Mismanagement of CO2 during CPB

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Discussion Topics:

- Blending CO_2 into Oxygenator Sweep Gas During Bypass Initiation
- CO_2 Administration With Dual Ventilation: Anesthesia Concurrently with Perfusion
    - Left heart bypass
    - Right heart bypass
    - Partial bypass
    - Pre and post bypass
- CO_2 as a Blower During Minimally Invasive Procedures

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Published and Proven

- The effects of Carbon Dioxide (CO2) have been published since the 1940's
  - An inhaled concentration of 5%-7% CO2 increased cerebral blood flow (CBF) by 75%

Kety S, Schmidt, C. The effects of active and passive hyperventilation on cerebral blood flow, cerebral oxygen consumption, cardiac output, and blood pressure of normal young men. Journal of Clinical Investigation 1946;25(1):107–119.

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Published and Proven

- Contemporary authors validate that elevated CO_2 levels increase CBF as well as mean arterial blood pressure (MAP)
- Two mechanisms controlling CBF through blood vessel diameter
  - Brain vessel reactivity to CO_2 and O_2
  - Autoregulation

Battisti-Charbonney A, Fisher J, Duffin J. The cerebrovascular response to carbon dioxide in humans. J Physiol. 2011;589(12)3039–3048.

Dual Mechanisms

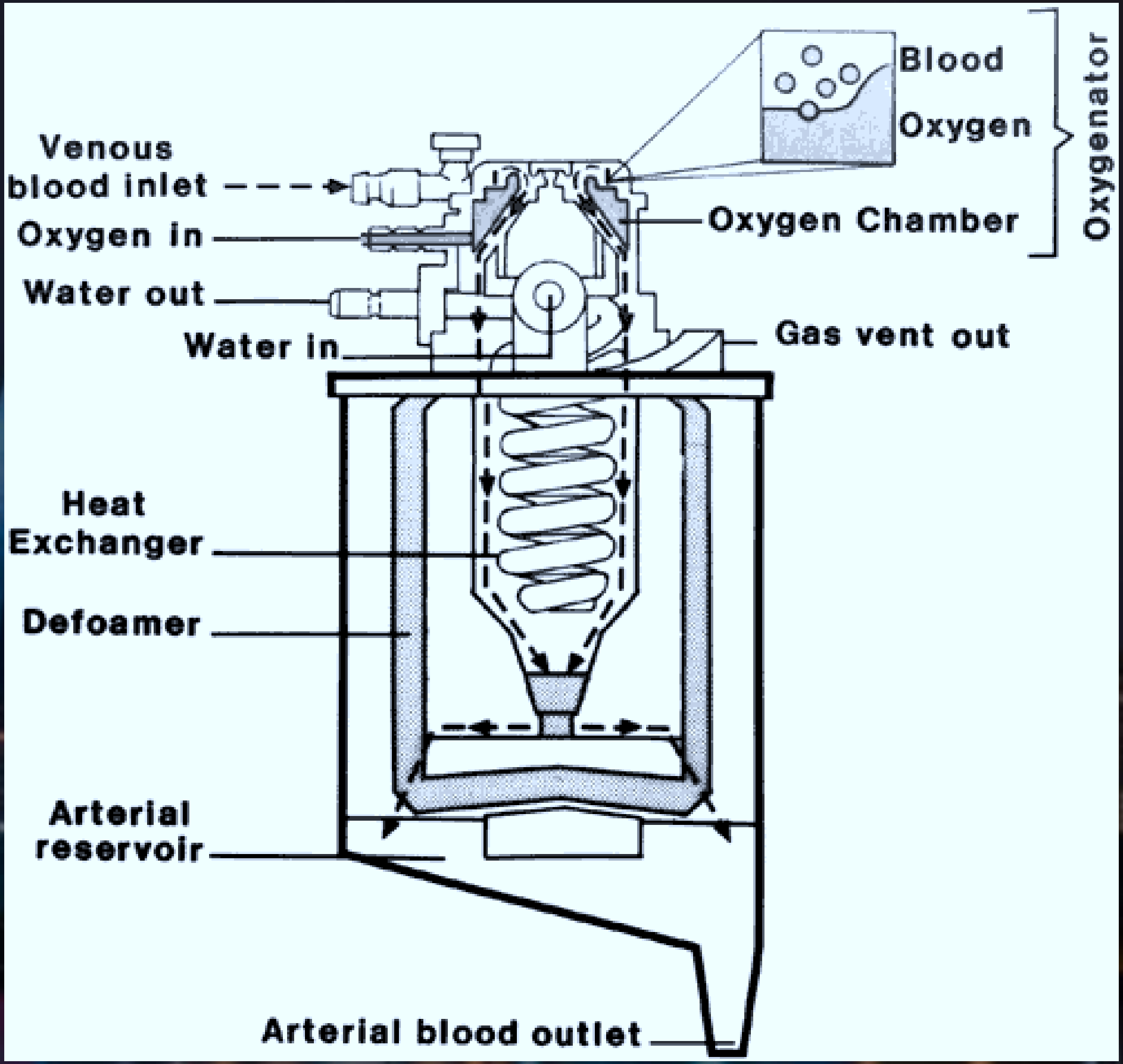
- Brain vessel reactivity to CO2 and O2
  - An important brain adjusting metabolism to meet metabolic requirements
- Autoregulation of CBF
  - Two components
    - Dynamic regulation
      - Occurs over a few seconds
    - Static regulation
      - Copes with gradual changes in perfusion pressure over time

Transient Hypotension with CPB Initiation

- Predominantly thought to be from dilution
  - Direct relationship between hematocrit and blood viscosity
- Alteration in systemic blood flow
  - Perfusionists have been taught to initiate CPB slowly
  - Exsanguination effects are real
  - Use of RAP, VAP or ASD
- Is the silent culprit CO2 depletion upon CPB initiation???

