I have received
- lecture support
- travel reimbursements
- equipment loans
- consulting fees
- meeting organizational support (NAVAt)

from basically all companies involved with inhaled agent delivery:

AbbVie, Acertys, Air Liquide, Allied healthcare, Armstrong Medical,
Baxter, Draeger, GE, Hospithera, Heinen und Lowenstein, Intersurgical,
Maquet, MDMS, MEDIC, Micropore, Molecular, NWS, Philips, Quantum Medical
Note: this lecture may contain more examples of one anesthesia machine than another. This by no means reflects any personal preference - the choices have been made purely for didactical reasons, and also reflect my current research topics.

How Technology Will Secure the Future of Inhalation Anesthesia

A means to visualize drug interactions and guide depth

Target controlled low flow anesthesia
Aisys  Zeus  FLOW-i

SmartPilot, Navigator
EEG derived? Both?

Target controlled low flow anesthesia

A means to visualize drug interactions and guide depth (seeing context sensitive halftimes at work)

The players (others to follow)...

Closest to conventional USA machine: Aisys upgraded for target control

Adjust vaporizer %, FGF

Measure patient FGF

Set $F_{\text{O}_2}$, $F_{\text{F} \text{GF}}$

Apply algorithm

Set $F_{\text{O}_2}$, $F_{\text{F} \text{GF}}$
The heart of the system: carrier gas delivery systems act as ventilator.
Injector

Volume reflector: physically open, functionally closed

How Technology Will Secure the Future of Inhalation Anesthesia

1. Why low flow (LFA)
2. Why target control
3. Why prediction displays
4. The smartest pilot and the really smartest pilot
How Technology Will Secure the Future of Inhalation Anesthesia

1. Why low flow (LFA)
2. Why target control
3. Why prediction displays
4. The smartest pilot and the really smartest pilot

Low flow anesthesia makes sense
- less waste
- less pollution
- less costs
- heat & humidity

Sevo usage 5 - 60 min ($F_A = 1.8\%$)

Alyo: De Cord, ESA 2014 Annual meeting, abstract 3API-7
FLOW-i: Caretto R et al. Maquet ESA grant 2014, in writing
How low can you go?
Minimum we need?

<table>
<thead>
<tr>
<th>Gas</th>
<th>uptake</th>
<th>Fresh gas flow (L/min)</th>
<th>Sevoflurane usage (mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂</td>
<td>180 (37) mL/min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N₂O</td>
<td>200</td>
<td>100 mL/min (10' 1h)</td>
<td></td>
</tr>
<tr>
<td>Desflurane</td>
<td>12.5 mL liquid</td>
<td>10.3 mL by patient</td>
<td>2.2 mL circuit + lungs</td>
</tr>
<tr>
<td>Sevoflurane</td>
<td>7.0 mL liquid</td>
<td>6.0 mL by patient</td>
<td>1.0 mL circuit + lungs</td>
</tr>
</tbody>
</table>

Lowest you can go

O₂ uptake: 180 (37) mL/min
N₂O uptake: 200 mL/min (10' 1h)
Desflurane (6% F₆₆, 1h): 12.5 mL liquid
Sevoflurane (2% F₆₆, 1h): 7.0 mL liquid

De Cooman S et al. BMC Res Notes 2014 July 23:7:469
Severinghaus J. J Clin Invest 1954;33:1183-9
Hendrickx J et al. Br J Anaesth 1997;84:413-8
De Cang M, ESA 2014, 3AP1-7

Low flow anesthesia makes sense

- less waste
- less pollution
- less costs
- heat & humidity
All agents impede infrared radiation to outer space (GWP)

Global effect = 1 coal fired power plant
               = 1 million passenger cars

<table>
<thead>
<tr>
<th>Compound</th>
<th>Maximum (mL/min)</th>
<th>Maximum radiation efficiency (%)</th>
<th>24 hours later</th>
<th>Removed (%)</th>
<th>Global warming potential (GWP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>20</td>
<td>0.95</td>
<td>30</td>
<td>60</td>
<td>0.04</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>5</td>
<td>1.0</td>
<td>30</td>
<td>90</td>
<td>0.02</td>
</tr>
<tr>
<td>Chlorine</td>
<td>0.1</td>
<td>0.45</td>
<td>20</td>
<td>90</td>
<td>0.01</td>
</tr>
<tr>
<td>Oxygen</td>
<td>1</td>
<td>0.89</td>
<td>30</td>
<td>90</td>
<td>0.006</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1</td>
<td>0.69</td>
<td>30</td>
<td>90</td>
<td>0.005</td>
</tr>
<tr>
<td>Ethylene</td>
<td>1.5</td>
<td>0.86</td>
<td>30</td>
<td>90</td>
<td>0.004</td>
</tr>
</tbody>
</table>

