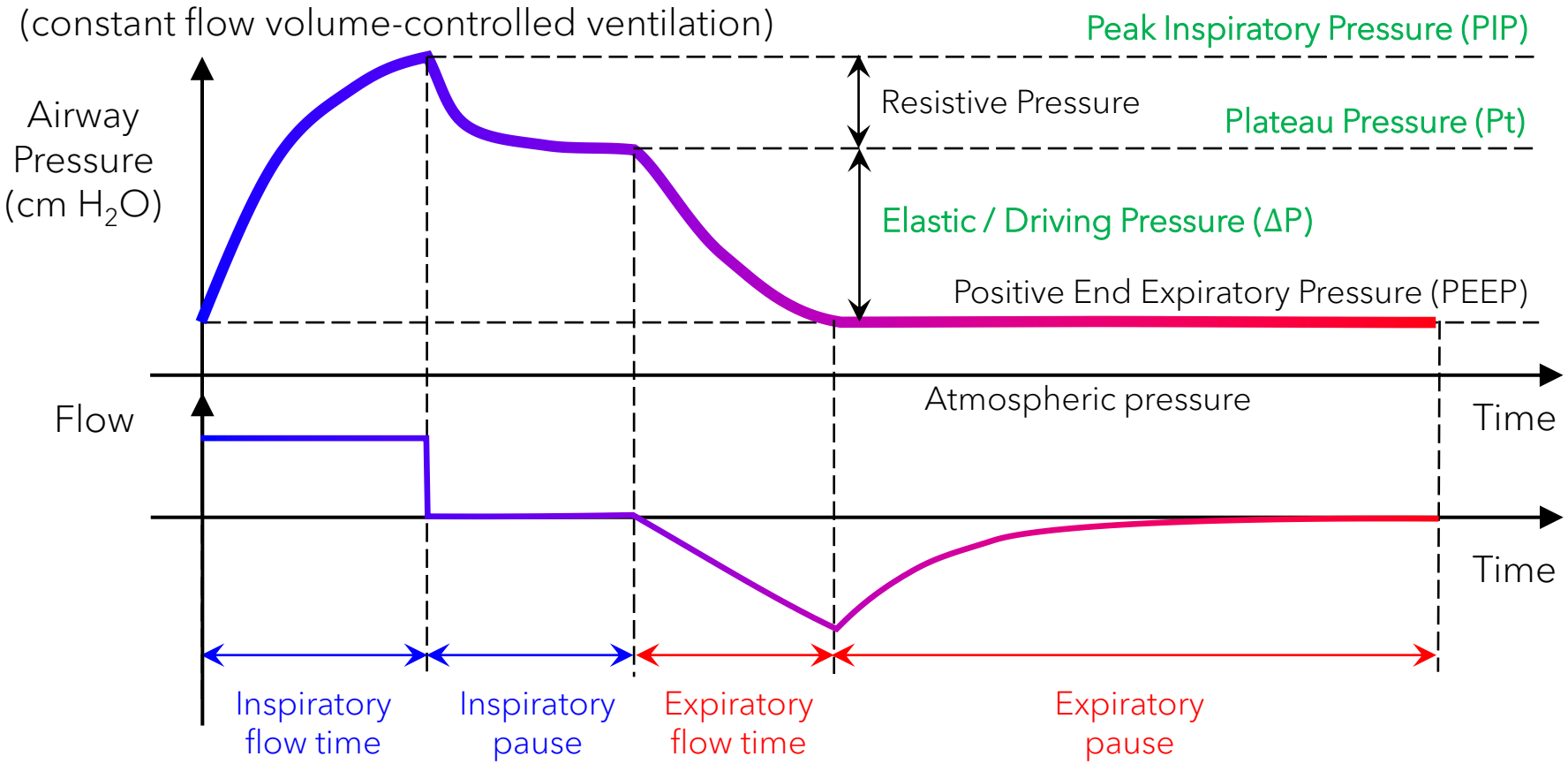
Positive pressure ventilation

Control Type	Delivers
Volume controlled (VC)	Preset air volume
Pressure controlled (PC)	Air until pressure limit reached
Dual controlled	Combination of VC/PC

Mode	Description
Control	Ventilator controls breathing (patient unconscious / sedated)
Assist	Patient initiates breath → triggers ventilator
Mixed	Assist-control, Intermittent Mandatory Ventilation (IMV)

Respir Care. 2002 Apr;47(4):416-24; discussion 424-6. Pressure-controlled versus volume-controlled ventilation: does it matter? Campbell RS1, Davis BR.ncbi.nlm.nih.gov/pubmed/11929615
adph.org/ems/assets/StudentManual_Ventilators.pdf

Mechanical Ventilation - Terminology – input / output



Typical **output to be monitored**:
- PIP
- Pt
- Driving pressure (ΔP)
- PEEP
- Transpulmonary pressure, P_L

Typical ventilator inputs parameters:

Vt = 400 ml, optionally 250-800 ml in ΔVt = 50 ml

- **Tidal volume (Vt)**: air volume exchanged per breathing cycle. (e.g., ARDSNet protocol: VT=6 mL/kg × Predicted Body Weight, if Pt < 30 cmH2O).
- **Respiratory rate (RR)**: breaths per minute (12-20 normal). Higher RR: +reduces CO2 levels; -may cause lung damage. RR = 10-30bpm, ΔRR=2
- **Inspiration to Expiration Ratio (I:E)**: controls *inspiratory airflow* and pulmonary stress. I:E=1:2 in normal breathing. I:E = 1:2, optionally 1:1-1:4
- **Fraction of Inspired Oxygen (FiO2):** (0.21 for natural room air; higher value implies oxygen-enriched air)
- **PEEP**: +keeps lungs open, +stabilizes alveoli, +improves oxygenation,+increases lymphatic flow; - over-distension, - cardiac performance.

"The basics of respiratory mechanics: ventilator-derived parameters" Silva & Rocco Transl. Med. 2018 Oct; 6(19): 376. doi: 10.21037/atm.2018.06.06, ncbi.nlm.nih.gov/pmc/articles/PMC6212352/

Minimal requirements for emergency ventilators

Monitored parameters	**PIP** ≤ Pt+2 cm H_2O, and PIP ≤ 40 cm H_2O
	Pt ≤ 35 cm H_2O
	PEEP = 5-25 cm H_2O, ΔPEEP = 5 cm H_2O
Minimum controllable parameters	Vt = 400 ml, optionally 250-800 ml in ΔVt = 50 ml
	RR = 10-30bpm, ΔRR=2
	I:E = 1:2, optionally 1:1-1:4

+ FiO_2 control + heat & moisture exchanger + HEPA filtration (to avoid aerosolized virus spread)

Several specifications of requirements for clinically acceptable emergency ventilators have been issued:

USA

FDA U.S. FOOD & DRUG ADMINISTRATION

March 24, 2020

To Manufacturers and Other Stakeholders:

This Emergency Use Authorization (EUA) is being issued in response to concerns relating to insufficient supply and availability of FDA-cleared ventilators for use in healthcare settings to treat patients during the Coronavirus Disease 2019 (COVID-19)[1] pandemic.

Medicines & Healthcare products Regulatory Agency

MHRA

Rapidly Manufactured Ventilator System

(RMVS)

Document RMVS001 - Specification

UK

...