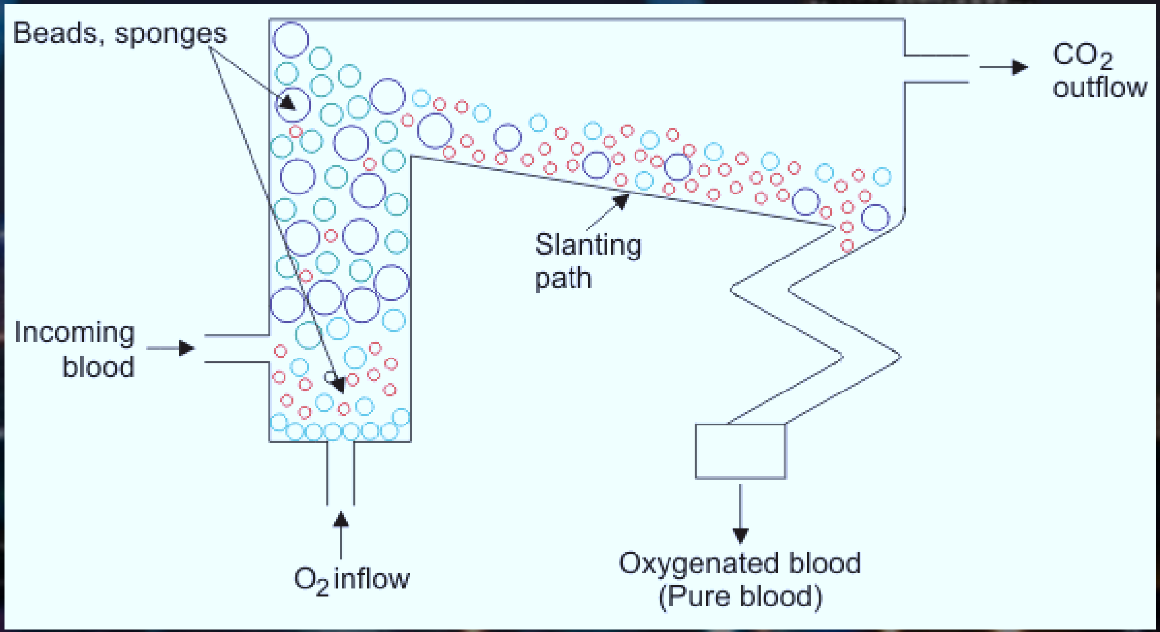
CO2 depletion in CPB prime began with the production of the membrane oxygenator…

Bubble Oxygenator



3 Chambers of Bubble Oxygenator

- Bubble Chamber
- De-foaming or de-bubbling chamber
- Settling Chamber



Bubble Oxygenator Operation

- Typically a bubble oxygenator provided an inlet means for oxygen and an outlet means for oxygen and carbon dioxide
- In known bubble oxygenators there was one gas inlet, and if one wanted to increase the partial pressure of the oxygen (PO_2), the gas flow to the oxygenator was increased

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Bubble Oxygenator Operation

- This was also true if one wanted to decrease the CO_2, i.e. the gas flow to the inlet (flow of O_2 into the oxygenator) was increased
- During cooling the problem was being able to remove or blow off CO_2, and in order to blow off more CO_2, it was necessary to provide a higher gas flow of O_2

Bubble Oxygenator

- Advantage
  - Easy to assemble
  - Relatively small priming volume
  - Deforming the frothy blood
  - Low cost
- Disadvantages
  - Micro emboli
  - Blood cell trauma
  - Destruction of plasma protein
  - Excessive removal of CO2
  - Deforming capacity exhausted

Bubble oxygenator

- Bubble oxygenator
  - Larger bubbles improve removal of CO_2
  - Smaller bubbles are very efficient at oxygenation but poor in CO_2 removal
  - Larger the No. of bubbles, Greater the efficiency of the oxygenator

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Sparger Plate

- Venous blood drained into a chamber where gas was infused through a diffusion plate
- The sparger produced thousands of bubbles (36um)
- Gas exchange occurred at thin blood/gas interface

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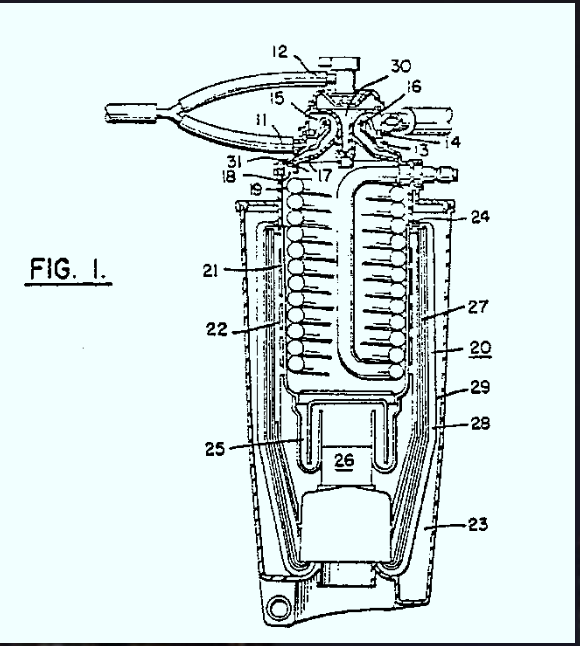
Bubble Oxygenator limitation:

- Transferring CO_2 out of the blood while at the same time lowering the O_2 transfer into the blood

The Bentley 10 included first and second oxygen inlets associated with the oxygenator and a variable gas flow device associated with both the first and second oxygen inlets for allowing the amount of oxygen flowing from each of the inlets to the oxygenator to vary and thereby independently control oxygen and carbon dioxide transfer



