Exploring Health and Wellness through Respiratory Sensing

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Work done with
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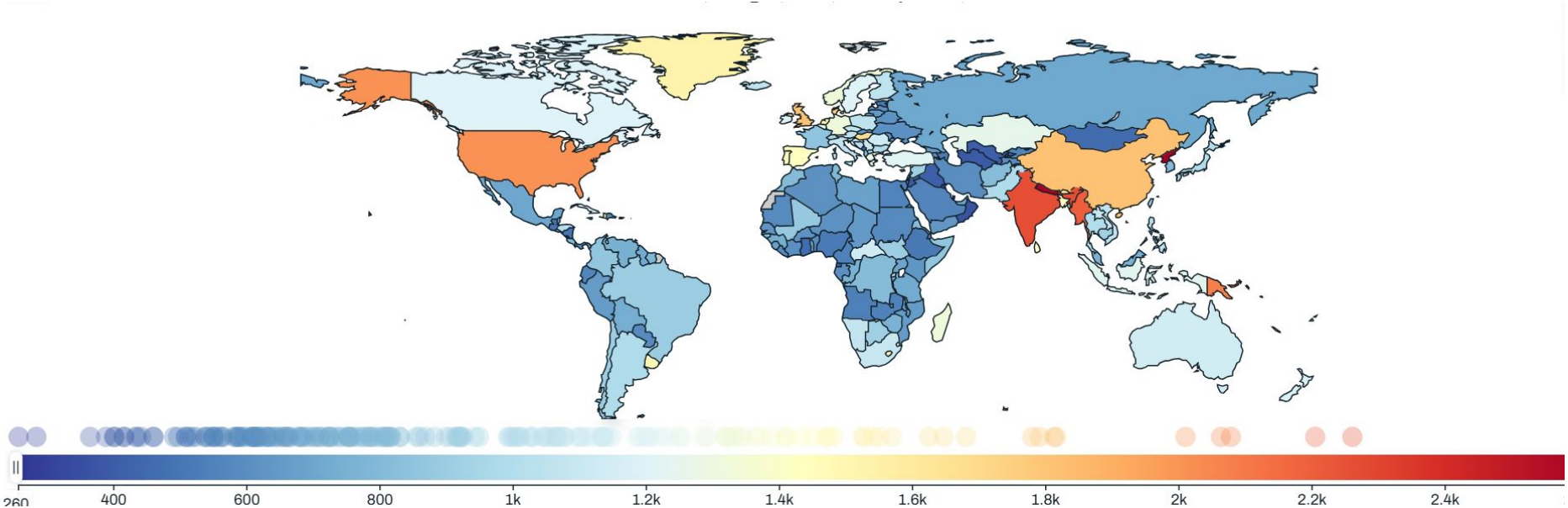
SUSTAINABILITY LAB

Background



Chronic Respiratory Disease, Both Sexes, All Ages, DALYs per 1000,000

Source: Global Burden of Disease, Healthdata.org

Respiration Rate

- The number of breaths you take per minute.
- It is an important biomarker to diagnose respiratory illness.*

Strauß, Richard, et al. "The prognostic significance of respiratory rate in patients with pneumonia: a retrospective analysis of data from 705 928 hospitalized patients in Germany from 2010–2012." *Deutsches Ärzteblatt International* 111.29-30 (2014): 503.

Respiration Rate

- In patients, unrecognized changes in respiration rate is associated with poorer health outcomes.*

Disease/Condition	Biomarker
Stress, [Ref], Anxiety [Ref]	> 25 BrPM
Pneumonia [Ref]	> 30 BrPM
Cardiopulmonary arrest [Ref]	> 27 BrPM
COVID-19	Irregular breathing

*Cretikos, Michelle A., et al. "Respiratory rate: the neglected vital sign." Medical Journal of Australia 188.11 (2008): 657-659.

Respiration Rate

Respiration rate is hardly monitored in clinical or home setting.*

A doctor in a clinic monitors blood pressure, temperature but not respiration rate. Credit: Firstpost

*Cretikos, Michelle A., et al. "Respiratory rate: the neglected vital sign." Medical Journal of Australia 188.11 (2008): 657-659.

Respiration Rate

Respiration monitoring is missing from consumer wearables.

We investigated techniques to sense breathing and using that information for **wellness** and **diagnosis**.

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Wellness

- **JoulesEye:** Energy Expenditure Estimation and Respiration Sensing from Thermal Imagery While Exercising [ACM IMWUT'24]

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Wellness

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Diagnosis

- **ApneaEye:** Thermal Imaging for Lightweight and Accurate Sensing of Sleep Apnea. [Under Review, ACM IMWUT 2025]
- **Spiromask:** Measuring Lung Function Using Consumer Grade Mask [ACM HEALTH'23]

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What is Energy Expenditure?

- Amount of energy that an individual expends or uses during various activities - **Energy Expenditure (EE)**.

