Wearable Respiratory Monitoring: Algorithms and System Design

An IEEE Distinguished Lecture, 2011

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Wearable Respiratory Monitoring: Algorithms and System Design

An IEEE Distinguished Lecture, 2011

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The IEEE

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324 sections worldwide
<table>
<thead>
<tr>
<th>Membership (38 Societies in IEEE)</th>
<th>IEEE</th>
<th>CASS</th>
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<td>&gt; 400,000</td>
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<td>8,513</td>
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<tr>
<td>Number of Chapters</td>
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CASS is the 9th largest IEEE Society (after CS, ComSoc, MTTS, PES, SPS, SSCS, EDS, and IA)
Nanyang Technological University (NTU)

- 1955: Established as the 1st Chinese-medium university outside China
- 1981: Nanyang Technological Institute (NTI) set up (English) with 3 Engineering Schools
- 1991: NTU was inaugurated, incorporating National Institute of Education
- Now (2011): 3rd NTI/NTU President
  - College of Engineering
  - Nanyang Business School
  - College of Science
  - College of Humanities, Arts and Social Sciences
  - School of Medicine
  - Student Population > 30,000
Outline of Presentation

I. Introduction – A Clinical Perspective

II. Motivations and Problem Formulation

III. Wearable Wheeze Monitoring System @ NTU
   a) Overall System Design
   b) Wearable Signal Processing Algorithms
   c) Wearable Sensors and Platform Suite

IV. Lab Tests, Pre-Clinical Trials and Results

V. Conclusions and Future Work
Wearable Respiratory Monitoring: Algorithms and System Design

Research Team

Nanyang Technological University, Singapore
- A/Prof. W Ser, Dr. J Zhang, J Yu, Dr. T Zhang

National University Hospital, Singapore
- A/Prof. Dr. Daniel YT Goh and Team
Introduction

A Clinical Perspective
Respiratory Disorders

Chronic respiratory diseases include disorders that affect any part of the respiratory system, not only the lung but also the upper airway (nose, mouth, pharynx, larynx, and trachea), chest wall and diaphragm, as well as the neuromuscular system that provides the power for breathing.
Our Lungs and Airways

Major features of lungs: bronchi, bronchioles and alveoli

OSA disorder is characterized by repetitive collapse of the upper airway
Basic Types of Respiratory Sounds

- **Normal Breath Sounds**
  - Normal vesicular sounds (100 – 1000 Hz)
  - Normal tracheal sounds (from <100 to >3000 Hz)

- **Adventitious Sounds**
  - Continuous sounds (e.g. Wheezes)
  - Discontinuous sounds (e.g. Crackles)

- **Upper Airway Sounds**
  - Snore
Wearable Respiratory Monitoring: Algorithms and System Design

Motivations & Problem Formulation
Why Monitor Respiratory Disorders?

- Common and important cause of illness and death
- Can affect people of all ages, both genders
- 300 million people suffer from Asthma and 210 million people with COPD (2007), world-wide
- Responsible for over 10% of hospitalizations & over 16% of deaths in Canada (including lung cancer)
- 1 in 7 in UK affected by chronic lung disease
Wearable Respiratory Monitoring: Algorithms and System Design

Market / Commercialization Potential

U$ (billions)

Respiratory Devices

COPD

Source: GlobalData Report
Wheezing is a common noise in respiratory disorders

Prevalence of Childhood Asthma:
* 10% - 20% (varies with countries)

Adult Asthma:
* 12%
  - USA
    - 23 million Asthmatics

Adult COPD:
* 5%
  - Over 15 million cases of COPD
Wheeze Monitoring

Values

- Accurate detection and assessment of wheezes → prompt diagnosis & appropriate treatment of Asthma, COPD, etc,
- Improved symptom (wheeze) control → reduced hospitalization → healthcare savings

How (Current Clinical Methods)

- Auscultation using a stethoscope
- Based on history - patient recall or asthma diary or audio or audio-visual recording by patients
Problem of Wheeze Monitoring