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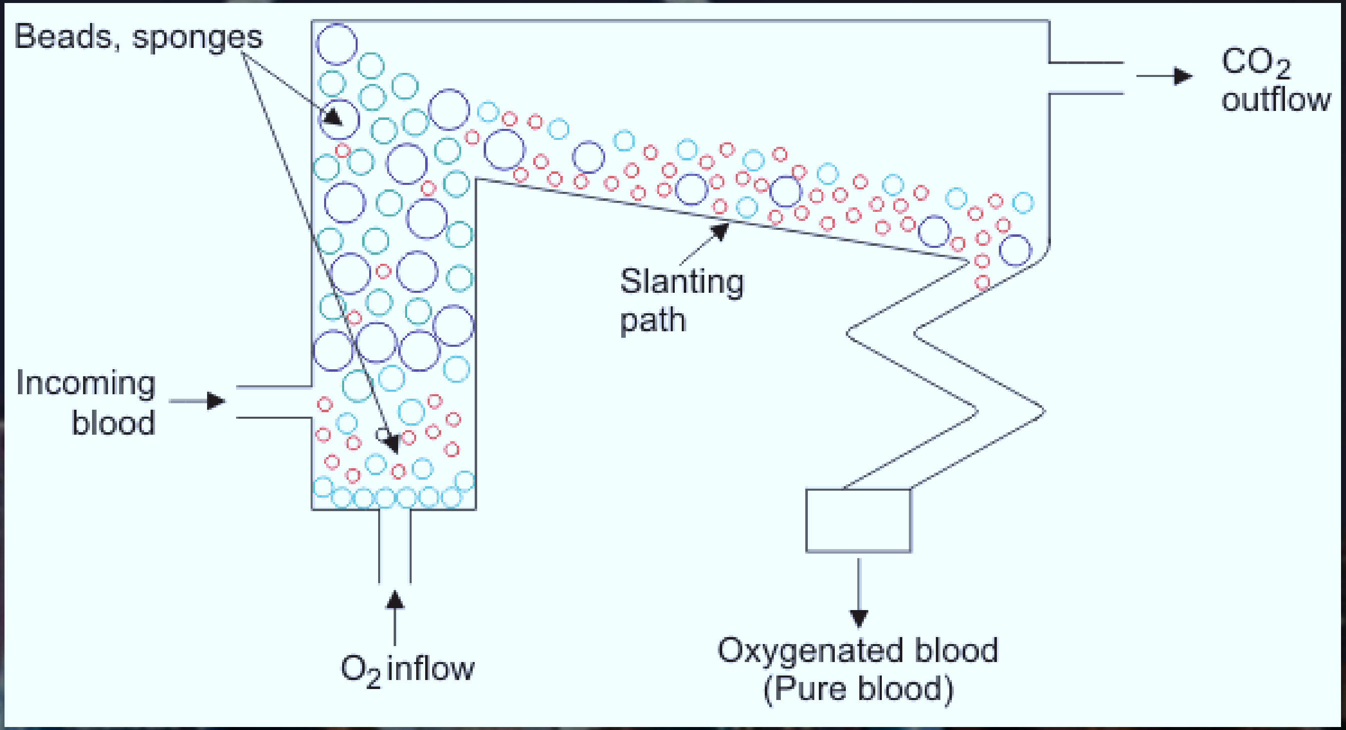
CO2 dissolves 22 times easier than O2 in plasma!!!



Prior to the late 1970’s, bubble oxygenators frequently used a gas mixture which was 5%CO2&95%O2 or 6%CO2&94%O2 throughout the priming process as well as the bypass run.

Blending CO2 assured normal CO2 levels in the crystalloid and/or blood prime during bypass initiation and throughout the bypass run.

Carbogen (CO4)

- A gas mixture called carbogen (CO4), also called Meduna’s Mixture after its inventor Ladislas Meduna, is any mixture of CO2 and O2.
- Carbogen can be used as an inhalant with radio sensitizing properties to produce vasodilatation.
- The purpose of CO4 in a bubbler oxygenator was to preserve normal CO2 levels in the blood path.

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Carbogen (CO4)

- Any mixture of CO_2 and O_2 (CO4)
- Molecular weight of 76.007 g/mol
- Used during CPB today for:
  - Acquiring true pH Stat
  - Apnea testing on ECMO
  - CPB initiation
  - Minimally Invasive Procedures as a Blower
  - Etc.,

CO_2 depletion began with the production of the membrane oxygenator…

The blending of CO2 and O2 into the gaseous phase of an extracorporeal oxygenator, even with membrane oxygenators, has a long, proven history of being safe practice.

Bartlett R, Gazzaniga A, Jefferies M, Huxtable R, Haiduc N, Fong S. Extracorporeal Membrane Oxygenation (ECMO) Cardiopulmonary Support in Infancy. JECT. 1979(11);1:26-41.

