What is patient monitoring?

“Repeated or continuous observations or measurements of patients, their physiological function, and the function of life support equipment for the purpose of guiding and assessing the efficacy of patient management decisions, such as therapeutic interventions.”
(Gardner and Shabot)

• Automated (noise prone)
• Semi-automated (decision support, human filters)
• Manual (integrative, low-cost, traditional, subjective) (Usually well trained, intelligent monitors!)
Who needs intensive monitoring?

There are at least 5 categories of patients who require intensive physiological monitoring:

1. Patients with unstable physiological regulatory systems (e.g. a patient with impaired respiratory system)
2. Patients with suspected life-threatening conditions (e.g. acute MI)
3. Patients at risk of developing a life threatening condition (e.g. major post-operative patients)
4. Patients in critical physiological state (e.g. trauma/shock)
5. Mother and baby during the labor and delivery process
Reasons for monitoring & storing data

- For decision support and management of patient
- To allow the review of historical data
- To organize and allow concise reporting (billing?)
- To allow data mining for retrospective studies
- To measure severity of illness and provide optimization of resource allocation
- Automated data fusion, and ‘conflict resolution’
- To allow quality control through assessment and evaluation of performance (outcomes, LOS, infection rates, costs, etc)
Variety of monitoring situations

- Paramedics (light/variable)
- E.R. (light/variable)
- O.R. (hyper-intensive)
- I.C.U. (intensive)
- General Wards (light)
- Outpatient / Home (light)
Why admit a patient to the ICU?

- Life-threatening acute problems

- Requires ‘constant’ vigilance and care (by humans and/or technology)

- Patient is unstable

- Leave when stable:
  - Life sustaining tech. not req’d
  - Continuous round-the-clock care not req’d

**Endpiece**

When to discharge a patient

It is not always an easy matter for a physician to judge, with precision, when a patient ought to be discharged from the hospital. It sometimes happens that patients, whose circumstances at home are necessitous, and their lives laborious, wish to loiter in the house as patients, and being cured of real diseases, would amuse the physician with fictitious feelings, of which he cannot constitute himself a judge, as pain in the stomach or the bowels, general or local rheumatisms, and a variety of similar complaints.

*The history and statues of the Royal Infirmary of Edinburgh.*
Edinburgh: E Balfour and Smellie, 1778:86

Jeremy Hugh Baron, honorary professorial lecturer, Mount Sinai School of Medicine, New York
IT in the hospital

- Sensors
- Monitors
- Data transmission
- Feedback
Most important parameters to monitor

- RR (respiratory rate),
- SpO₂ (oxygen saturation),
- ECG (electrocardiogram),
- HR (heart rate),
- Core temperature (inside the heart)
- Peripheral temperature (on top of the instep),
- CI (cardiac output index, CO/m²),
- Systematic pressures (SSAP, systematic systolic arterial pressure; SDAP, systematic diastolic arterial pressure; SMAP, systematic mean arterial pressure),
- CVP (central venous pressure),
- Pulmonary pressures (PSAP, pulmonary systolic arterial pressure; PDAP, pulmonary diastolic arterial pressure; PMAP, pulmonary mean arterial pressure),
- svO₂ (oxygen saturation in the lung artery),
- ETCO₂ (outcoming carbon dioxide),
- FIO (ingoing oxygen),
- Diuretics,
- Drip drugs (type and rate)
- Bolus (oral/hypodermic) drugs
- Patient’s weight,
- Fluid balance (ingoing and outcoming fluids)
- Electroencephalogram (EEG)
- Intra-cranial pressure (ICP)
Other important information

- X-rays (masses, pneumonia, pneumothorax, fracture)
- MRI & CT scans (stroke)
- Ultrasound diagnostics (fluid, labor)
- Admit note/patient history
- Nursing progress notes
- Problem lists
- Alarms
- Events/procedures/interventions (intubation, surgery, transfers …)
- Laboratory tests
- Movement & consciousness (GCS, actigraphy)
Data volume in the ICU
• 1MB-2GB/patient/day