Auscultation with stethoscope is subjective, not for long-duration monitoring

History of occurrence is important but patients’ descriptions are often subjective with limited accuracy

Wheeze often occur at night; Intermittent wheezes are not easily monitored at night
The System Needed

- A screening system that records and analyzes wheezes over an extended duration of time
- A simple and robust system suitable for both clinical and home use
- A system that allows the patient to use at anywhere and anytime - hence no skin contact, no external wirings that restrict movements

→ Non-Skin Contact Wearable System
Wearable Respiratory Monitoring: Algorithms and System Design

III

Wearable Wheeze Monitoring System @ NTU

Overall System Design
Overview of our Solutions

- Wearable wheeze detection and recording system with Signal Analysis Tools for physicians

PI: A/Prof. W Ser (NTU) and A/Prof. Daniel YT Goh (NUH)
Funded by A*STAR & MOE
Wearable System Design

- Respiratory sounds (lung, tracheal) are recorded by sound sensors (stethoscopes or air-conductance microphones)
- Sensor outputs are band-passed, amplified, sampled, and segmented.
- A low-complexity algorithm is applied to detect presence of wheezes
- Segments with wheezes are recorded & their severity estimated; respiratory & heart rates are estimated too
Signal Analysis Tools (SAT)

- Data (wheezing sounds) recorded in wearable suite are further processed by the SAT.
- The SAT has several functions:
  - Signal manipulation
  - General signal processing
  - Respiratory signal analysis
- The SAT can also be used for training purposes.

Respiratory Signal Analysis

- Respiratory parameters
  - Amplitude & periodicity of wheeze, Wheeze length in a breathing cycle, etc.
- Physiological parameters
  - Types of wheeze (monophonic or polyphonic, inspiration or expiration, etc.), changes in severity after treatment, Wheeze location, etc.

- Signal copy, cut, paste
- Signal amplification
- Labeling
- Filtering
- Segmentation
- Signal Energy Analysis
- Power Spectral Analysis
- Pitch Analysis
- Format Analysis
- Zero-Crossing Analysis
- Classification

- Respiratory parameters
- Physiological parameters

The SAT can also be used for training purposes.
Problems and Challenges I

- Sound based design sensitive to external audio noise
  - How sensors are placed on wearable suite important
  - Need filter and noise reduction algorithms

- Wearable → power and packaging constraint
  - Need to operate at low sampling rates
  - Need low complexity processing algorithms
  - Need low-power platform (processor)
  - Only small dry batteries allowed
  - No external wiring
Problems and Challenges II

- Unsupervised wearing and monitoring
  - Need to design for ease of wearing
  - Need to use multiple sensors
  - Cannot have air-gap between sensors and body

- Different sizes of wearers
  - Need flexible length of suite fastening
  - Need a few sizes

Wearable Respiratory Monitoring: Algorithms and System Design
Wearable Respiratory Monitoring: Algorithms and System Design

Wearable
Wheeze
Monitoring
System @ NTU

Wearable Signal Processing Algorithms
Types of Wheeze Detection Algorithms

- Time-domain methods (waveform analysis, Kurtosis, zero-crossing rate …)
- Frequency-domain spectral analysis methods
- Time-frequency analysis (peak detection)
- Pattern recognition approach
- etc.
Wearable Respiratory Monitoring: Algorithms and System Design

Spectral Analysis Methods

- $f_1$ to $f_2$: Wheeze frequencies
- $P_{\text{ave}}$: Average power in $f_1$ to $f_2$
- $A_f$: Scaling factor ($= 15$)

- Wheeze Detection Criteria:
  - $> f_1$ and $> A_f \times P_{\text{ave}}$

- Results: (5 Asthmatic and 2 normal teenagers): < 2% for false +ve and false -ve

Pattern Recognition Methods

- Typically 3 stages: Feature extraction → Dimensionality reduction → Pattern classification.

- **Commonly used Features:**
  - MFCC, LPC, AR model, Wavelet coefficients, etc.

- **Dimensionality Reduction Algorithms:**
  - SVD, PCA, etc.