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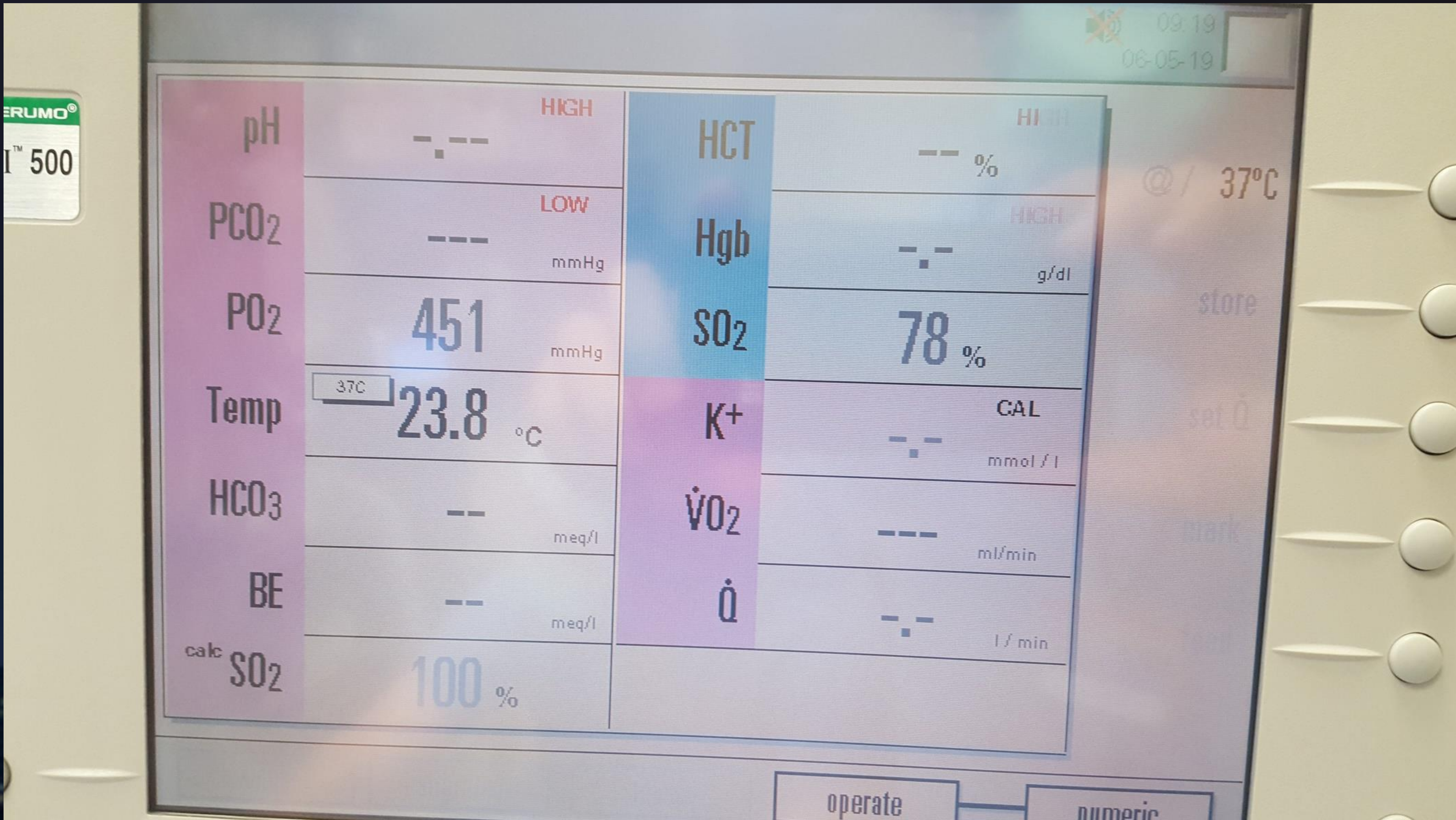
Science of CO2 blending

- Volume % of CO2 to maintain a pCO2 is derived by dividing that pCO2 into atmospheric pressure

For example: a desired pCO2 of 42mmHg

42mmHg / 760mmHg = 5.5%

- Acquiring true pH Stat
- Apnea testing on ECMO
- CPB initiation



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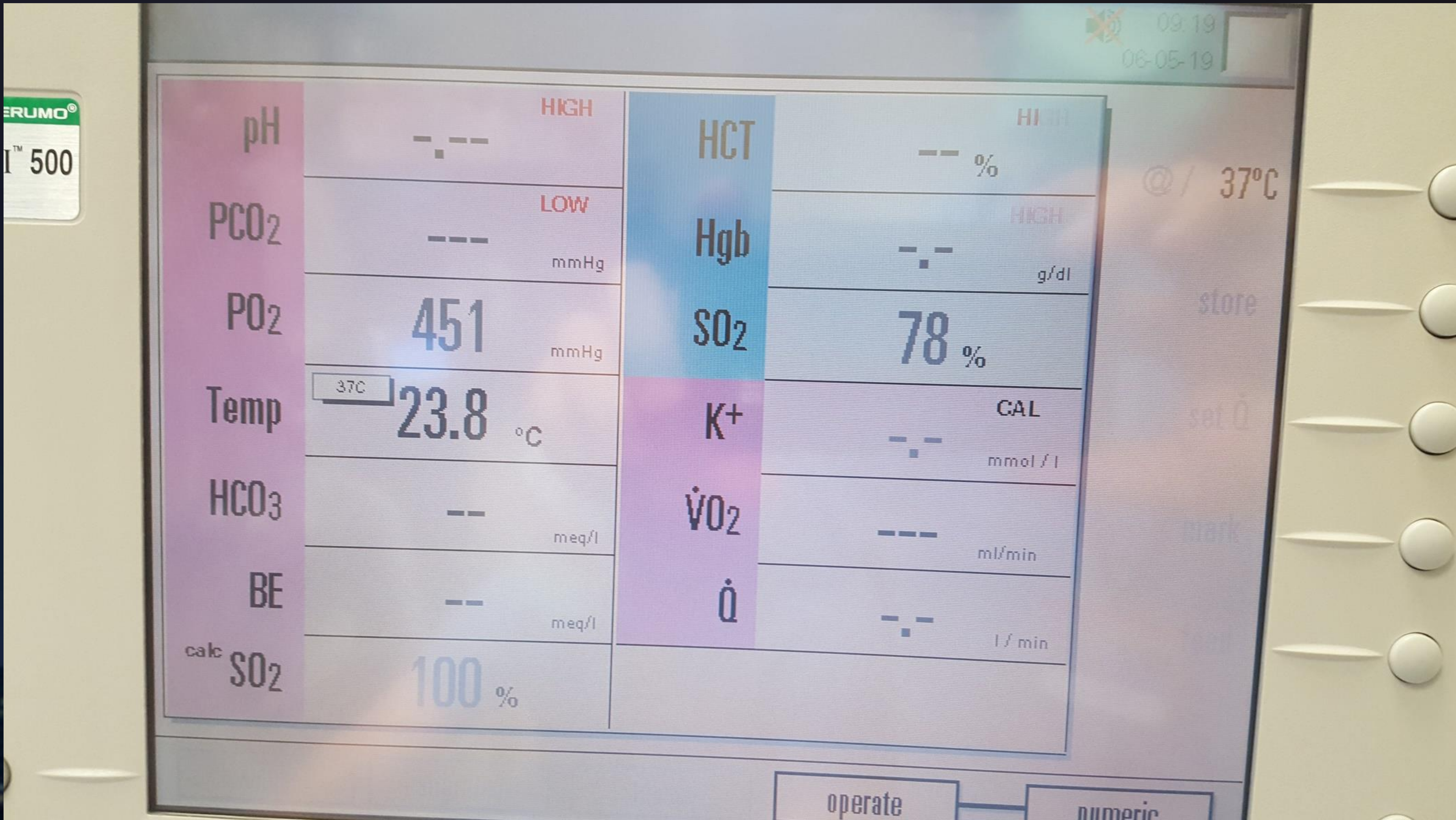

