Principles of Monitoring

James H. Philip, M.E.(E.), M.D. C.C.E.
Anesthesiologist and Director of Bioengineering, Brigham and Women's Hospital Medical Liaison, Partners Department of Biomedical Engineering Associate Professor of Anaesthesia, Harvard Medical School

© Copyright 1989 - 2015, James H Philip, all rights reserved.
Principles of Monitoring

James H. Philip, M.E.(E.), M.D. C.C.E.
Anesthesiologist and
Director of Bioengineering, Brigham and Women's Hospital
Medical Liaison, Partners Department of Biomedical Engineering
Associate Professor of Anaesthesia, Harvard Medical School

Gas Man® and Med Man Simulations, Inc. are a nonprofit charitable organization.
I have performed research on many of the drugs and devices described.
Through the BWH Ventures Office, I have a financial interest in some of the products described.
Anesthesia = "without sensation"

By loss of sensation, anesthesia allows the patient's brain to tolerate pain that the body was not designed to survive.
General Anesthesia

Requires continuous resuscitation during the ongoing administration of lethal drugs
General Anesthesia

Requires continuous resuscitation during the ongoing administration of lethal drugs

Every drug I administer is dangerous

Therapy I provide is life-preserving
Monitoring Goal

Protect the patient against adverse outcomes
The Acute Patient Care Loop describes the anesthesiologist’s actions in clinical management.

Patient → Monitor → Anesthesiologist → Patient

Measurements → Interpretation

The Acute Patient Care Loop describes the anesthesiologist’s actions in clinical management:

1. **Patient**
2. **Monitor**
3. **Anesthesiologist**

The loop involves:
- **Measurements** from the patient monitored by the anesthesiologist.
- **Interpretation** of monitored data by the anesthesiologist to adjust care.
The Acute Patient Care Loop describes the anesthesiologist’s actions in clinical management.
The Acute Patient Care Loop describes the anesthesiologist’s actions in clinical management.
Patient State

Set of all variables that must be known to manage the case.

The “case” is the patient, the diagnosis, and the treatment.

For an Anesthesiologist, this is the patient and his pre-existing conditions who begins awake, is rendered unconscious, undergoes surgery, and is then re-animated to his initial state.

Dimensions of Life, under anesthesia

Circulation
Metabolism
Respiration
Anesthesia

If these are independent and a complete set
These are the dimensions, Eigenvectors of life
There are measures along these dimensions
These are the Eigenvalues of life
Goal of monitoring is to monitor the Eigenvalues
More on theory later
Anesthesia Monitoring History
In the distant past

We monitored our patients using only our senses
A finger on the pulse
A hand on the reservoir bag
Listening to sounds through a stethoscope.
Observing color of skin and lips
In the 1960s

We began to monitor the cardiovascular system
We measured it in many ways

We believed that detecting cardiac arrest fast was important
I was an HP (Hewlett Packard) Engineer back then
   We really did work hard to detect a stopped heart

We did not yet realize that under anesthesia cardiac arrest is almost always the result of lack of ventilation or lack of oxygen

For a long time without detection
In the 1970s we learned

Most anesthesia mishaps are due to human error
Equipment contributes little to the problem
Better designed equipment can detect errors
Vigilance aids can improve outcome by detecting problems before they occur
This applies especially to airway problems

Cooper JB. Critical Incident Studies (Anesthesiology) 1976-1990. (Harvard Data)
The greatest danger was circuit disconnection.
Which we could easily miss with the technology we had, then
Especially at times of decreased vigilance
In the early 1980s patients learned

Anesthesia is dangerous
1,000 times more dangerous
than in an airplane 30,000 feet in the air.