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Amplitude Range</th>
<th>Freq Range (Hz)</th>
<th>Sampling Freq (Hz)</th>
<th>Bit rate (kb/s)</th>
<th>Amplitude resolution (bit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cuff BP</td>
<td>10-400 mmHg</td>
<td>0-60</td>
<td>~0.001</td>
<td>&lt;10^{-4}</td>
<td>8</td>
</tr>
<tr>
<td>IBP</td>
<td>10-400 mmHg</td>
<td>0-60</td>
<td>~125</td>
<td>0.25</td>
<td>8-16</td>
</tr>
<tr>
<td>PAP</td>
<td>0-50 mmHg</td>
<td>0-60</td>
<td>~125</td>
<td>0.25</td>
<td>8-16</td>
</tr>
<tr>
<td>CVP</td>
<td>0-50 mmHg</td>
<td>0-60</td>
<td>~125</td>
<td>0.25</td>
<td>8-16</td>
</tr>
<tr>
<td>ECG</td>
<td>±4mV</td>
<td>0.01-500</td>
<td>100-2k Hz</td>
<td>0.2-6</td>
<td>8-16</td>
</tr>
<tr>
<td>SpO2</td>
<td>80-100%</td>
<td>0-30</td>
<td>~80</td>
<td>&lt;0.2</td>
<td>8-10</td>
</tr>
<tr>
<td>C.O.</td>
<td>4-25 L/min</td>
<td>0-20</td>
<td>~&lt;0.001</td>
<td>10^{-5}</td>
<td>8</td>
</tr>
<tr>
<td>Temp</td>
<td>32-40 °C</td>
<td>0-0.1</td>
<td>1</td>
<td>&lt;10^{-3}</td>
<td>8</td>
</tr>
</tbody>
</table>
Multiple databases, multiple sources

- Practices differ in different units
- Data formats differ in each DB
- Synchronization difficult
- Data may be contradictory
Telemetry Instrumentation
Wireless Telemetry Infrastructure

- Complex
- Delays
- Time stamp issues
- Protocols (HL7)
- Security issues
- Patient ID
Alarms - ICU

• Straight thresholds
  – HR < 60 BPM == Bradycardia
  – No inspiratory gas flow ≥ 20s == Apnea

• Multi-parameter thresholds
  – No inspiratory gas flow < 20s, bradycardia, cyanosis, or pallor == Apnea
  – Data Fusion (HR from ECG, BP and PPG)

• Subjective/objective reasoning & logic
  – Pallor (subjective?)
  – Temporal reasoning – if this, then that, check this, then …

• Complex classifiers
  – Linear regression (SAPS)
  – Nonlinear/nonstationary (ANN, EKF)
Subjective scales

Glasgow Coma Score

<table>
<thead>
<tr>
<th>Eyes Opening</th>
<th>Verbal Response</th>
<th>Motor Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>spontaneous</td>
<td>obeyes</td>
</tr>
<tr>
<td></td>
<td>to speech</td>
<td>localizes pain</td>
</tr>
<tr>
<td></td>
<td>to pain</td>
<td>withdraws (flexion)</td>
</tr>
<tr>
<td></td>
<td>absent</td>
<td>decorticate (flexion) rigidity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>decerebrate (extension) rigidity</td>
</tr>
</tbody>
</table>

Glasgow Coma Score = 6

2+2+2≤9 … Patient needs CT scan to rule our *traumatic brain injury*

Riker Scale

<table>
<thead>
<tr>
<th>#</th>
<th>Riker</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Unarousable</td>
<td>Minimal or no response to noxious stimuli</td>
</tr>
<tr>
<td>2</td>
<td>Very Sedated</td>
<td>Aroused to physical stimuli but does not communicate or follow commands</td>
</tr>
<tr>
<td>3</td>
<td>Sedate</td>
<td>Difficult to arouse but awakens to verbal stimuli or gentle shaking</td>
</tr>
<tr>
<td>4</td>
<td>Calm/Cooperative</td>
<td>Follows commands, easily arousable, Calm</td>
</tr>
<tr>
<td>5</td>
<td>Agitated</td>
<td>Anxious or physically agitated, calms to verbal instructions</td>
</tr>
<tr>
<td>6</td>
<td>Very agitated</td>
<td>Requiring restraint and frequent verbal reminding of limits, biting ETT</td>
</tr>
<tr>
<td>7</td>
<td>Dangerously agitated</td>
<td>Pulling at ET tube, trying to remove catheters, climbing over bedrail, striking at staff, thrashing side-to-side</td>
</tr>
</tbody>
</table>

• ~80% inter-observer agreement
... and (semi) objective parameters

SAPS: Simplified Acute Physiology Score

- \( f(Age, HR, SBP, Temp, Resp, Urine O/P, BUN, HCT, WBC, Glucose, K, Na, HCO_3, GCS) \)

HCT = Hematocrit
WBC = White Blood Cell Count
GCS = Glasgow Coma Score.
BUN = blood urea nitrogen.
Urine O/P = total urine output in first 24 hours

Figure 3: Hospital mortality rate and SAPS I score distribution from the 10,934 adult patient records containing all metrics required for SAPS I.
SAPS II: New Simplified Acute Physiology Score

- Provides an estimate of the risk of death without having to specify a primary diagnosis

- 12 physiology variables, age, type of admission (scheduled surgical, unscheduled surgical, or medical), and the GCS.