Low flow anesthesia makes sense
- less waste
- less pollution
- combined cost agent + CO₂ absorber
- less cost
- heat & humidity does continue to decrease with ↓FGF
Low flow anesthesia makes sense

- less waste
- less pollution
- less costs
- heat & humidity. CO₂ − CO₂ absorbent reaction
  = exothermic, H₂O producing
  = no need for HME, only filter

Then why

- the hesitancy to use low flow fresh gas flows (FGF) ?
- the intuitive use of 1.5 - 2 L/min FGF ?
- the ill defined fear of FGF << 1L/min ?

Teaching alone does not work...

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>After being taught to use lower FGF</th>
<th>And 6 months later...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td></td>
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<td></td>
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<tr>
<td>Compliance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Satisfaction</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Hard to believe this continues to be an issue

Sevoflurane used routinely with closed-circuit anesthesia

If medicolegal issue: use Amsorb Plus, SpiraLith, LithoLyme

The reasons for the hesitancy to use FGF << 1L/min explain why we need target control delivery of agents and O₂

1. Why low flow (LFA)
2. Why target control
   - LFA more convenient, less distraction
   - conventional LFA teaching = inconsistent use
   - safety agent O₂
3. Why prediction displays (drug interactions, times)
4. The smartest pilot and the really smartest pilot

How Technology Will Secure the Future of Inhalation Anesthesia
Clinical Example

How to adjust vaporizer setting ($F_D$) to maintain sevoflurane $F_A$ at 1.3% with FGF from 0.3 to 8 L/min $O_2/N_2O$ with conventional machine (ADU®)?


Vaporizer setting (= $F_D$)
- $n=8$ per FGF group
- only average $F_D$ per FGF group presented
- start at maximum $F_D = 8\%$ sevoflurane

$F_D$ (%)
- $1\text{ L/min}$
- $8\text{ L/min}$

Time (min)
- 0 10 20 30 40 50 60

% sevoflurane
- 0 2 4 6 8

Anesthesiology 1998; 89: A518
Lower FGF = higher $F_D$
"High" FGF: FGF > MV

Bellows fill with fresh gas only

Ventilation 5L/min

Sevo

\[ F_o = 2\% \]

O\(_2\) 2 L/min

N\(_2\)O 4 L/min

F\(_1\)
"Low" FGF: FGF < MV
Bellows fills with fresh gas
PLUS exhaled gas

Ventilation 5L/min
Sevo F\textsubscript{IO} = 2%
O\textsubscript{2} 0.3 L/min
N\textsubscript{2}O 0.4 L/min

Rebreathing of exhaled gas with vapor
congestion < F\textsubscript{D} causes F\textsubscript{I} ↓ and thus F\textsubscript{A} ↓

To maintain same F\textsubscript{I} and thus F\textsubscript{A}, F\textsubscript{D} has to be increased.
A difference has developed between $F_1$ and $F_D$.

This "dilutional" effect becomes more prominent with $FGF < 1.5 - 2$ L/min.
With lower $FGF$, we have the impression to "lose control".
This is why we intuitively use $FGF = 1.5 - 2$ L/min: $F_D$ still matches $F_1$.

$FGF << 1$ L/min not frequently used because
- more vaporizer adjustments needed
FGF << 1 L/min not frequently used because
- more vaporizer adjustments needed
- it becomes harder to predict $F_D$ in the individual patient
FGF << 1 L/min not frequently used because
- more vaporizer adjustments needed
- it becomes harder to predict $F_D$ in the individual patient
- choice of carrier gas effect $F_D$ more pronounced

Clinical implication:
more attention needed
potentially more distracting
especially right after induction
→ over- and under-dosing
Even with high flows we under-dose many of our patients...

• Prospective study
• Target: \( \geq 0.7 \) MAC

Overall, during the maintenance of anesthesia,
the ETAC was greater than 0.7 age-adjusted MAC a median of 84.8% of the time (interquartile range, 67.2 to 95.3).

15.2% was underdosed
Obvious solution: target $F_A$
Let machine manage $FGF$ and $F_D$ to get target $F_A$
Target control makes the use of low flow very simple, so we now use it routinely

---

Zeus

![FGF vs Liquid injection rate](image)

Time (min)  |  Time (min)
---|---
0 | 0
5 | 5
10 | 10

Personal observations
How Technology Will Secure the Future of Inhalation Anesthesia

1. Why low flow (LFA)
2. Why target control
   - teaching alone insufficient
   - more convenient, less distraction → consistent use
3. Why prediction displays (drug interactions, times)
4. The smartest pilot and the really smartest pilot
Ensuring 21% O₂ at the common gas outlet does not ensure F₁O₂ = 21%.
Anesthesia circle breathing system alters relationship between delivered and inspired $O_2$ %.