*ABC Television 20/20 Report, 1982*
In the 1980s we learned

Two monitors could make a difference

**Capnography** (airway CO2) detects many problems early

**Pulse oximetry** detects most problems, but does so late

**Standards** could improve outcome

1985 Harvard Anesthesia Monitoring Standard

1) **Continuous presence** of a dedicated anesthesia care provider
2) Blood pressure and heart rate CV measured & recorded at least every five minutes
3) Electrocardiogram ECG continuously displayed
4) Circulation continuously monitored - any technique
5) Ventilation continuously monitored - any technique
6) Disconnect-detecting device used during mechanical ventilation
7) Oxygen in the breathing circuit monitored with alarm
8) Temperature monitoring capability
Standards for Patient Monitoring During Anesthesia at Harvard Medical School

John H. Eichhorn, MD; Jeffrey B. Cooper, PhD; David J. Cullen, MD; Ward R. Maier, MD; James H. Philip, MD; Robert G. Seeman, MD
Standards for Patient Monitoring During Anesthesia at Harvard Medical School

John H. Eichhorn, MD; Jeffrey B. Cooper, PhD; David J. Cullen, MD; Ward R. Maier, MD; James H. Philip, MD; Robert G. Seeman, MD
Anesthesia Safety Saving Lives

Nine doctors hope others will adopt standards
By Judy Foreman
Globe Staff

As many as 1400 anesthesia deaths could be avoided each year if doctors nationwide abided by minimal but strict safety standards, says a team of nine Harvard doctors in a new report.
Boston Globe front page headline could have read:

Sloppy docs mop shop
or
Killer docs - cleaning up their act too little and too late

We were fortunate. The press was supportive.
1986 ASA Monitoring Standard

Extended the Harvard Monitoring Standard

**Encouraged** the use of

- Pulse Oximetry
- Capnography
- Airway gas flow or volume
1989 Amendment to ASA Mon. Std.

Required pulse oximetry to assess blood oxygenation during general anesthesia.
1990 Amendment to ASA Mon. Std.

Required CO2 measurement to verify correct placement of the tracheal tube.

Encouraged use of CO2 monitoring throughout case.
Most authorities believe

Anesthesia mortality has fallen from 1/3,000 in 1985 to 1/30,000 or 1/300,000 in 1996.

ICPAMM Report, 1996
(Intl Comm Peri-op Anes M&M)
Anesthesia insurance rates have fallen and continue to fall

<table>
<thead>
<tr>
<th>Year</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>$20,000</td>
</tr>
<tr>
<td>1990</td>
<td>$10,000</td>
</tr>
<tr>
<td>2000</td>
<td>$10,000</td>
</tr>
<tr>
<td>2005</td>
<td>$10,000</td>
</tr>
</tbody>
</table>
Anesthesia insurance rates have fallen and continue to fall.

<table>
<thead>
<tr>
<th>Year</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>$20,000</td>
</tr>
<tr>
<td>1990</td>
<td>$10,000</td>
</tr>
<tr>
<td>2000</td>
<td>$10,000</td>
</tr>
<tr>
<td>2005</td>
<td>$10,500</td>
</tr>
</tbody>
</table>

Why?
Anesthesia insurance rates have fallen and continue to fall.

<table>
<thead>
<tr>
<th>Year</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>$20,000</td>
</tr>
<tr>
<td>1990</td>
<td>$10,000</td>
</tr>
<tr>
<td>2000</td>
<td>$10,000</td>
</tr>
<tr>
<td>2005</td>
<td>$10,000</td>
</tr>
</tbody>
</table>

Why?

We stopped hurting people!
Other specialties have not fared as well
Most anesthesia injury & death today is caused by

Failed airway management
Other complex events
Many require additional resources
Including
   Equipment, supplies, help, consults
   LMA (laryngeal mask airway)
   Special intubating scopes & devices
   Surgical Airway
Most anesthesia injury & death today is caused by

Failed airway management
Other complex events
Airway and CV complications may occur with regional anesthesia
High Spinal or High Epidural block
Intravascular Injection
Unconscious sedation
How and why we monitor in Anesthesia
Risk Management in Anesthesia

Monitor when you must

You must monitor for
That which goes wrong commonly and causes a minor bad outcome
That which goes wrong uncommonly but causes a very bad (expensive) outcome

Expected Value of a Loss =
Cost or Value of the loss if it occurs
\( \times \)
Probability that the loss will occur

The optimal amount to spend to avert a loss is the Expected Value of the Loss
Spend less and have a loss; This is Negligence
Spend more and have no loss: This is conservative, overly safe, possibly wasteful
Spend this amount and have or have not a loss; This is Properly Managed Risk