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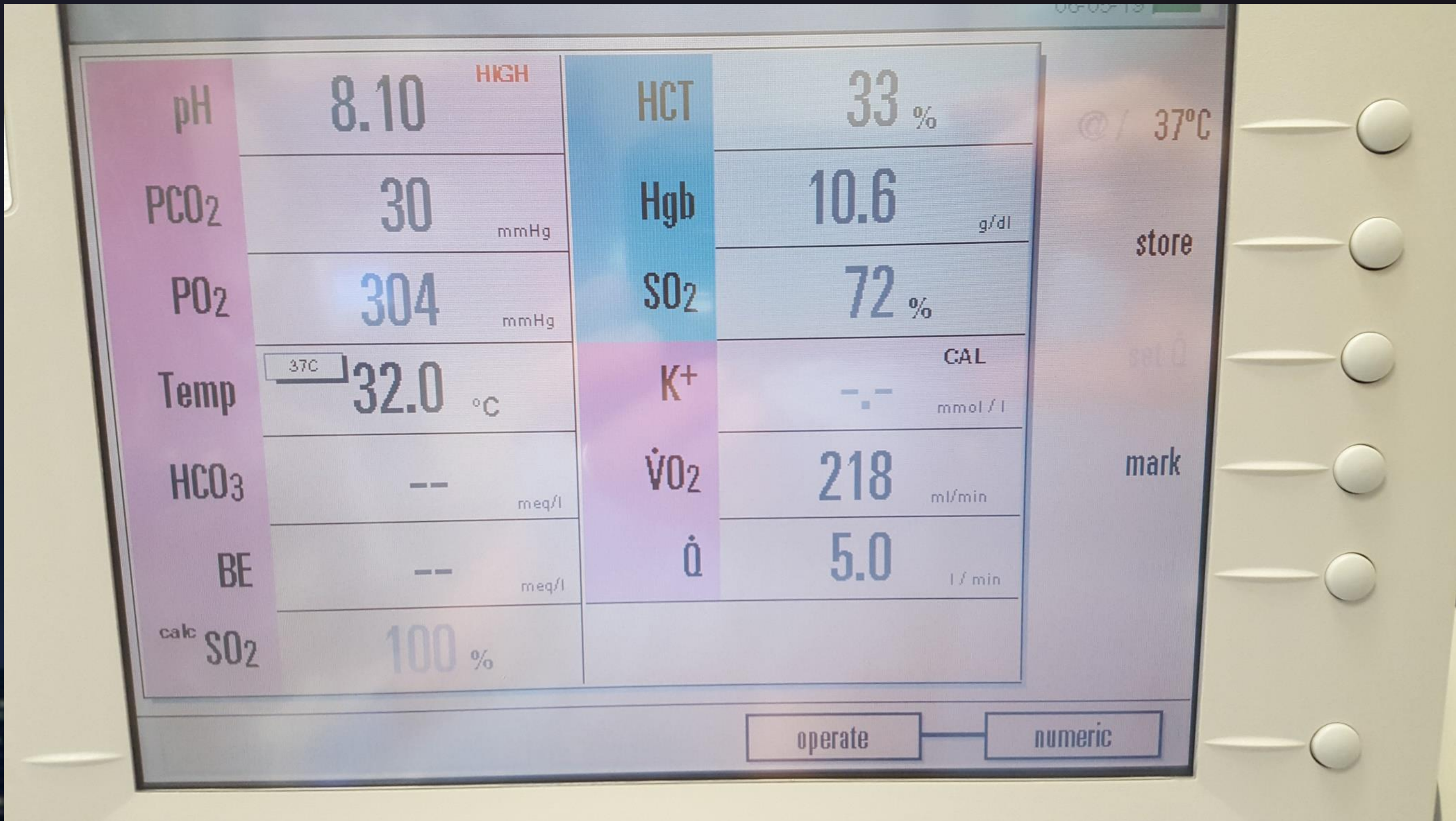