MIT E-Vent | MIT Emergency Ventilator

Emergency ventilator design toolbox

Home | Clinical | Mechanical | Controls & Electrical | Testing

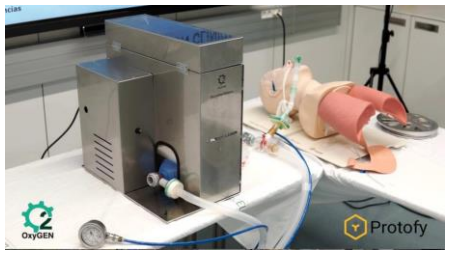
Key Ventilation Specifications

fda.gov/media/136423/download

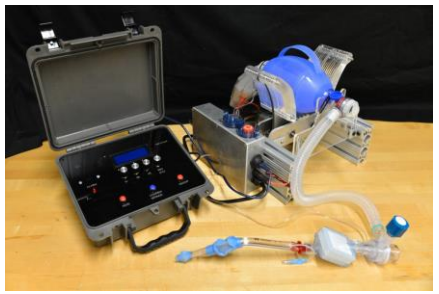
gov.uk/government/publications/coronavirus-covid-19-ventilator-supply-specification/rapidly-manufactured-ventilator-system-specification

e-vent.mit.edu/clinical/key-ventilation-specifications/

Mechanical Ventilation - Spectrum



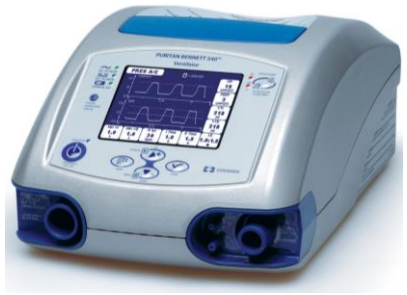
Oxygen (Protofy.xyz)



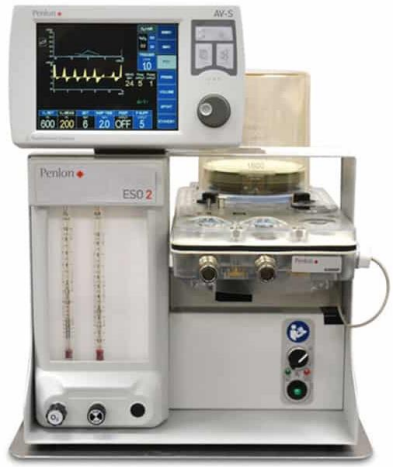
E-Vent (MIT)

VITAL (NASA/JPL-Caltech)

Spiro Wave (Boyce Technologies)



Medtronics
Puritan Bennett
PB 560



Penlon Prima ESO2
(VentilatorChallengeUK)

features
& cost ↑

Open-source | Closed/Licensed | Open-source | Modified models | Existing models

Emergency ventilators

seek emergency use authorization for clinical trials

Commercial solutions

approved for medical use

newsroom.medtronic.com/news-releases/news-release-details/medtronic-shares-ventilation-design-specifications-accelerate
ventilatorchallengeuk.com
oxygen.protofy.xyz
https://medeng.jpl.nasa.gov/covid-19/ventilator/
e-vent.mit.edu
nytimes.com/2020/04/20/technology/new-york-ventilators-coronavirus.html

Open-Source Ventilators

Large number of open-source designs pursued in the last few months.

Only a few: - have been approved for human clinical trials by government authorities.
- published all information required to build them.
- started mass production (some have already stopped for lack of demand).

Evaluation of Open Source Ventilators

File Edit View Insert Format Data Tools Add-ons Help

Share

4	Link to definition of evaluation criteria:	https://docs.google.com/document/d/e/2PACX-1vRl9yZ27KvslftcNvweHgH1A81pO8gHL62TWpY_VY-UELWdK9x-4-3hNw3DbkemClzExPsg8RfnxilP/pub												
5	*Project Name*	*Project Link*	*Openness*	*Buildability (1 unit)*	*Community Support*	*Functional Testing*	*Reliability Testing*	*COVID-19 Suitability*	*Clinician Friendly*	*Average*	*Manufacturability (1000s)*	*Date Last Evaluated*	*Point of Contact*	*Team Needs*	*Drive*
6	Medtronic Puritan Bennett (PB) 5(	http://newsroom.medtronic.com	4	2.5	4	5	5	4	5	4.21	4	2020-04-19			Pump
7	Ambovent	https://1nn0v8ter.rocks/AmboV	4.5	4	4.5	4	3	4	4	4.00	3	2020-04-19	dreliram@gmail.(		AmbuBag
8	MUR (Minimal Universal Respirat	https://www.mur-project.org/	4	4	4	3.5	4	3.5	3.5	3.79	2.5	2020-04-19			Pressure Regulat
9	Open Source Ventilator Project	https://simulation.health.ufl.edu	4	3.5	5	3.5	2.5	4	3.5	3.71	4	2020-04-19	https://simulation		Bellows
10	Rice OEDK Design: ApolloBVM	http://oedk.rice.edu/apollobvm/	5	4	4	2.5	2.5	3	2.5	3.36	2.5	2020-04-19	amy.k@rice.edu		AmbuBag
11	A.R.M.E.E. Ventilator	www.armeevent.com	5	5	4	2	3	2	2.5	3.36	5	2020-04-19	warrenkoch@gm		Pnuematic
12	COVID-19 Rapid Manufacture Ve	https://www.instructables.com/i	5	4	4	3	0	3.5	3.5	3.29	2.5	2020-04-19	https://www.instru		AmbuBag
13	OpenVentilator (PopSolutions)	https://www.popsolutions.co/en	5	3.5	4	3.5	3	2	2	3.29	3	2020-04-08	contact@openve		Bellows
14	Low-Cost Open Source	https://github.com/jcl5m1/ventil	5	4	4	3	1	3	3	3.29	3	2020-04-19	https://github.com		Pump
15	DIY-Beatmungsgerät [Respirator]	https://devpost.com/software/d	5	4	3	2.5	2	3	3	3.21	0	2020-04-19	https://docs.goog		AmbuBag
16	PREVAIL NY	https://jmawireless.com/prevail	4.5	4	3	2.5	0	4	3.5	3.07	3.5	2020-04-19	customerservice(		AmbuBag
17	VentilAid	https://www.ventilaid.org/	5	4	4	3	0	2.5	2.5	3.00	2.5	2020-04-08	media@urbicum.		Bellows
18	CoroVent	https://www.corovent.cz/	3.5	2.5	4	4	0	3.5	3.5	3.00		2020-04-10	simon.rakosnik@		Bellows
19	Flow-i Bridge Project	https://grabcad.com/library/flow	4	2.5	3	2	2	3.5	4	3.00		2020-04-25		clinical validation	Servo Gas Modul
20	Protofy Team OxyGEN	https://oxygen.protofy.xyz/	5	4	4	3	1	2	1	2.86	3	2020-04-19	https://www.oxyg		AmbuBag
21	Jeff Ebin's Prototpye	https://www.ebcore.io/?fbclid=I	5	4	3	1	0	4	3	2.86	1	2020-04-08	jeffrey@ebcore.i(		AmbuBag
22	Open Breath Italy	https://www.openbreath.it/	3.5	2.5	3.5	3	1	3.5	2.5	2.79		2020-04-19	info@openbreath		Pressure regulat

Online Evaluation of Open-Source Ventilators: docs.google.com/spreadsheets/d/1inYw5H4RiL0AC_J9vPWzJxXCdlkMLPBRdPgEVKF8DZw

Open-Source Ventilators

Selection based on reproducibility and maturity (how close to clinical trials):

