Lessons Learned from Cardiopulmonary Clinical Decision Support Systems

Nicolas W. Chbat, PhD
Principal Member Research Staff
Philips Research North America, New York

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Agenda

..from a personal account..

- Biomedical Engineering Vs. Medicine
- Fields of Biomedical Engineering
- Decisions need in medicine
- Clinical Decision Support in cardiopulmonary medicine
- Examples and lessons (hopefully) learned
- Conclusion
Engineering, Medicine: Knowledge Sources

Implicit or Explicit Structure of Models
Biomedical Engineer

• Engineering design (devices, etc.)
• Sensor development (chemistry, physics, material, etc.)
• Signal processing (Imaging, physio/biological signals, etc.)
• **Algorithm development (feature extraction, CDS, etc.)**
• Wet lab work (biological, chemical, tissue, etc.)
• Software development (cloud, interop, GUI design, etc.)
• Regulatory processes (IRB, ICBE, Contracts, FDA, etc.)
• Testing and verification (eng’g testing and V&V, RCTs, etc.)
• Many others
Decisions Need in Medicine

- Strategic decisions
- Tactical decisions
- Functional decisions

Fig. 1. Problem space.

- ED
- Ambulance/Helicopter
- General Ward
- OR
- **ICU**
- Care Facility
- Home

A. Seiver, Discussions, 2010–Present
Decisions in Critical Care Medicine

What will happen to the patient? When will it happen?

Should I…
• set PEEP to 10?
• remove ventilation support?
• administer antibiotics?

Will the patient develop ARDS? When?

When will fluids improve kidney perfusion? When will I have caused additional lung injury?

Propofol dosage?

Steroids? Delaying death or improving life?

Outcomes
• Home
• Care Facility
• ICU LOS
• Delayed death
• Short-term disability
• Long-term disability
• Mortality

How can we answer these questions? One approach is...
• Develop a model for early detection of acute illness, so we can...
• Predict time dynamics of patients’ vitals, labs, etc., enabling Forecasting
The Cardiopulmonary System and the Importance of Modeling
The Cardiopulmonary System

- Heart and Circulatory System
- Lungs and Gas Exchange
- Tissue Metabolism

Control Mechanisms:

- **Short-term:**
  - Baroreceptors
  - Chemoreceptors
  - Lung Stretch Receptors

- **Long-term:**
  - Renal control
  - Humoral control (ADH, RAAS)
  - Capillary fluid shift
Importance of Physiological Modeling

Clinical medicine needs a quantitative approach to:

- Understand complex interactions and underlying mechanisms
- Assess physiological variables/parameters non-invasively
- Predict patient response to treatments
- Test medical devices more effectively and efficiently
Cardiopulmonary Model Developed

Cardiovascular System

Autonomic Nervous System
- Autoregulation
- Parasympathetic
- Sympathetic

CNS Ischemic Response
Baroreceptors
Lung Stretch Receptors

Peripheral Chemoreceptors
Central Chemoreceptors
Ventilatory Control System

Respiratory System
- Respiratory Muscles
- Lung Mechanics
- Mechanical Ventilator

Cardiovascular Control System

Heart
Circulation
Blood Flows
Blood Volumes

Gas Exchange and Transport
- Tissue Gas Exchange
- Lung Gas Exchange

Tidal Volume

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Validation: Hypercapnia

7% CO₂ step input

Respiratory Response

Cardiovascular Response

8% CO₂ step input

Cardiovascular Response

<table>
<thead>
<tr>
<th>ΔHR (beats/min)</th>
<th>ΔMAP (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+9.75</td>
<td>+15.5</td>
</tr>
<tr>
<td>+9.7</td>
<td>+12.5</td>
</tr>
</tbody>
</table>

**Averaged data over 10 subjects

Reynolds et al. (1972) *

Model

Mengesha et al ** (2000)

* Averaged data over 14 subjects

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Model Implementation
Graphical User Interface

Cardiopulmonary Model

### Heart
- **Right Atrium**
  - Compliance: 31.25 ml/mmHg
  - Resistance: 0.0025 mmHg·s/ml
  - Unstressed Volume: 22 ml

- **Left Atrium**

### Lungs

#### Neural
- **Right Ventricle**
  - Resistance Coeff.: 0.0014 s/ml
  - Unstressed Volume: 35.904 ml
  - Maximal Elastance: 1.412 mmHg/ml

### Circulation

#### Metabolism

#### Gas Exchange

### Variables
- Plot selection: Upper left, Upper right, Lower left, Lower right
  - Plot 1: Arterial O2 pressure
  - Plot 2: Alveolar O2 pressure