- **Classification Methods:**
  - k-NN Classifier, DTW, VQ, NN, HMM, etc.
Pattern Recognition Methods (Example 1)

- Use Wavelet Packet Decomposition for feature extraction
- Use Learning Vector Quantization for classification

<table>
<thead>
<tr>
<th>Sample</th>
<th>True positives</th>
<th>False positives</th>
<th>False negatives</th>
<th>Sensitivity (%)</th>
<th>Positive predictivity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>48</td>
<td>19</td>
<td>11</td>
<td>81.4</td>
<td>71.7</td>
</tr>
<tr>
<td>W2</td>
<td>15</td>
<td>83</td>
<td>5</td>
<td>75.0</td>
<td>15.4</td>
</tr>
<tr>
<td>W3</td>
<td>34</td>
<td>54</td>
<td>15</td>
<td>66.7</td>
<td>38.7</td>
</tr>
<tr>
<td>W4</td>
<td>34</td>
<td>64</td>
<td>61</td>
<td>35.8</td>
<td>34.7</td>
</tr>
<tr>
<td>Total</td>
<td>131</td>
<td>220</td>
<td>92</td>
<td>58.7</td>
<td>37.3</td>
</tr>
</tbody>
</table>

Results \{ Sensitivity = TP / (TP + FN); Positive predictivity = TP / (TP + FP) \}

L. Pesu, P. Helistö, E. Ademovic, J.-C. Pesquet, A. Saarinen and A.R.A. Sovijärvi,
Pattern Recognition Methods (Example 2)

- MFCC as Features: \( x_1, x_2, \ldots, x_D, D = 39 \)

- GMM based Classification: 
  \[
  \mu = E[\bar{x}]; \quad \Sigma = E[(\bar{x} - \mu)^T(\bar{x} - \mu)]
  \]

  - \( D \)-Variate Gaussian PDF: 
    \[
    p_i(\bar{x}) = \frac{1}{D} \exp\left\{ \frac{-(\bar{x} - \mu_i)^T \Sigma_i^{-1} (\bar{x} - \mu_i)}{2} \right\}
    \]

  - Weighted Sum of \( M \) Gaussian Densities: 
    \[
    p(\bar{x} | \lambda) = \sum_{i=1}^{M} w_i p_i(\bar{x})
    \]

  - Decision: 
    \[
    c = \arg \max_{1 \leq k \leq N} \prod_{t=1}^{T} p(\bar{x}_t | \lambda_k);
    \quad \text{wheeze is present} \quad \text{if} \quad c > 0
    \quad \text{no wheeze} \quad \text{if} \quad c \leq 0
    \]

Pattern Recognition Methods (Example 2)

- Results: More than 90% accuracy in Wheeze detection

Pattern Recognition Methods (Example 3)

- 4 Time and Frequency Domain Features, $x_1$ to $x_4$
- FDA (Fisher Discriminant Analysis) Classification
  - Mean vector: $m_j = \frac{1}{n_i} \sum_{x \in \Pi_j} x_i; j = 1, 2$
  - Find $w$ that maximizes $w^T (m_1 - m_2)$
  - Projection vector: $y_i = w^T x_i$
  - Neyman Pearson Hypothesis: Compare $y_i$ with $\tau$

Pattern Recognition Methods (Example 3)

- Results: 93.5% success rate

Problems of Existing Algorithms

Not accurate enough or computationally too expensive for wearable solutions

Our Approach

Review wheeze signal characteristics and attempt to derive simpler but effective methods that over-detect/record
Re-visiting Wheeze Signals

- Energy concentrates at well below 1000 Hz
- Contrasting energy distribution across frequency
- Typically, wheeze occurs only in part of a breathing cycle
Our Wheeze Detection Algorithm

- **Design goal:** 1 or 2 parameters, low complexity, robust, and suitable for wearable systems

- Received signals: \( s(t) = w(t) + n(t) \)
  - \( w(t) \): Wheeze signal
  - \( n(t) \): Non-wheeze signals (e.g. breath sound, noise)
Our Wheeze Detection Algorithm (Cont’d)

- **Short-Time Fourier Transform**

  \[
  S(\tau, f) = \int_{-\infty}^{+\infty} s(t) h^*(t - \tau) e^{-j2\pi ft} \, dt
  \]

  - \( h(t) \) is the window function, \( \tau \) is the time shift, and \( \ast \) is the complex conjugate operator.