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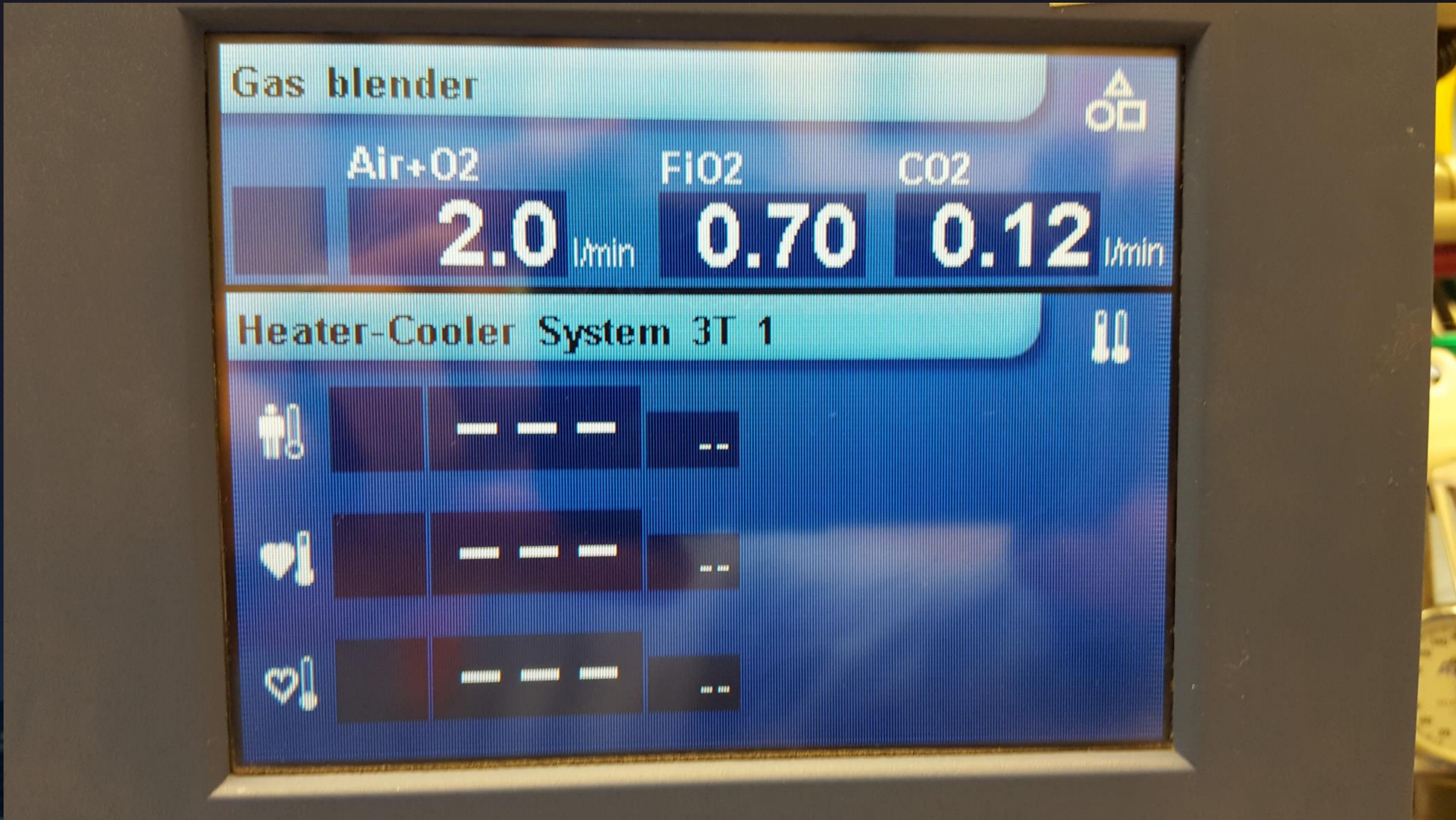
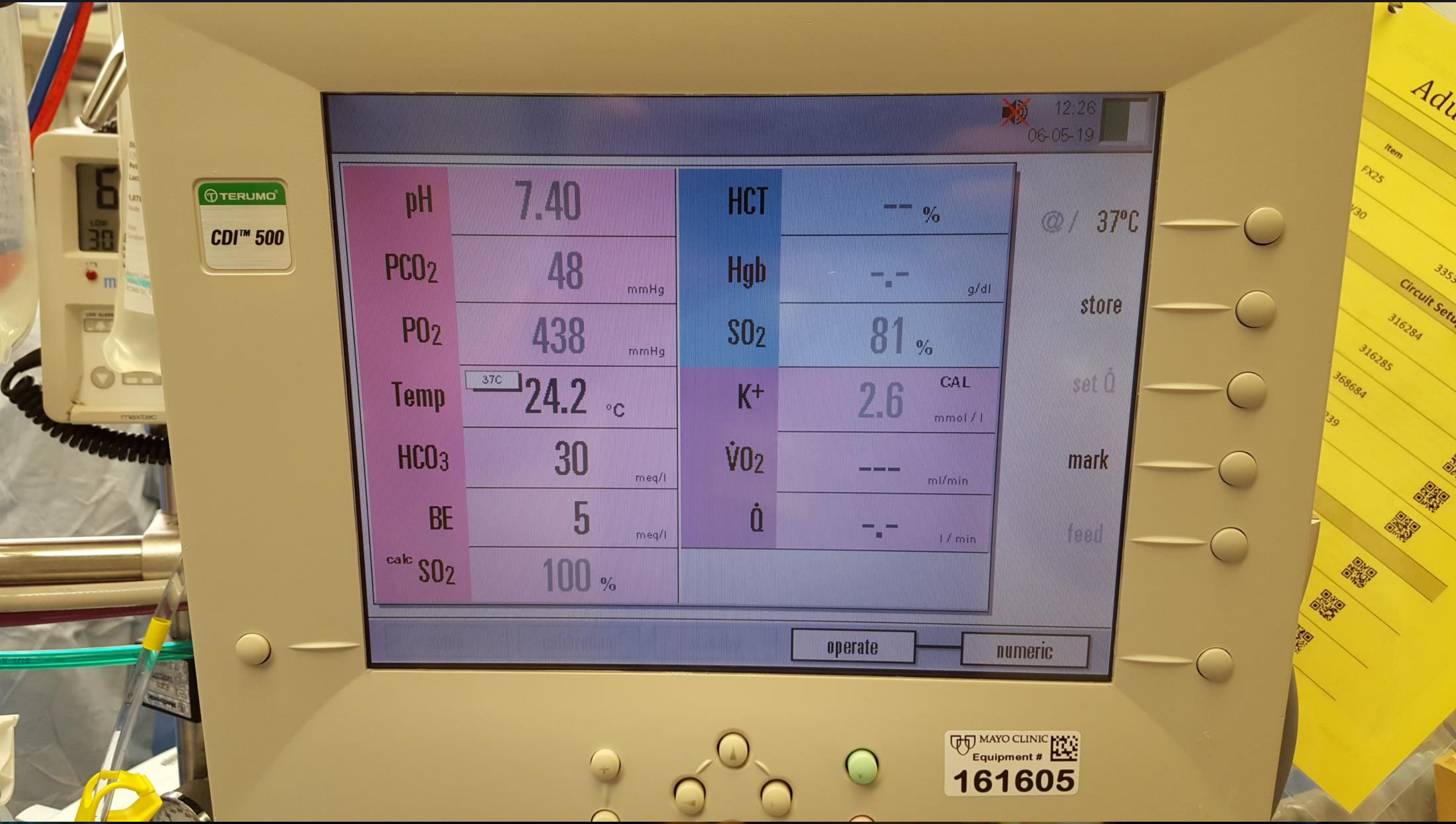
pH
7.75
PCO2
42
mmHg
PO2
306
mmHg
Temp
37C
32.9
°C
HCO3
--
meq/l
BE
--
meq/l
calc SO2
100
%
HCT
33
%
Hgb
10.6
g/dl
SO2
70
%
K+
CAL
-.-
mmol / l
V̇O2
207
ml/min
Q̇
5.0
l / min
37°C
store
mark
operate
numeric