If $FGF < MV$: rebreathing kinetics.

Protection Against Accidental Delivery of Hypoxic Gas Mixtures
ANSI Standard 51.13.1

The anesthesia workstation shall be provided with

- a device to protect against an operator selected delivery
- of a $O_2/N_2O$ mixture
- having $<21\%\ O_2$ in the fresh gas or in the inspired gas.
Examples of hypoxic guard systems

Ohmeda Link 25
a chain that links N\textsubscript{2}O and O\textsubscript{2} mechanical

Dräger S-ORC
Sensitive Oxygen Ratio Controller pneumatical - mechanical

S-ORC limits = lowest possible F\textsubscript{D}O\textsubscript{2} % the S-ORC allows us to use with a certain FGF

![Graph showing S-ORC limits]

- Always > 25 % O\textsubscript{2}!
S-ORC limits = lowest possible $F_D O_2 \%$ the S-ORC allows us to use with a certain FGF

Always $\geq 250 \text{ mL min}^{-1} \% O_2$ (i.e., $O_2$ of awake adults)

But do these $F_D O_2$ limits ensure $F_I O_2 \geq 21 \%$?


These hypoxic guard limits did ensure $F_I O_2 \geq 21 \%$ ...
... but these did NOT: this is NOT a safe zone!

% of patients with F\textsubscript{O\textsubscript{2}} < 21 %

Time after which F\textsubscript{O\textsubscript{2}} < 21 %
(baseline = 25%)

---

---

---
In some patients < 60 seconds!

Machine standards are outdated:
- effect of rebreathing not taken into account
- no requirements for O₂/air mixtures

Worse still: hypoxic guards perform worst with FGF
many of us are comfortable working with: 1-2 L/min!
Solution?

O₂ anybody?

Jan F.A. Hendriks, Andre M. De Wolf and Stefan De Hert

Where do we go from here?

Solution = target F₁O₂ or F₁O₂ directly

Aisys
Zeus
FLOW-i

Solution = target F₁O₂ or F₁O₂ directly

Aisys
Zeus
FLOW-i
need back-up

override inadequate settings if $F_{O_2} < 21\%$

If $F_{O_2}$ decreases below 21\%, within 20\% of the critical value, the system will increase the fresh gas flows and the $O_2$ concentration delivered at the patient circuit, ensuring $F_{O_2}$ to at least 21\% within 7s after its activation.
How Technology Will Secure the Future of Inhalation Anesthesia

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Target controlled low flow: what target sevo to select?
You have to pick a number
Depending on which drug is eliminated faster, you might want to choose more hypnotic or opioid to maintain a certain anesthetic depth - this will help ensure a fast emergence, as guided by the prediction.

Drug combinations possible.

The orange circle/black circle/white circle navigates you.
Optimizing desflurane in terms of drug interactions/context-sensitive $t_{1/2}$ guided by SmartPilot

Desflurane usage for same depth (NSRI = 5)
≤ 53%

Carette R. Submitted, ESA 2016

Input info readily available:
- infusions: from injector, pump
- bolus: enter yourself or via bar codes in future
- "freebee": no need for electrodes


Road to more consistent and predictable wake-up
Vastly under-used and under-appreciated

Technology Has Secured the Future of Inhalation Anesthesia

We need to embrace it and implement it. Don't let technology pass you by.

- patient covariates
- surgeon's covariates (procedure, duration)
- costs of drugs, CO₂ absorbent, other
- adjust anticipated wake-up time

Machine will steer drug administration

Margin of error for inhaled agents: can be washed-out

Smartest Pilot

Enter

- patient covariates
- surgeon's covariates (procedure, duration)
- costs of drugs, CO₂ absorbent, other
- adjust anticipated wake-up time

Machine will steer drug administration

Margin of error for inhaled agents: can be washed-out
Really Smartest Pilot

Us!
Biological variability
Equipment failure

Still:
"One of the most important reasons we need anesthesiologists (at least for now) is that only anesthesiologists can determine what drugs and especially what combination of drugs (and their proportioning) will be used in a specific patient. This is something that can (will) be taken over by smart equipment, but not quite yet..."

Andre De Wolf
Northwestern University
Chicago, IL, USA

How Technology Will Secure the Future of Inhalation Anesthesia

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