- **Peak Detection by Masking**: For each STFT, determine moving thresholds and use them to select “peaks” (dominant values)

  \[
  S_a(n, f) = \frac{1}{L} \sum_{n=1}^{L} S(n, f)
  \]

  \[
  S_p(n, f) = \begin{cases} 
  S(n, f) - S_a(n, f) & \text{if} \quad S(n, f) - S_a(n, f) > 0 \\
  0 & \text{if} \quad S(n, f) - S_a(n, f) \leq 0 
  \end{cases}
  \]
Our Wheeze Detection Algorithm (Cont’d)

- **Entropy based Feature Extraction**: Assuming there are \( N \) dominant components, \( C_1, C_2, \ldots, C_N \), in \( S_p(n,f) \), calculate

\[
p_n = \frac{c_n}{\sum_{n=1}^{N} c_n}, \quad n = 1, 2, \ldots, N
\]

- **Entropy** can be calculated as

\[
E = -\sum_{n=1}^{N} p_n \log_b(p_n)
\]

- **Smoothed Entropy (by averaging filtering)**

\[
E_a = \frac{1}{M} \sum_{t=1}^{M} E_t
\]

- **Features** can be extracted as, for example,

\[
E_{ratio} = \max(E_a) / \min(E_a)
\]

\[
E_{diff} = \max(E_a) - \min(E_a)
\]
Our Wheeze Detection Algorithm (Cont’d)

- **Wheeze detection:**

  - Set $T_{ratio}$ and $T_{diff}$ as the thresholds for $E_{ratio}$ and $E_{diff}$.

  - Presence of wheeze can be decided by (for example)

    Wheeze is present if $E_{ratio} > T_{ratio}$ and $E_{diff} > T_{diff}$

    No Wheeze if $E_{ratio} < T_{ratio}$ and $E_{diff} < T_{diff}$

    Unable to determine *Otherwise*
Our Wheeze Severity Estimation Algorithm

- $E_{ratio}$ or $E_{diff}$ are computed once every 3 seconds
- Severity Score = Number of positive detections in 1 minute
Our Respiratory Rate Estimation Algorithm

- Rate estimated from second peak of autocorrelation
Wearable Respiratory Monitoring: Algorithms and System Design

Wearable Wheeze Monitoring System @ NTU

Wearable Sensors & Platform Suite
Our Inward- & Outward- Hearing Sensing Designs

Medical Knowledge

Outward-hearing Microphone Array

Wearable Suite

Sound Sensors

Inward-hearing Distributed Sensors

Medical Knowledge + Sound Sensors

Outward-hearing Microphone Array

Wearable Suite
Wearable Wheeze Detection System

Version #1: Microphone Array, Sampling (1K, 12-bit)

DSP based System

- TMS320C6713 DSP board
- 4-channels Microphone Array (amplifier and filter included)
- LED Indicators

Experimental Set Up

- Notebook for Playing Sounds
- Speaker
Wearable Wheeze Detection System
(Version #2: PDA based, 2-microphone design)

PDA based System

- NI CF6004 DAQ
- 15-pin Compact Flash connector
- Microphones (head phone)
- Signal conditioning
- PDA (HP iPAQ hx2700 series)
- Wheeze and Snore Indicators
- Waveform display

Health Condition Monitor
- ai cont buffered
- Samples Per Channel: 3000
- File Name: soundrecord
- X: 200-400 0.00
- Y: 400-500 0.00
- Sound Condition
- Wheeze and Snore Indicators
- Parameter Set
- Waveform display
Wearable Wheeze Acquisition System
(Version #3: Embedded Processor based System)