### Parameters
- **Target PC**

### Heart Diseases
- Chronic Heart Failure: 0%
- Heart Attack: 0%
- Cardiogenic Shock: 0%
- Valve Disease: 0%
Model-based CDS for Mechanical Ventilation/Anesthesia
Current Practice in Mechanical Ventilation
Noninvasive model-based assessment of patient respiratory muscles effort
Patient Respiratory Muscles Effort

• Quantify non-invasively and in real-time the effort spent to breath (WOB) while on a ventilator

• WOB is critical to:
  – Assess patient readiness to extubation [1]
  – Select appropriate ventilator settings (PSV levels) [2]
  – Prevent muscle fatigue and atrophy [3]

• Monitoring of WOB at the bedside:
  – Reduces the risk of ventilator induced injuries
  – Saves cost of extended hospitalization

## Current state-of-art for WOB computation

### Campbell Diagram

- $C_L$: Lung Compliance line
- $C_{cw}$: Chest Wall Compliance line
- $I$: Integral of Respirator Muscle Pressure ($P_{mus}$) over Volume
- $E$: Esophageal catheter
- $0$: Pleural Pressure
- $V$: Volume

### Commercial Device

<table>
<thead>
<tr>
<th>Commercial Device</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BiCore CP100</strong> (Bicore, now CareFusion)</td>
<td>• Esophageal catheter used to estimate pleural pressure</td>
</tr>
<tr>
<td></td>
<td>• Expert operator and additional instrumentation required.</td>
</tr>
<tr>
<td><strong>Ventrak 1500</strong> (Novametrix, now Philips-Respironics)</td>
<td></td>
</tr>
</tbody>
</table>

### Alternative methods

<table>
<thead>
<tr>
<th>Commercial Device</th>
<th>Method</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VentAssist</strong> (Philips-Respironics)</td>
<td>Neural Network</td>
<td>• Averaged value over breaths</td>
</tr>
<tr>
<td><strong>PAV+</strong> (Puritan-Bennett, Covidien)</td>
<td>Integral of Respirator Muscle Pressure ($P_{mus}$) over Volume</td>
<td>• $P_{mus}$ estimation imprecise</td>
</tr>
</tbody>
</table>
A Model-Based Solution

Parameter Estimation

Lung Mechanics Model

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**Results:** Transition from 10 to 0 PSV

PSV=10 cmH\textsubscript{2}O

PSV= 0 cmH\textsubscript{2}O
**Results:** Campbell Diagram and WOB at 10 PSV

![Diagram showing Campbell Diagram and WOB at 10 PSV](image-url)
Results: Campbell Diagram and WOB at 0 PSV
Current Practice vs. CL Approach

Current Practice: physician-in-the-loop

New Approach: physician outside the loop
Model-based (heuristic and data mining) Critical Illness Detection
Acute Respiratory Distress Syndrome (ARDS)

**Inputs**
- Discussions with physicians
- Published research articles
- Published standards
- Database (ICU & EMR)

**Clinical Knowledge Sources**
- Experience, heuristics, research, definitions

**Clinical Data**
- Vitals, labs, interventions, chronics, demographics

**Algorithms**
- Knowledge-based Algorithms
- Data-based Algorithms

**Output**
- Algorithm Aggregator
- Syndrome Status (ARDS)

ARDS Model Architecture
Lessons Learned (1/2)

• Using deterministic models
  – Majority of eng’g education spent on learning mathematical models
  – Depending on the engineering application field, use of models primarily to
    • Test and verify an intuition that the engineer has
    • Test and verify an experiment that the engineer performed

• Healthcare professionals: clinicians, and... engineers
  – Used to Epidimiological studies
  – Statistics, correlations, etc. (data-based)
  – Fancier data based \(\rightarrow\) discomfort among end users (MDs) (case...)
  – Engineers (R&D, App), engineering managers

• Room for explicit heuristic models
• Room for explicit deterministic models
• Room for explicit stochastic models
Lessons Learned (2/2)

• Animal testing
  – New demands created due to the fact that we use a model (case...)
  – IACUC

• Human Research Clinical Trials
  – New demands created due to the fact that we use a model (case...)
  – IRB

• Evidence-based medicine (case...)
  – Evidence \(\rightarrow\) backed up by data
  – Fuzzy, Bayesian thinking of how MDs diagnose a disease is still very valuable

• Personalized medicine
  – Molecular, DNA, small-scale are important and vital in some diseases
  – Does not mean macro-scale is not vitally important for many diseases (case...)
  – Fine tune your models in real-time \(\rightarrow\) also individualized medicine

• Present a model-based CDS to the end user
  – MD (case...)
  – Product manager - market study, etc. (case...)
Thank you Osaka for hosting us!

Thank you audience for listening…

Questions?