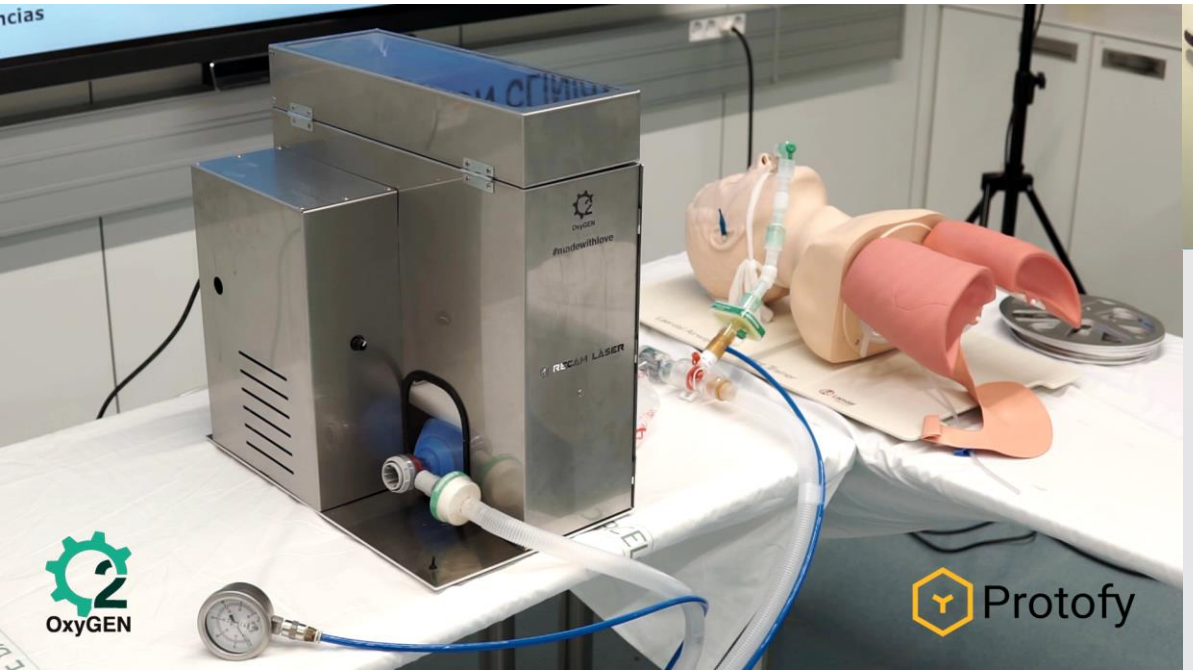
Model	Controlled	Type	
OxyGEN AmboVent E-Vent	Volume	Bag Valve Mask (Ambu Bag)	
Open-source Ventilator Project	Volume	Pressurized gas line	
Acute-19	Pressure	Turbine	

All models can set RR, I:E, FiO2.

Open-Source Ventilators – OxyGEN (Protofy)

- Passed clinical tests (in vitro & in vivo), EMC & safety certification. Durability: 3,000 h.
- Approved for use in clinical trials in two hospitals in Spain.
- Mass-produced by car manufacturer (target production of 300 units/day, currently stopped).
- Fully reproduceable from extensive online open documentation (legal, technical, medical).
- Materials: stainless steel, nylon, silicon, methacrylate.
- BOM: ~100 parts, of which the most specialized are windshield motor and PC power supply.
- Drawbacks: lacks comprehensive monitoring and alarms; cam replacement to change Vt.

oxygen.protofy.xyz github.com/ProtofyTeam/OxyGEN



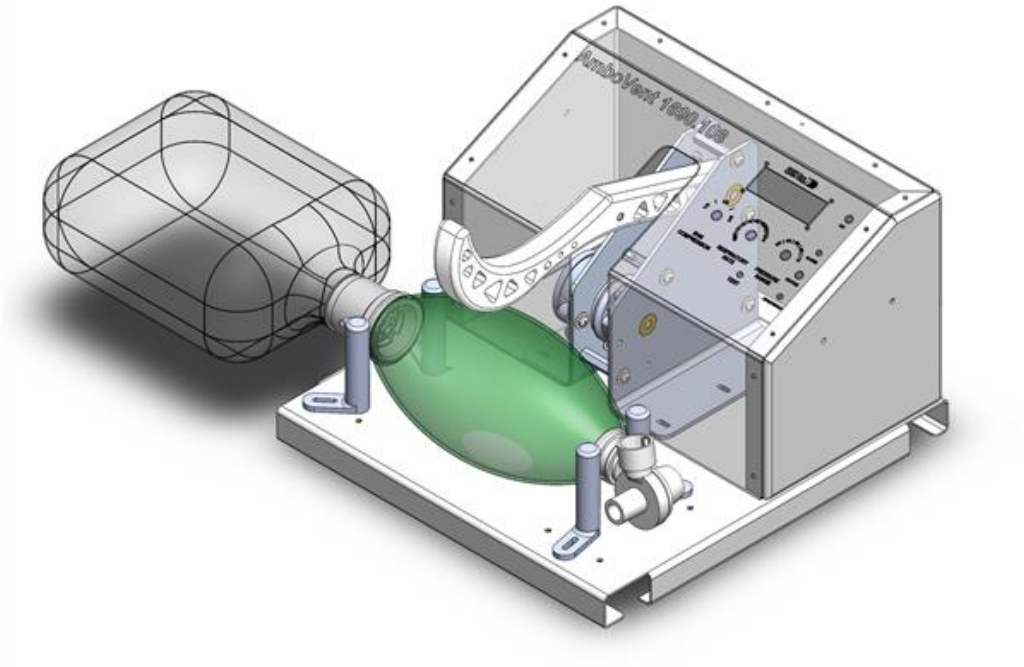
windshield motor

system of cams to vary Vt

Open-Source Ventilators – AmboVent (Israeli Air-Force)

- Not yet approved for clinical use. Follows U.K.'s "Rapidly Manufactured Ventilator System."
- Ongoing testing by Israeli Regulatory Authority for durability, safety, EMC, and functionality.
- Materials: aluminum, Akulon-nylon6.
- Production not yet detailed. Use fused deposition modeling, 3D printing & factory assembly.
- BOM: ~100 parts. Expected cost when mass produced: < $1,000.
- Enhanced control & monitoring: visual and audio alerts (battery, extreme pressure, rate failure), abnormal resistance detection (stops AmbuBag compression until next cycle).
- Moderately documented.

github.com/AmboVent-1690-108/AmboVent



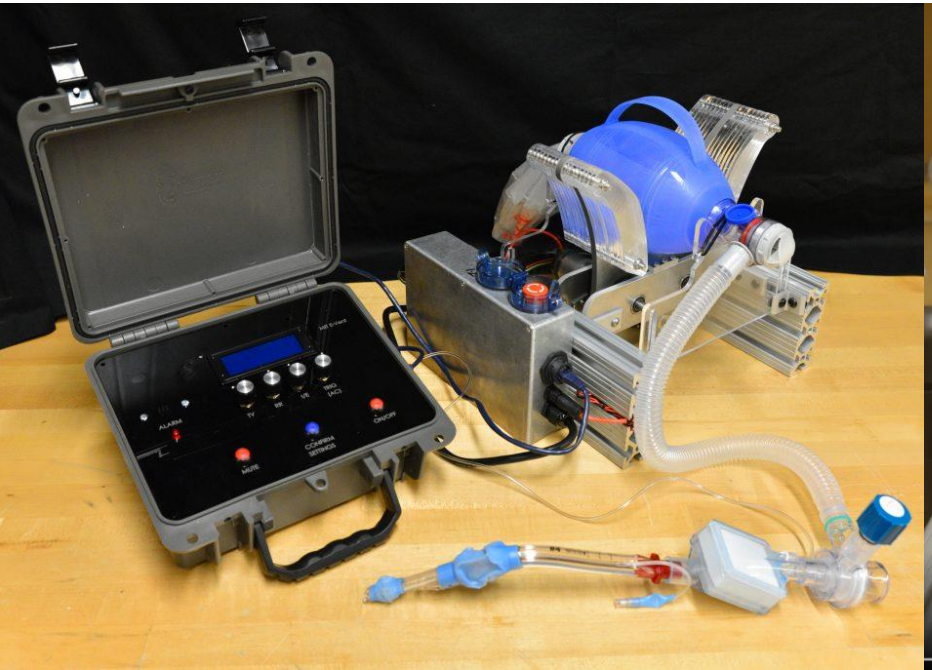
Open-Source Ventilators – E-Vent (MIT)