- Reason for admission (medical, scheduled or unscheduled surgery)

- 1 disease variable: 3 etiologies (acquired immunodeficiency syndrome, metastatic cancer, and hematologic malignancy).

- AUROC = 0.86

- Based on a large international sample of patients, (13,152)

- Adult disease etiologies more complex

- http://www.sfar.org/scores2/saps2.html
Critical Care Scoring Systems

- **APACHE II** Acute Physiology and Chronic Health Evaluation System
- **APACHE IV** Acute Physiology and Chronic Health Evaluation System
- **SAPS II** Simplified Acute Physiology Score (V2)
- **MPM 0** Mortality Prediction Model at admission
- **MPM 24** Mortality Prediction Model after 24 hours
- **MPM 48** Mortality Prediction Model after 48 hours
- **MPM Over Time** Mortality Prediction Model Over Time
- **SOFA** Sequential Organ Failure Assessment
- **MODS** Multiple Organ Dysfunction Score
- **PRISM** Pediatric Risk of Mortality
- **PIM2** Pediatric Index of Mortality
But … can we trust the data?

• How do we resolve discrepancies between databases?

• How do we know if we are ordering enough tests (or too many?)

• How do we know what we see on the monitor or in the database is true?

• What filters are the monitors using?

• What are the properties of the (aging) transducers?

• Are humans making mistakes?
Errors of commission

• Incorrect therapy or administration
  – Drug prescription/administration errors
  – Incorrect operations, or errors in surgery, anaesthesia, etc

• Procedural
  – Pneumothorax during a central line placement
  – False asystoles pollute ICU because of wrong settings on monitors.
  – Incorrect transducer location. E.g. BP transducer not at heart level, or ECG/resp sensor misplacement... Apneas are most frequent life-threatening alarm in ICU - respiration signals low quality due to bad placement of sensors, no adjustment and lack of data fusion.
  – Transcription errors
  – Unwarranted tests wasting time and resources that could be placed elsewhere.

Estimated 44,000-98,000 patients die preventable deaths annually in hospitals in the US with a cost of $38-50 billion from errors of commission. Errors due to omission may be even higher

Crossing the Quality Chasm: The IOM Health Care Quality Initiative Report Brief. To Err Is Human: Building a Safer Health System
Errors of omission

• **Under-sampling**
  – Pain observation every 4 hrs reduced $P(untreated\ pain)$ from 41% to 3%!
    (Pronovost et al.)

• **Time delays in administering drugs can add up**
  – Early detection and treatment is critical to patient recovery (e.g. sepsis)

• **Procedural**
  – Drug interactions & allergies
  – A-line placement checklist: 10 day line infection dropped from 11% to ~0%!
    Over 15 months prevented 43 infections, 8 deaths and saved $2m
    (Pronovost et al.)
  – Communication errors, forgetting to do something

• **Time interventional planning missing**
  – Not enough reasoning in ICU – c.f. with motor assembly line

• **Ignored alerts/alarms**
  – Lack of trust?
False alarms & noise

• Noise
  – Electrosurgical interference
  – Physiological activity (muscle noise, baseline wander)
  – Quantization noise
  – Filtering & interpolation artifacts (sample and hold!)

• Patient variability
  – Thresholds should be dependent upon age, gender, existing conditions, drugs, ...

• Missing data
  – Under-sampling
  – Sensor disconnects
  – Transmission errors
  – Hardware failures

• Recording Errors
  – Time inaccuracies
  – Typos, non-SI units, storage in wrong DB, incorrect labeling
ABP:

- Examples of artifacts in ABP waveforms:
  (a) transducer flushing,
  (b) motion,
  (c) movement,
  (d) proximal BP inflation
Signal quality assessment

- Signal quality is rarely reported to staff
- Clinicians either trust data or look at patient or monitor
- Sample-and-hold common
- Data fusion rare!
Signal quality of ICU data

- Signal quality is generally good, but ...
- Noise often occurs simultaneously with rare (but important) events – e.g. neonatal obstructive apnea

![ECG](image1.png)  ![ABP](image2.png)
## False ECG arrhythmia alarm frequency in ICU

Gold standard database of $N = 5386$ critical ECG arrhythmia alarms: relative frequency of true and false alarms on a per-alarm basis