Judge Learned Hand, Fifth Federal Circuit Court of New York, 1932
Effective State Monitoring

Monitor the Eigenvalues of Life under Anesthesia
Circulation
Metabolism
Respiration
Anesthesia
Monitor the physiology of each
Effective (Physiologic) Monitor

Select Physiology to monitor
Select the Variable that monitors the physiology
Monitor the variable Continuously
Extract Features from the continuous variable
Compare Observed to the Expected value
Interpret the deviation of observed from expected
Communicate the Interpretation - Alert or Alarm
Effective (Physiologic) Monitor

Select Physiology = Breathing
Variable to Monitor = Airway Capnogram
Mon. Continuously = Sample Airway Gases
Features = Rate, Max (Exp), Min (Insp), Plateau
Expectation = No Change unless Vent Change
Need a model for Vent Change -> pCO₂ Change
Interpret = ETpCO₂ change without change in Vent
Communicate = Audio and Visual Alert

Monitor the patient’s state
Correct Patient State

We start out with the patient in the correct state.

The correct state could be coded as green

Incorrect Patient State

First level of state definition.
All states are divided into correct and incorrect states.
The green becomes yellow.
The second level of state definition. The incorrect state has been expanded to express the four systems that can be deranged.
The third level of state definition. As an example, derangement of the circulation has been divided into three states.
Treatment follows state

- **Circulation**
  - **Volume**
    - Medium: Blood
  - **Pressors**
    - Conduits: Blood Vessels
  - **Assist**
    - Pump: Heart

Tx according to Dx
Treat according to diagnosis
Anesthetization Incorrect

Anesthesia

- Sleep
- Reflexes blocked
- Amnesia
- Paralysis
Respiration Incorrect

- Ventilation $V_A$
- Inspired Oxygen $P_{1O_2}$
- Perfusion CO
- Gas Exchange (Shunt, Dead Space, Diffusion)
An important attribute of State is Severity