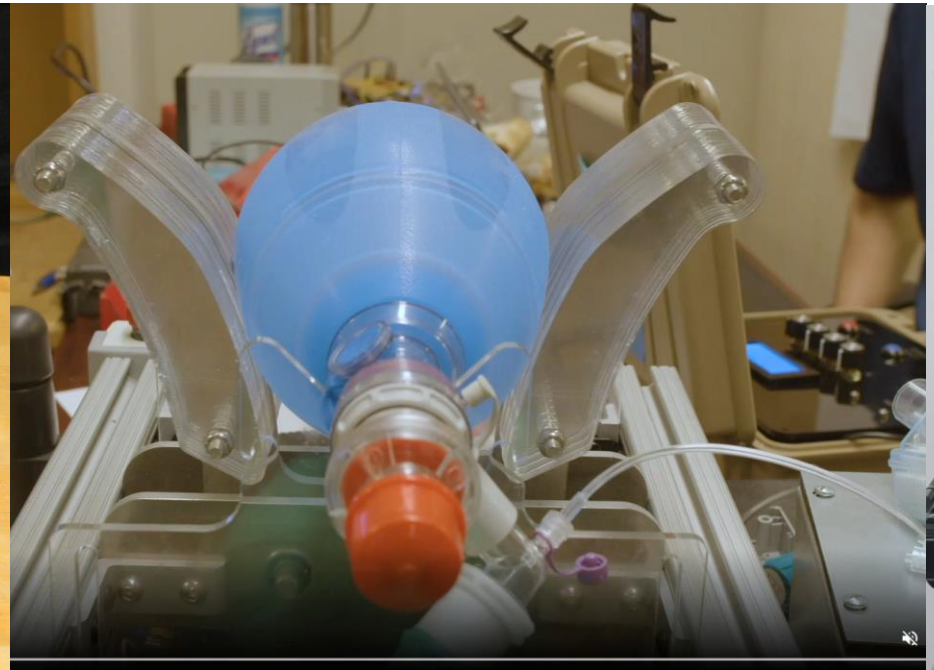
- Completed clinical studies in animals (porcine studies).
- Open-source through registration. More emphasis on research.
- Released prototype software code on April 28, 2020.
- Moderately documented regarding reproducibility.
- Production not yet detailed.
- Alarms: pressures, unmet volume, electrical, mechanical failure.
- It has inspired / spawned other projects, including:
  - Spiro Wave, FDA EUA, produced in NYC by Boyce Tech.

Image: Gabby Jones for The New York Times

e-vent.mit.edu

github.com/mit-drl/e-vent → ventilatorresponse.com



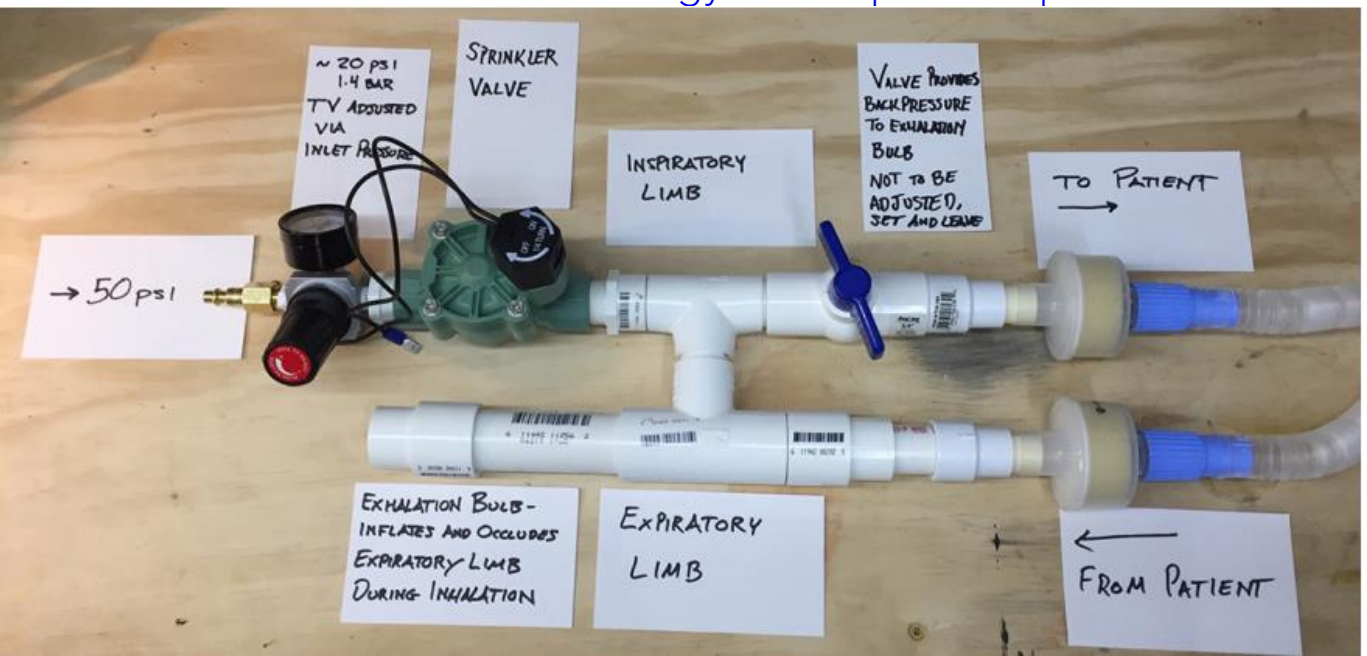


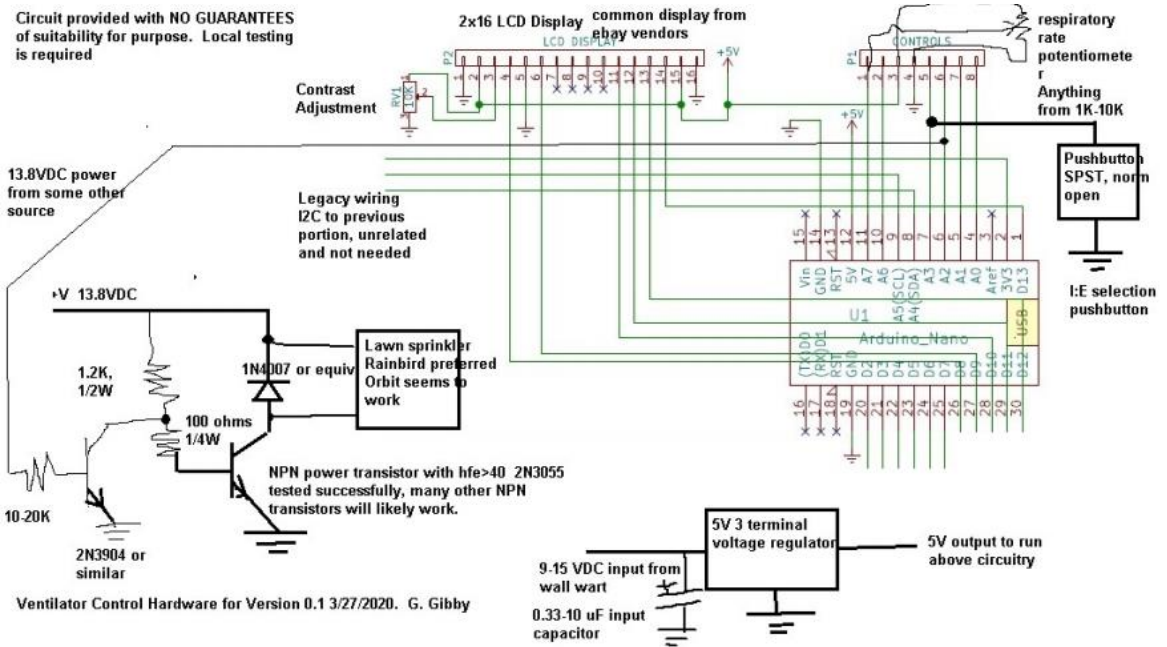
Open-Source Ventilators – OSV Project (U. Florida Health)

- Requires connection to a 50 psi wall pipeline or gas blender.
- Two designs: A) Open-source through GitHub repository. B) Closed, seeking FDA EUA.
- Current emphasis on controller software/electronics. (VentSim)
- Assembly instructions provided (DIY approach)
- Scalable production not yet detailed. Cost of parts stated as $300.
- Detailed design specifications (preliminary). Unknown maturity.
- Clinical studies not yet detailed.