Gas blender
Air+O2
2.0 l/min
FiO2
0.70
CO2
0.12 l/min
Heater-Cooler System 3T 1



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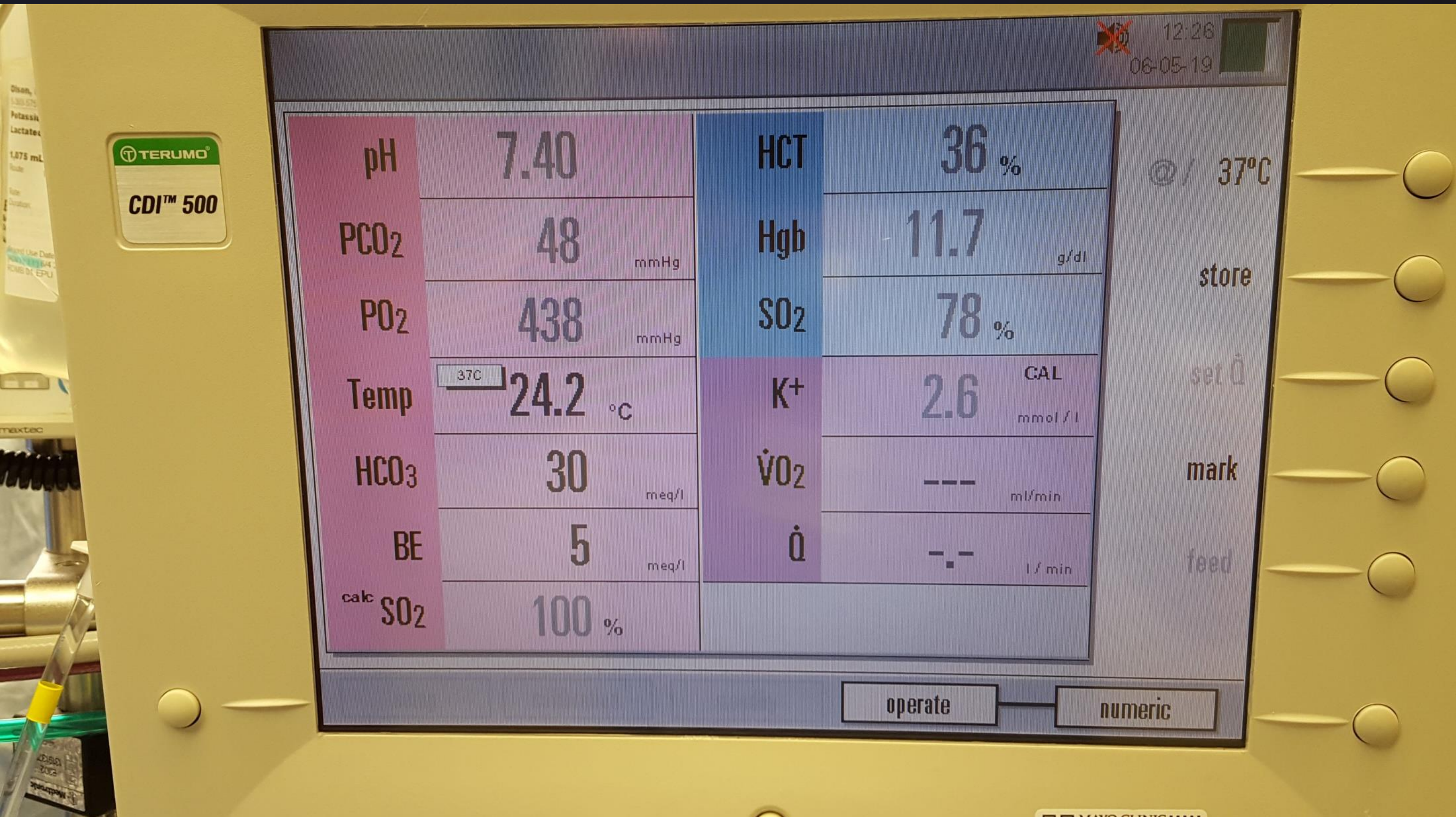