<table>
<thead>
<tr>
<th>Alarm type</th>
<th>All alarms</th>
<th>True alarms</th>
<th>False alarms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total alarms</td>
<td>% Of all alarms</td>
<td>N</td>
</tr>
<tr>
<td>Asystole</td>
<td>579</td>
<td>10.8</td>
<td>54</td>
</tr>
<tr>
<td>Extreme bradycardia</td>
<td>717</td>
<td>13.3</td>
<td>507</td>
</tr>
<tr>
<td>Extreme tachycardia</td>
<td>1877</td>
<td>34.8</td>
<td>1444</td>
</tr>
<tr>
<td>VTach</td>
<td>1900</td>
<td>35.3</td>
<td>1015</td>
</tr>
<tr>
<td>VTach/VFib</td>
<td>313</td>
<td>5.8</td>
<td>64</td>
</tr>
<tr>
<td>All</td>
<td>5386</td>
<td>3084</td>
<td>57.3</td>
</tr>
</tbody>
</table>

Average true alarm rate = 57.3%.
ECG Alarm Example 1

Ventricular Tachycardia False Alarm – mimicdb/260/260

- ECG (mV)
- ABP (mmHg)
- mSNI

Time (s)
ECG Alarm Example 2

True Ventricular Tachycardia – mimicdb/485/485

ECG (mV)

ABP (mmHg)

mSNi = 0.6

Alarm Onset

SNIVENT = 0.95
Data fusion for false alarm suppression

<table>
<thead>
<tr>
<th>Alarm type</th>
<th>Training set (n = 267)</th>
<th>Test set (n = 180)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suppression rates</td>
<td>FA rates</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FA (%)</td>
<td>TA (%)</td>
<td>Before suppression (%)</td>
</tr>
<tr>
<td>Asystole</td>
<td>93.5</td>
<td>0.0</td>
<td>90.7</td>
</tr>
<tr>
<td>Brady</td>
<td>81.0</td>
<td>0.0</td>
<td>29.3</td>
</tr>
<tr>
<td>Tachy</td>
<td>63.7</td>
<td>0.0</td>
<td>23.1</td>
</tr>
<tr>
<td>VTach</td>
<td>33.0</td>
<td>9.4</td>
<td>46.6</td>
</tr>
<tr>
<td>VT/VF</td>
<td>58.2</td>
<td>0.0</td>
<td>79.6</td>
</tr>
<tr>
<td>ALL</td>
<td>59.7</td>
<td>2.4</td>
<td>42.7</td>
</tr>
</tbody>
</table>
Are we over-monitoring?

- Not all parameters are useful, and can be harmful
  - Swan-Ganz catheter measures wedge pressure in pulmonary artery – estimates heart’s pre-load
    - Can do more harm than good for a some sub-population – e.g. for patients where pressure-volume level is not constant, as patient management depends this assumption
  - Intensivit care may be associated with worse outcomes because we tend to do more monitoring, diagnostic procedures and therapeutic interventions.

- Does extra monitoring stress the patient (mentally and physically). Waking a patient to see if they are asleep?

- Are the metrics predictive?
  - Discrimination often good for populations
    - You can compare performance between units
  - Poor for individual management
    - Calibration is poor

- Need to determine who requires monitoring
Conclusions on monitoring

• Monitoring is very complex – too many parameters for humans to keep track of patient state – highly dimensional

• Many sources of errors in parameter values (artifacts in recording, transmission errors, transcription errors, data discarded)

• Time stamping of data is often inaccurate – Need more accurate temporal recording of data, particularly drugs if we are to use all the data available

• Data in multiple databases, often in different (non-open) formats – Need for open standards

• False alarms common! Clinical staff are desensitised to alarms. – More data fusion and signal quality reporting required

• Need to determine who we should monitor – sometimes monitoring is harmful

• Perhaps we need to over-monitor before we can optimally monitor
Readings

- Reed M. Gardner and M. Michael Shabot, **Patient Monitoring Systems** Ch 17 in “Biomedical Informatics; Computer Applications in Health Care and Biomedicine” Edited by Edward H. Shortliffe and James J. Cimino


- Atul Gawande, **Annals of Medicine: The Checklist; If something so simple can transform intensive care, what else can it do?** New Yorker, December 10, 2008 http://www.newyorker.com/reporting/2007/12/10/071210fa_fact_gawande
The MIMIC II Database – a resource for all!

- 30k patient stays, almost all hospital data
Clinical studies that might interest you?

• Can you predict renal function from pulse pressure variations?

• Time of death during day linked to some physiology or just CMO/DNR after rounding in the afternoon/eve?

• Impending sepsis and hemodynamic deterioration

• Prediction of impending respiratory failure

• Predictors of immediate reintubation after extubation.

If interested, please contact Prof. Mark: rgmark@mit.edu, Dan and Mauro – maurov@mit.edu, djscott@mit.edu