simulation.health.ufl.edu/technology-development/open-source-ventilator-project/

cssaltlab.github.io/Open_Source_Ventilator

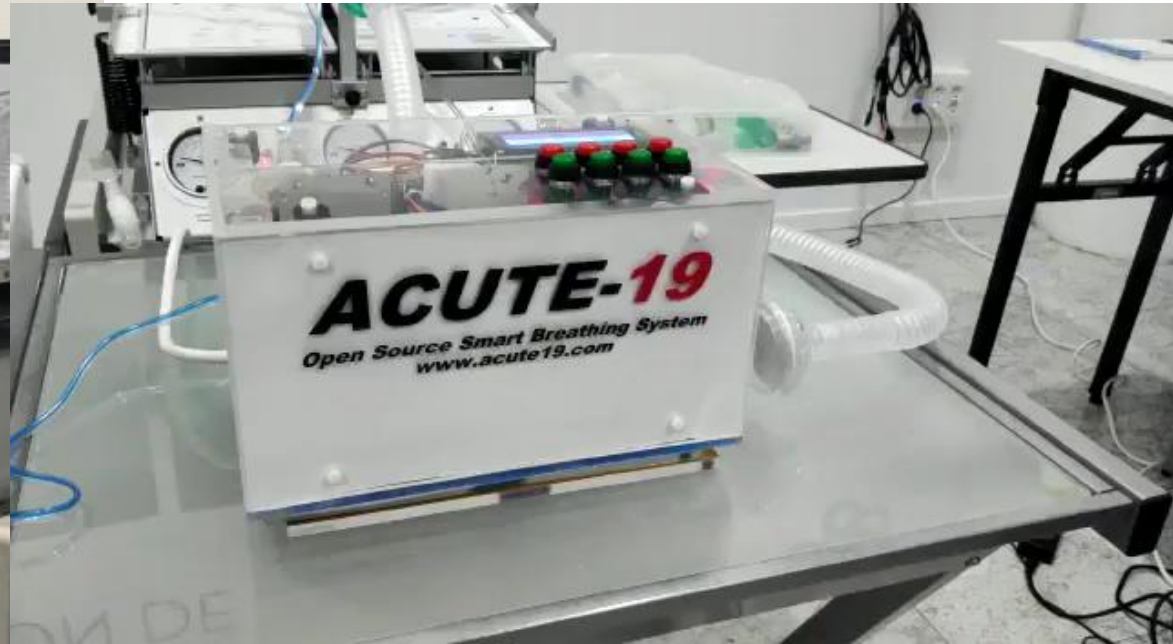




Open-Source Ventilators – Acute19 (U. Florida Health)

- Bi-level turbine ventilator for pressure-controlled ventilation.
- Adjustable settings: Inspiratory PAP (control variable), PEEP, Expiratory PAP, I:E, RR.
- Allows weaning and supports CPAP ventilation.
- Clinical studies completed in animals. Currently seeking emergency-use medical approval.
- Open-source but limited documentation released.
- Ongoing EMC certification (medical electrical equipment safety compliance)

acute19.com/



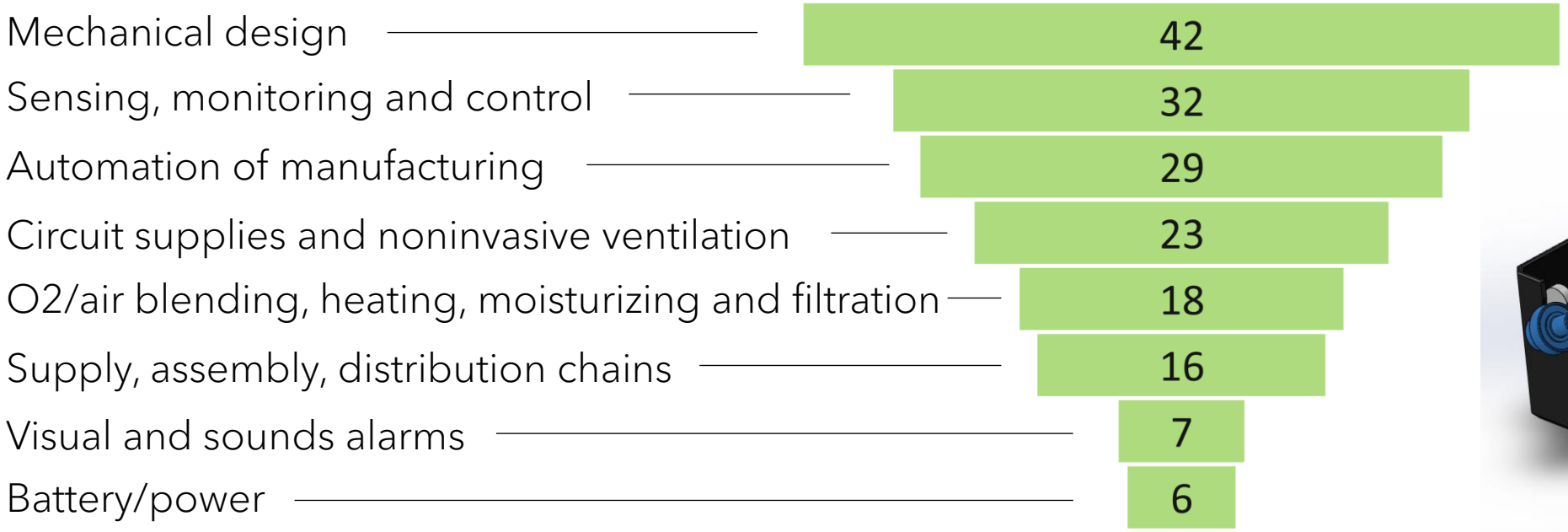
Activities in AME at USC

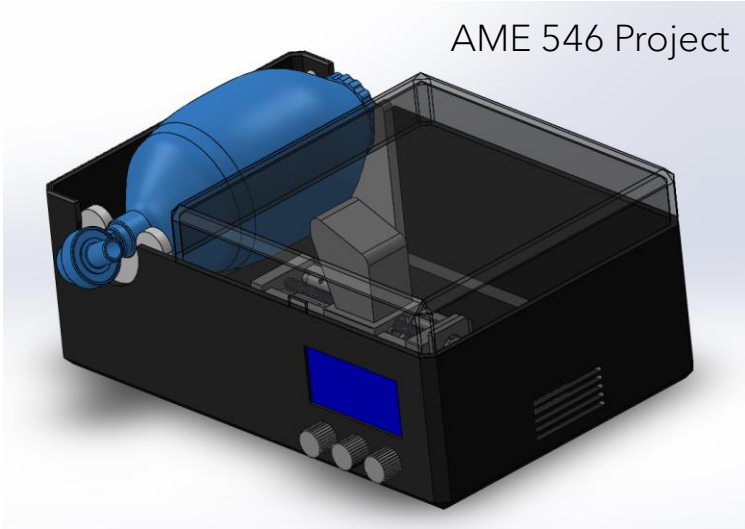
Many students at USC are interested in joining efforts to mitigate COVID-19 related challenges.

Use emergency ventilators as case study to enhance student learning experiences at this time of crisis:

- AME 546 – "Design for Manufacturing and Assembly" (S.K. Gupta): improving designs from the manufacturing cost perspective, end-of-semester projects.