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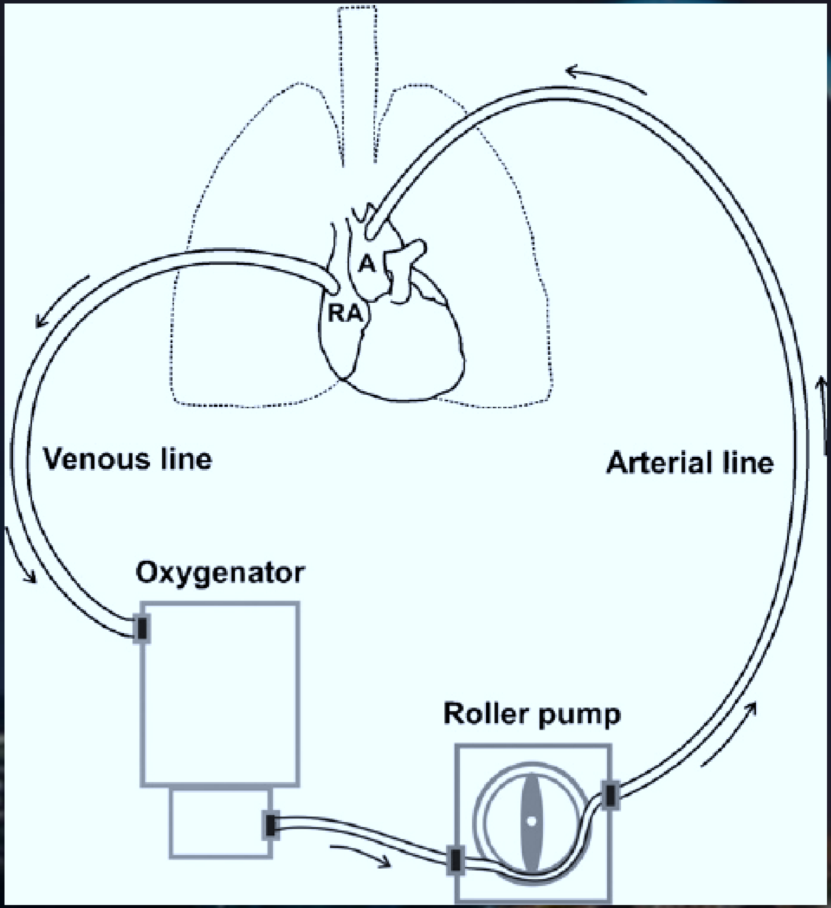
So Now What?

Concurrent Dual Ventilation



- Left heart bypass
- Right heart bypass
- Partial bypass
- Pre and post bypass

Partial Bypass Story…

- 53yo Male with right sided aorta for distal aortic arch repair
- Right thoracotomy approach
- Stay warm and keep the heart ejecting similar to left heart bypass
- Monitor NIRS

NIRS

- Initiated bypass
- Partial occluding clamp placed to the innominate artery
- Things looked great!
- Four minutes later the NIRS < 40
- Blood flow and blood pressure increased with no altered effect

$CO2_{ET}$ or ETCO2

- During periods of bypass where anesthesia and perfusion are both ventilating, it also remains important to maintain an end-tidal CO2 (ET_{CO2}) above 30mmHg to avoid deleterious effects.
- Must remain above 20 in infants

Bagwell T, Abramo T, Albert G et al. Cerebral oximetry with blood volume index and capnography inintubated and hyperventilated patients. Am. J. of Emerg. Med 2016;34:1102–1107.

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Pediatric Considerations

- Proportionally, pediatric circuits harbor much greater reserve capacity
- It takes much longer for an infant to compensate CO2 depletion than an adult
- Pediatric patients experience much greater oncotic dilution

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Anesthesia Weaning Conundrums

- Lower pCO2 lowers K+ level
- Lower pCO2 increases pulmonary hypotension
  - Eases the afterload of the right heart

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Minimally Invasive Cases where CO_2 overwhelms the Oxygenator…

- Drop in sucker is utilized
- 100% CO_2 used for a blower in the chest
  - CO_2 reduces lung fire risks
  - Anesthesia trained to go to 30% FiO_2 when lung fire is a risk
- Blender is at max sweep and pCO_2 > 60mmHg
- Oxygenator is at max rated sweep for IFU
  - Oftentimes times requires second gas source

Can 100% CO_2 be safely reduced to 70% by mixing with 30% O_2?

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Tested Results of CO_2 and O_2 Mixtures:

- Sealed in a sandblasting chamber
- Humidity increased to > 85%
- Four different concentrations tested
  - 75% CO_2 & 25% O_2
  - 50% CO_2 & 50% O_2
  - 25% CO_2 & 75% O_2
  - 100% O_2

Tested Results of CO_2 and O_2 Mixtures:

- Utilized electrocautery on a sponge @ 100 with hamburger meat
- Changed gas concentrations
  - Increased O_2 concentrations decreased time of fire initiation
  - Higher O_2 concentrations demonstrated faster growth of flame
  - 75% CO_2 and 25% O_2 was very difficult to ignite on dry sponge but did indeed ignite!
  - When sponges were moistened with saline even 100% O_2 would not ignite

Recommendation: Decrease CO_2% with O_2 and wet sponges!

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Takeaway Considerations:

- Blending CO_2 into Oxygenator Sweep Gas During Bypass Initiation is Safe
- CO_2 Administration During Dual Ventilation often proves necessary
  - Left heart bypass
  - Right heart bypass
  - Partial bypass
  - Pre and post bypass
- pCO_2 is lower when mixed with O_2 and wet sponges in minimally invasive procedures where the blower overwhelms the oxygenator

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Thank you!

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