Signal Conditioning

NI Daq

Signal conditioning

4-channel modified stethoscopes or microphones

Font View of Wearable Suite

Notebook for experimental control
Wearable Respiratory Monitoring: Algorithms and System Design

Sensors and Placements of Sensors

**Inward-looking system**
- Stethoscope is modified by replacing long acoustic tube with a microphone and wire
- Microphone based system uses special acoustic coupler design
- 4 distributed sensors: tracheal, left lung, heart, and right lung

**Outward-looking system**
- 4-channel microphone array design
- End-fire array configuration
Bandpass Filter, ADC, Platform

- The bandpass filter is designed to have a bandwidth of up to 1 KHz (without DC)
- The ADC has a sampling rate of 2 KHz and a resolution of 10 bits
- The platform uses one MSP430 chip for each channel (for 4 channels)
- The selected sounds are stored in a micro SD card
### Data Processing & Recording

#### 1 Recording Cycle

<table>
<thead>
<tr>
<th>ADC 1</th>
<th>Data Block (3 sec)</th>
<th>Data Block (3 sec)</th>
<th>Data Block (3 sec)</th>
<th>Data Block (3 sec)</th>
<th>Data Block (3 sec)</th>
<th>Data Block (3 sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC 2</td>
<td>Data Block (3 sec)</td>
<td>Data Block (3 sec)</td>
<td>Data Block (3 sec)</td>
<td>Data Block (3 sec)</td>
<td>Data Block (3 sec)</td>
<td>Data Block (3 sec)</td>
</tr>
<tr>
<td>ADC 3</td>
<td>Data Block (3 sec)</td>
<td>Data Block (3 sec)</td>
<td>Data Block (3 sec)</td>
<td>Data Block (3 sec)</td>
<td>Data Block (3 sec)</td>
<td>Data Block (3 sec)</td>
</tr>
<tr>
<td>ADC 4</td>
<td>Data Block (3 sec)</td>
<td>Data Block (3 sec)</td>
<td>Data Block (3 sec)</td>
<td>Data Block (3 sec)</td>
<td>Data Block (3 sec)</td>
<td>Data Block (3 sec)</td>
</tr>
</tbody>
</table>

**Used for Processing**

(Wheeze Detection)

**Used for Processing**

(Wheeze Detection)
IV

Lab Tests, Pre-Clinical Trials, Results
Results of Wheeze Detection (Downloaded Data)

- At SNR = 2dB, 80% of Sensitivity & Specificity have been achieved (9 wheezy samples and 6 normal samples)
  - Sensitivity = \( \frac{TP}{TP + FN} \times 100\% \); Specificity = \( \frac{TN}{TN + FP} \times 100\% \)
Results of Wheeze Detection (Pre-Clinical Trial)

- **Data Collection at National University Hospital, Singapore**
- **More than 80 samples have been collected**
- **Performance:** Sensitivity > 85%; Specificity > 70%
# Results of Severity Estimation Algorithm (Pre-Trial)

<table>
<thead>
<tr>
<th>Samples</th>
<th>Severity Scores</th>
<th>Doctor’s Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>No Wheeze</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>Low</td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>Low</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>Low</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>Low</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>Low</td>
</tr>
<tr>
<td>8</td>
<td>95</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Results of Respiratory Rate Estimation (Pre-Trial)
Conclusions and Future Work
Conclusions & Future Work

- Wearable sound based sensing (+ PC signal analysis) can be effective for automatic wheeze detection.
- Sensitivity higher than 85% and specificity above 70% have been achieved using our algorithm/system for data collected from some real patients (more data are needed to validate the results).
- Future work includes extensive clinical trials and studies on other types of respiratory disorders.
Some of our Research Publications

Some other References

Some other References (Cont’d)

- Patents and product information of KarmelSonic Products
- School of Medicine, University of California at Davis, USA, Review of Lung Sounds. [Online] [http://medocs.ucdavis.edu/IMD/420C/sounds/lngsound.htm](http://medocs.ucdavis.edu/IMD/420C/sounds/lngsound.htm)
Thank You

Questions or Comments?