- Summer directed research for M.Sc. Students (Bermejo-Moreno, Gupta, Luhar, Penkova): identified 8 areas for short-term design improvements through collaborative research. Students response:





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- Open-source designs
- Activities in AME at USC
- Dialogue

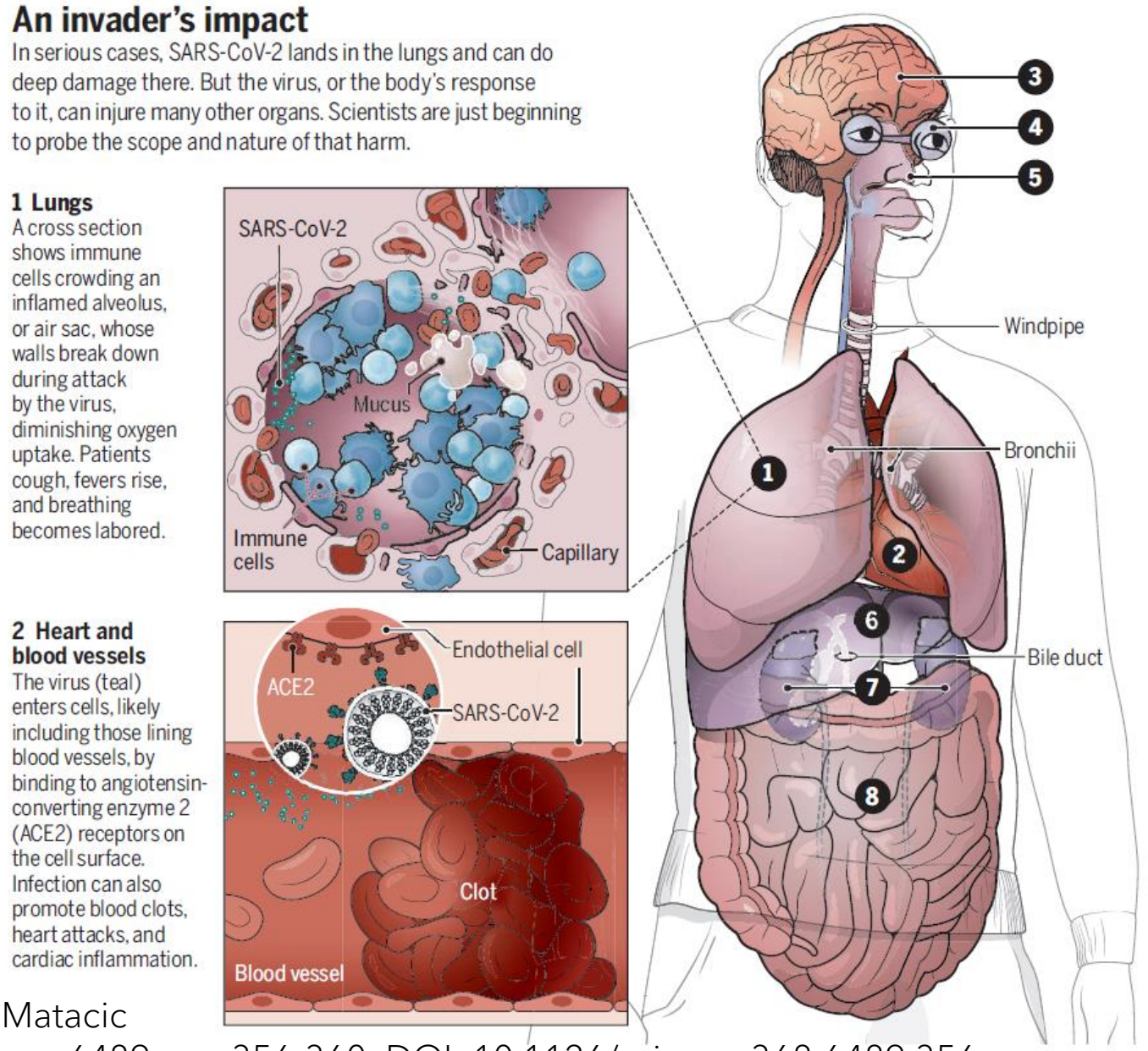
Extra slides

- Additional References
- Answers to possible Questions

Differences

COVID-19 ARDS differs from other lung diseases:

Inflammation in many organs (liver, kidneys), blood clots (heart attack and strokes) → systemic disease. (1)



"A rampage through the body"
Wadman, Couzin-Frankel, Kaiser, Matacic
Science 24 Apr 2020, Vol. 368, Issue 6489, pp. 356-360, DOI: 10.1126/science.368.6489.356
science.sciencemag.org/content/368/6489/356/

nytimes.com/video/health/100000007056651/covid-ards-acute-respiratory-distress-syndrome.html

Differences with other ARDS

"Update on recent clinical experience
10th April 2020

Clinical experience in the UK of COVID-19 has developed rapidly in a way that impacts on the requirements of the ventilators needed. Bear in mind that this specification is tailored to the UK healthcare system and UK clinical practice.

Firstly, more weight is being put on the closed suctioning test covered in Appendix B.
This is because clinical advice is that respiratory secretions are much more copious than in 'normal' critical care pneumonia, necessitating suction of secretions up to hourly and that derecruitment of lung during suctioning is particularly severe.

Second, the duration of intubation is longer than 'normal' and so the relative number of ventilators needed in different categories is changing.

While a mix of transport, simple mandatory ventilation and complex full featured ventilators is still needed, a greater proportion of these need to be capable of supported spontaneous breathing modes to provide resource for the latter portion of intubation episodes."

gov.uk/government/publications/coronavirus-covid-19-ventilator-supply-specification/rapidly-manufactured-ventilator-system-specification

Differences with other ARDS

<<Even stranger, some COVID-19 patients who show very low blood oxygen levels still appear to be breathing fairly comfortably, raising even more questions about how much support they need.

Dr. Ken Lyn-Kew, a pulmonologist at National Jewish Health in Colorado, agrees that there are some differences between classic ARDS and COVID-19, but he emphasizes that there's a lot of variation among COVID-19 patients he's treated. He says most still meet the criteria for an ARDS diagnosis. In his view, coronavirus patients likely have ARDS *plus* other issues, but they still have ARDS. With so much unknown, and with treatment protocols being updated on the fly, he thinks it's too soon for doctors to go off-book and avoid conventional protocols like mechanical ventilation.

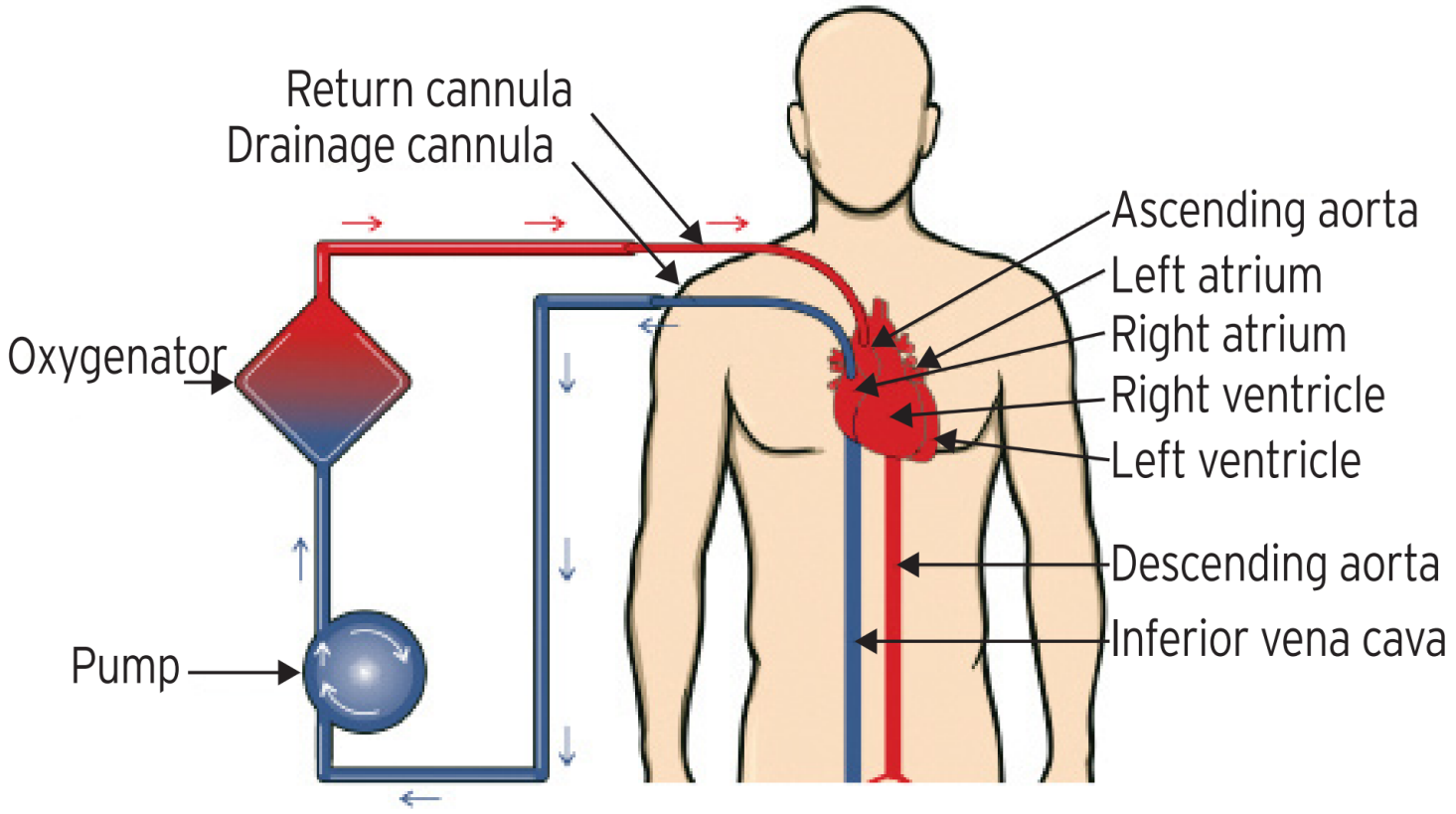
"The world is not a dichotomous, black-and-white place, but a lot of people are having trouble with that," Lyn-Kew says. "We might be able to do better, but in the absence of data on the way to do that, we need to follow our societal guidelines and 25 years of research." >>