Severity is the opposite of Safety

Patient State Severity Diagram =
Patient Safety State Diagram

Patient Safety State Diagram

ACCEPTABLE OUTCOMES

CORRECT STATE

1° Patient change

INCORRECT REVERSIBLE STATE

ACCEPTABLE STATES

Patient Safety State Diagram

ACCEPTABLE OUTCOMES

CORRECT STATE

1° Patient change

INCORRECT REVERSIBLE STATE

Tx Correct

Tx Incorrect

Dx Known or Missed Briefly

ACCEPTABLE STATES

Patient Safety State Diagram

ACCEPTABLE OUTCOMES

CORRECT STATE

1° Patient change

INCORRECT REVERSIBLE STATE

Tx Incorrect

Successful Corrective Tx

Dx Known or Missed Briefly

ACCEPTABLE STATES

Patient Safety State Diagram

ACCEPTABLE OUTCOMES

CORRECT STATE

1° Patient change

INCORRECT REVERSIBLE STATE

Dx Missed

Tx Unsuccessful

REVERSIBLE MORBIDITY

ACCEPTABLE STATES

CORRECT STATE

Tx Correct

Successful Corrective Tx

Dx Known or Missed Briefly

Tx Incorrect

SUCCESSFUL OUTCOMES

REVERSIBLE OUTCOMES

ADVERSE OUTCOMES

SEVERE OUTCOMES

UNACCEPTABLE STATES

ACCEPTABLE OUTCOMES

CORRECT STATE

1° Patient change

INCORRECT REVERSIBLE STATE

Dx Missed

REVERSIBLE MORBIDITY

Tx Missed

GRIEVOUS OUTCOMES

SEVERE OUTCOMES

SUCCESSFUL Tx

SUCCESSFUL SALVAGE Tx

SUCCESSFUL MAINTENANCE Tx

IRREVERSIBLE MORBIDITY

ACCEPTABLE STATES

UNACCEPTABLE STATES

Successful Corrective Tx

Dx Known or Missed Briefly

Successful Tx

Patient Safety State Diagram

ACCEPTABLE OUTCOMES

CORRECT STATE
1° Patient change
Tx Correct

INCORRECT REVERSIBLE STATE
Dx Missed
Tx Incorrect

REVERSIBLE MORBIDITY
Dx Known or Missed Briefly
Successful Salvage Tx

SEVERE OUTCOMES
Dx Missed
Tx Unsuccessful
Successful Maintenance Tx

ADVERSE OUTCOMES

GRIEVOUS OUTCOMES
Dx Missed
IRREVERSIBLE MORBIDITY

UNACCEPTABLE STATES

DEATH
Successful Chronic Tx

Oxygen deprivation -> fast transition

ACCEPTABLE OUTCOMES

1° Patient change
INCORRECT REVERSIBLE STATE
Dx Missed
Tx Incorrect
Successful Corrective Tx
Tx Correct
Dx Known or Missed Briefly
Successful Salvage Tx
SUCCESSFUL MORBIDITY
SUCCESSFUL SALVAGE Tx
SUCCESSFUL MAINTENANCE Tx
SUCCESSFUL CHRONIC Tx
SUCCESSFUL Tx

ADVERSE OUTCOMES

SEVERE OUTCOMES
Dx Missed
Tx Unsuccessful
SUCCESSFUL MAINTENANCE Tx
SUCCESSFUL CHRONIC Tx
SUCCESSFUL Rx

GRIEVOUS OUTCOMES
Dx Missed
Tx Unsuccessful
SUCCESSFUL MAINTENANCE Tx
SUCCESSFUL CHRONIC Tx
SUCCESSFUL Rx

UNACCEPTABLE STATES

ACCEPTABLE STATES

Thank you
Monitor needs to know expectation
With inhalation anesthesia

We can monitor and predict
Gas and vapor concentration
In the breathing circuit
In the patient
Gas Man® does this
The second level of state definition. The incorrect state has been expanded to express the four systems that can be deranged.

Potential Derangements

Incorrect State

- Circulation
- Metabolism
- Anesthesia
- Respiration
Monitors

General Electric = GE = Marquette
Spend time pushing buttons (every button)
Figure them out
Ask for help
Ask
Biomed,
Your Attending
Me
Department Web Site
http://www.etherweb.bwh.harvard.edu/
Education/
Educational Resources/
Technology matters/
Anesthesia Technology Resources/
http://www.etherweb.bwh.harvard.edu/
http://www.asahq.org/publicationsAndServices/sgstoc.htm
Alarms and Alerts
Alarms and Alerts

Try to keep them all ON, all the time
If you can’t keep an alarm ON, there is a problem
Either
   patient vital signs are bad, for real
   monitor measurement error or malfunction
   monitor design inadequacy
If something alarms too often, report it
   To: Biomedical Engineering
   Page: 1-1055
   Outlook e-mail: BWH Anes Biomed
   Voicemail: 3-1291
   Cc: me (jphilip@partners.org)
Smart Alarms communicate Information
Conventional Monitors

Alarms are always turned off
  if there is a switch
Data is reported and displayed
Data is disconnected from past and future
Repetitive waveforms are shown
  as if there is new information conveyed
But, data which does not change knowledge
  is not information.
Information changes knowledge
The static knowledge is BP is stable at 120/80
Alerts communicate information

Information is that which changes our knowledge
Each BP = 120/80 reading conveys no information
When BP rises to 150/90
That is information!
That needs to be communicated!

Smart Alarms communicate Information
Alert Zones
Ohmeda Central Display 1992 Alert Zones

Where we are

Where we Alert

Alert Zones
Future Monitoring

Probably not today
What will we monitor next?

Brain Monitoring - will it become Standard?

Oxygenation of specific tissues? What tissues?

Automated Information Management - when?

Predicted drug level in target organ now

Predicted time to criteria (e.g., awake, asleep)
Learn More - BWH Anes Department Web Site

http://bwhanesthesia.org and click:
Education
Anesthesia Technology

http://www.asahq.org/publicationsAndServices/sgstoc.htm

or

http://www.asahq.org/publicationsAndServices/standards/02.pdf
Thank you