"Why Ventilators May Not Be Working as Well for COVID-19 Patients as Doctors Hoped"
BY JAMIE DUCHARME APRIL 16, 2020 7:00 AM EDT
time.com/5820556/ventilators-covid-19

Motivation – Then, are ventilators a good treatment?

Alternative/complementary treatments to invasive mechanical ventilation have shown promising outcomes, such as:

ECMO (Extra Corporeal Membrane Oxygenation)



Hung et al (2012) JICS 13(1) 31-38

https://www.dicardiology.com/article/fda-approves-ecmo-treat-covid-19-patients

https://www.umc.edu/CoronaVirus/Mississippi-Health-Care-Professionals/Clinical-Resources/ECMO-for-COVID-19-Patients.html

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Wadman, Couzin-Frankel, Kaiser, Matacic
Science 24 Apr 2020, Vol. 368, Issue 6489, pp. 356-360
DOI: 10.1126/science.368.6489.356
https://science.sciencemag.org/content/368/6489/356/

“Forecasting the impact of the first wave of the COVID-19 pandemic on hospital demand and deaths for the USA and European Economic Area countries”
IHME COVID-19 health service utilization forecasting team, Christopher JL Murray
doi: https://doi.org/10.1101/2020.04.21.20074732
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https://www.propublica.org/article/ventilators-arent-going-to-cure-covid-19-heres-what-they-can-do

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Based on data from two hospitals in Wenzhou, Zhejiang, China, identified features on initial presentation with COVID-19 that were most predictive of later development of ARDS. A mildly elevated alanine aminotransferase (ALT) (a liver enzyme), the presence of myalgias (body aches), and an elevated hemoglobin (red blood cells), in this order, are the clinical features, on presentation, that are the most predictive. The predictive models that learned from historical data of patients from these two hospitals achieved 70% to 80% accuracy in predicting severe cases.

Vol.63, No.1, 2020, pp.537-551, doi:10.32604/cmc.2020.010691 OPEN ACCESS ARTICLE
Towards an Artificial Intelligence Framework for Data-Driven Prediction of Coronavirus Clinical Severity
Xiangao Jiang1, Megan Coffee2, 3, *, Anasse Bari4, *, Junzhang Wang4, Xinyue Jiang5, Jianping Huang1, Jichan Shi1, Jianyi Dai1, Jing Cai1, Tianxiao Zhang6, Zhengxing Wu1, Guiqing He1, Yitong Huang7

Eur Rev Med Pharmacol Sci. 2020 Mar;24(6):3385-3389. doi: 10.26355/eurrev_202003_20705.
Successful treatment of COVID-19 using extracorporeal membrane oxygenation, a case report.
Zhan WQ1, Li MD, Xu M, Lu YB.

Extracorporeal membrane oxygenation: coming to an ICU near you
M Hung, A Vuylsteke, K Valchanov
JICS Volume 13, Number 1, January 2012
http://learntech.uwe.ac.uk/Data/Sites/3/docs/Ventilation/Hung.pdf

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Clinical Progression

Among patients who developed severe disease, the medium time to dyspnea ranged from 5 to 8 days, the median time to acute respiratory distress syndrome (ARDS) ranged from 8 to 12 days, and the median time to ICU admission ranged from 10 to 12 days.[5,6,10,11] Clinicians should be aware of the potential for some patients to rapidly deteriorate one week after illness onset. Among all hospitalized patients, a range of 26% to 32% of patients were admitted to the ICU.[6,8,11] Among all patients, a range of 3% to 17% developed ARDS compared to a range of 20% to 42% for hospitalized patients and 67% to 85% for patients admitted to the ICU.[1,4-6,8,11] Mortality among patients admitted to the ICU ranges from 39% to 72% depending on the study.[5,8,10,11] The median length of hospitalization among survivors was 10 to 13 days.[1,6,8]

https://www.cdc.gov/coronavirus/2019-ncov/hcp/clinical-guidance-management-patients.html

The World Health Organization designated the disease term COVID-19 (ie, Coronavirus Disease 2019) [1]. The virus that causes COVID-19 is designated severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2).

https://www.uptodate.com/contents/coronavirus-disease-2019-covid-19-critical-care-issues

April 14, 2020

Clinical Outcomes of Patients with COVID-19 Pneumonia in Intensive Care in Lombardy

Hana M. El Sahly, MD reviewing Grasselli G et al. JAMA 2020 Apr 6

Investigators observed a mortality rate of 26%.

In Lombardy, the epicenter of Italy's COVID-19 pandemic, health authorities created a network of intensive care units (ICUs) to coordinate management of the overwhelming number of patients. This report is an analysis of data on the clinical characteristics and outcomes of all critically ill patients admitted with COVID-19 to the ICUs, starting on February 20, 2020.

The analysis includes 1591 patients with laboratory-confirmed COVID-19. The median patient age was 63 years (median age was used to define younger versus older patients); 82% were male. Common comorbidities included hypertension (49% of patients), cardiovascular disease (21%), and hypercholesterolemia (18%). Data on respiratory support were available on 1300 patients, and of those, 1150 required intubation with mechanical ventilation; the frequency of need was comparable between younger and older patients. The median positive end-expiratory pressure (PEEP) used was 14, and a fraction of inspired oxygen of at least 50% was needed in 89% of patients. Prone ventilation was performed in 27%. As of March 25, 58% of the patients remained in the ICU, 16% had been discharged, and 26% died. The mortality was lower in younger versus older patients (15% vs. 36%).

COMMENT

The reported mortality of patients with COVID-19 admitted to the ICU varies in different cohorts. The difference reflects, in part, the variable disease severity required to be admitted to the ICU in different areas. In Northern Italy, patients requiring noninvasive ventilation were managed outside the ICU, which is not always the case in other cohorts. In this and other cohorts, age continues to be the most consistent predictor of mortality.

https://www.jwatch.org/na51334/2020/04/14/clinical-outcomes-patients-with-covid-19-pneumonia

Practical differences between pressure and volume controlled ventilation

•In general, volume control favours the control of ventilation, and pressure control favours the control of oxygenation.
•Volume and pressure control modes have distinct advantages and disadvantages which are mainly related to the flow and pressure patterns of gas delivery.
•Volume control:
- Advantages:
  - Guaranteed tidal volumes produces a more stable minute volume
  - The minute volume remains stable over a range of changing pulmonary characteristics.
  - The initial flow rate is lower than in pressure-controlled modes, i.e. it avoids a high resistance-related early pressure peak
- Disadvantages:
  - The mean airway pressure is lower with volume control ventilation
  - Recruitment may be poorer in lung units with poor compliance.
  - In the presence of a leak, the mean airway pressure may be unstable.
  - Insufficient flow may give rise to patient-ventilator dyssynchrony.

•Pressure control:
- Advantages:
  - Increased mean airway pressure
  - Increased duration of alveolar recruitment
  - Protective against barotrauma
  - Work of breathing and patient comfort may be improved
- Disadvantages:
  - Tidal volume is variable and dependent on respiratory compliance
  - Uncontrolled volume may result in “volutrauma“ (overdistension)
  - A high early inspiratory flow may breach the pressure limit if airway resistance is high.

•Adaptive control modes combine the advantages of pressure and volume control modes without the disadvantages
•A good example of an adaptive control mode of ventilation is PRVC, which guarantees a prescribed volume while maintaining a square pressure waveform and therefore a high mean airway pressure.
•One disadvantage of the adaptive control targeting schema is that the mean airway pressure will be somewhat variable, depending on compliance and patient effort.

https://derangedphysiology.com/main/cicm-primary-exam/required-reading/respiratory-system/Chapter%20542/practical-differences-between

Getting oxygen in

Oxygen uptake via the lungs is dependent on a number of factors. Some can be manipulated to a large extent by mechanical ventilation:

- •PAO2, which in turn can be manipulated by altering:
  - inspired oxygen concentration (FIO2)
  - alveolar pressure
  - ventilation
- •ventilation-perfusion matching - by re-opening collapsed alveoli, thereby reducing intra-pulmonary shunting
  - positive end-expiratory pressure (PEEP) helps re-open alveoli and splint open alveoli

Getting carbon dioxide out

- •Carbon dioxide elimination via the lungs is largely dependent on alveolar ventilation.
- •Alveolar ventilation = Respiratory rate x (tidal volume - dead space)

Main controls

To improve oxygenation:

- •increase FIO2
- •increase mean alveolar pressure
  - increase mean airway pressure
    - increase PEEP
    - increase I:E ratio (see below)
- •re-open alveoli with PEEP

To improve CO2 elimination:

- •increase respiratory rate
- •increase tidal volume

https://www.aic.cuhk.edu.hk/web8/mech%20vent%20intro.htm

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To improve CO2 elimination:

- increase respiratory rate
- increase tidal volume

Other controls

Inspiratory time, inspiratory pause and I:E ratio

- inspiratory time is the time over which the tidal volume is delivered or the pressure is maintained (depending on the mode)
  - in time-cycled modes either inspiratory time or I;E ratio are set (flow is adjusted to ensure that the set tidal volume is delivered in that time). These modes include:
    - pressure control
    - volume control (Siemens and Drager ventilators)
    - pressure regulated volume control
  - in volume-cycled modes the flow is set and inspiration ends when the set tidal volume has been delivered. These modes include:
    - volume control (Puritan-Bennett and Bear ventilators)
  - in pressure support mode the patient determines the duration of inspiration
- inspiratory pause time is only set in modes where a fixed tidal volume is set and delivered (volume control and volume preset SIMV modes)
- expiratory time is whatever time is left over before the next breath
- I:E ratio
  - =(inspiratory time + inspiratory pause time):expiration
  - usually set to 1:2 to mimic usual pattern of breathing
- in general longer inspiratory times:
  - improve oxygenation by:
    - increasing the mean airway pressure (longer period of high pressure increases mean airway pressure over the entire respiratory cycle)
    - allowing re-distribution of gas from more compliant alveoli to less compliant alveoli
  - increase risk of gas trapping, intrinsic PEEP and barotrauma by reducing expiratory time
  - are less well tolerated by the patient, necessitating a deeper level of sedation
  - decrease peak pressure by decreasing inspiratory flow

Trigger sensitivity

- this determines how easy it is for the patient to trigger the ventilator to deliver a breath
- in general increased sensitivity is preferable in order to improve patient-ventilator synchrony (ie to stop the patient "fighting" the ventilator) but excessively high sensitivity may result in false or auto-triggering (ie ventilator detects what it "thinks" is an attempt by the patient to breath although the patient is apnoeic)
- triggering may be flow-triggered or pressure triggered. Flow triggering is generally more sensitive.
- the smaller the flow or the smaller the negative pressure the more sensitive the trigger

Rise time

- determines speed of rise of flow (volume control mode) or pressure (pressure control and pressure regulated volume control modes)
- very short rise times may be more uncomfortable for the patient
- long rise times may result in a lower tidal volume being delivered (pressure control mode) or higher pressure being required (volume control and pressure regulated volume control modes)

https://www.aic.cuhk.edu.hk/web8/mech%20vent%20intro.htm

The I:E ratio is the ratio of the duration of inspiratory and expiratory phases. It represents a compromise between ventilation and oxygenation.

A normal I:E ratio is 1:2.

All abnormal I:E ratios are uncomfortable and require deep sedation

More inspiratory time (I:E 1:1.5 or 1:1) increases mean airway pressure, and favours better oxygenation, at the cost of CO_2 clearance.

- The disadvantage of this is more haemodynamic instability and the possibility of gas trapping
- Oxygenation may paradoxically worsen due to changes in pulmonary blood flow; particularly in volume-depleted patients

More expiratory time (I:E 1:4 and higher) increases the expiratory CO_2 clearance and favours better ventilation

- The disadvantage of this is the possibility of atelectasis

An inspiratory pause is a period during inspiration during which flow ceases.

- This decreases CO_2 clearance in scenarios of high airway resistance
- In ARDS, the decreased alveolar dead space instead improves CO_2 clearance

Inspiratory rise time is the rate at which the ventilator achieves the pressure control variable.

- This should be left short (shortest possible) to decrease work of breathing and patient-ventilator dyssynchrony
- One may decrease the inspiratory rise time to decrease the rate of inspiratory flow if the peak airway pressure is high due to excessive airway resistance

https://derangedphysiology.com/main/cicm-primary-exam/required-reading/respiratory-system/Chapter%20539/inspiratory-pause-ie-ratio-and

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Pressure-controlled versus volume-controlled ventilation: does it matter?

Campbell RS[1], Davis BR.

Author information

Abstract

Volume-controlled ventilation (VCV) and pressure-controlled ventilation (PCV) are not different ventilatory modes, but are different control variables within a mode. Just as the debate over the optimal ventilatory mode continues, so too does the debate over the optimal control variable. VCV offers the safety of a pre-set tidal volume and minute ventilation but requires the clinician to appropriately set the inspiratory flow, flow waveform, and inspiratory time. During VCV, airway pressure increases in response to reduced compliance, increased resistance, or active exhalation and may increase the risk of ventilator-induced lung injury. PCV, by design, limits the maximum airway pressure delivered to the lung, but may result in variable tidal and minute volume. During PCV the clinician should titrate the inspiratory pressure to the measured tidal volume, but the inspiratory flow and flow waveform are determined by the ventilator as it attempts to maintain a square inspiratory pressure profile. Most studies comparing the effects of VCV and PCV were not well controlled or designed and offer little to our understanding of when and how to use each control variable. Any benefit associated with PCV with respect to ventilatory variables and gas exchange probably results from the associated decelerating-flow waveform available during VCV on many ventilators. Further, the beneficial characteristics of both VCV and PCV may be combined in so-called dual-control modes, which are volume-targeted, pressure-limited, and time-cycled. PCV offers no advantage over VCV in patients who are not breathing spontaneously, especially when decelerating flow is available during VCV. PCV may offer lower work of breathing and improved comfort for patients with increased and variable respiratory demand.