Gold standard of measuring Energy Expenditure

- **Indirect calorimeters** measure energy expenditure by analyzing oxygen consumption and carbon dioxide production during respiration.

A participant wearing the indirect calorimeter, chest belt and a smartwatch (not visible in the frame)

Gold standard of measuring Energy Expenditure

- **Indirect calorimeters** measure energy expenditure by analyzing oxygen consumption and carbon dioxide production during respiration.
- $E = f(HR, SV, \Delta_{av}O_2, \gamma)$
  - HR: Heart Rate **(bpm)**
  - SV: Stroke Volume **(l)**
  - $\Delta_{av}O_2$: Net difference of oxygen content between aorta and vein. **(l_{02}/l_b)**
  - γ: Oxygen to Energy Coeff **(Kcal/l)**

A participant wearing the indirect calorimeter, chest belt and a smartwatch (not visible in the frame)

Fitness tracking via Smartwatches

- Step count
- Heart rate
- Energy Expenditure (or calories burned)

Fitness tracking via Smartwatches

- Smartwatches' estimates of energy expenditure are typically about **37%** off when compared to measurements from an indirect calorimeter.*

*Wrist-worn wearables for monitoring heart rate and energy expenditure while sitting or performing light-to-vigorous physical activity: validation study by Duking et al. JMIR mHealth and uHealth 8, 5 (2020).

Fitness tracking via Smartwatches

- Smartwatches rely on heart rate for fitness monitoring.
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Smartwatches compared to Indirect Calorimeter

Smartwatches

Indirect calorimeter

- Inaccurate EE estimation
- Does not monitor O_2
- Relies on Heart Rate to measure EE

- Accurate EE estimation
- Monitors O_2 concentration

Smartwatches compared to Indirect Calorimeter

Smartwatches

JoulesEye

Indirect calorimeter

- Inaccurate EE estimation
- Does not monitor O_2
- Relies on Heart Rate to measure EE

- More accurate than smartwatch
- More practical to use compared to calorimeter

- Accurate EE estimation
- Monitors O_2 concentration


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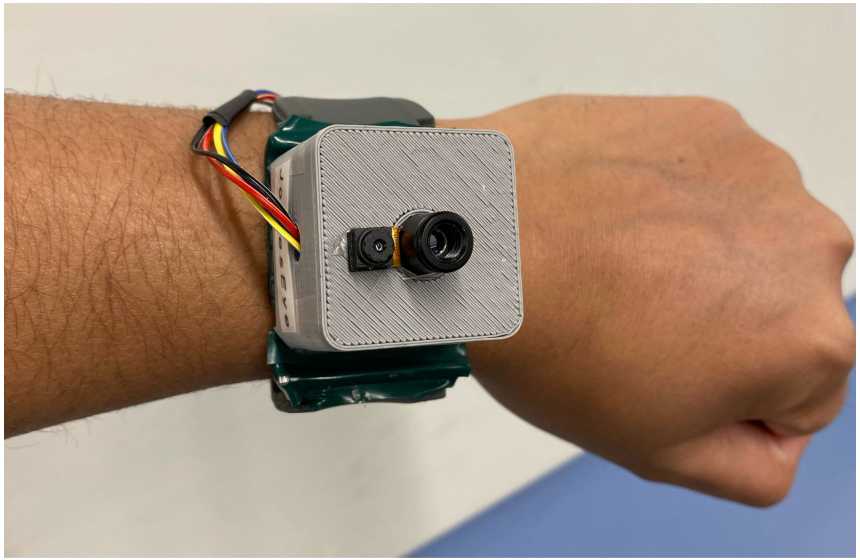
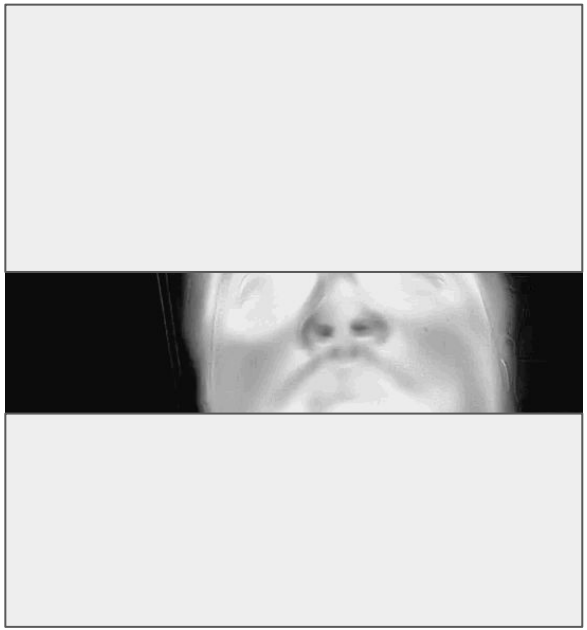


Thermal camera for sensing respiration while exercising

The respiratory rate is identified by monitoring temperature changes in the airways caused by the flow of air.



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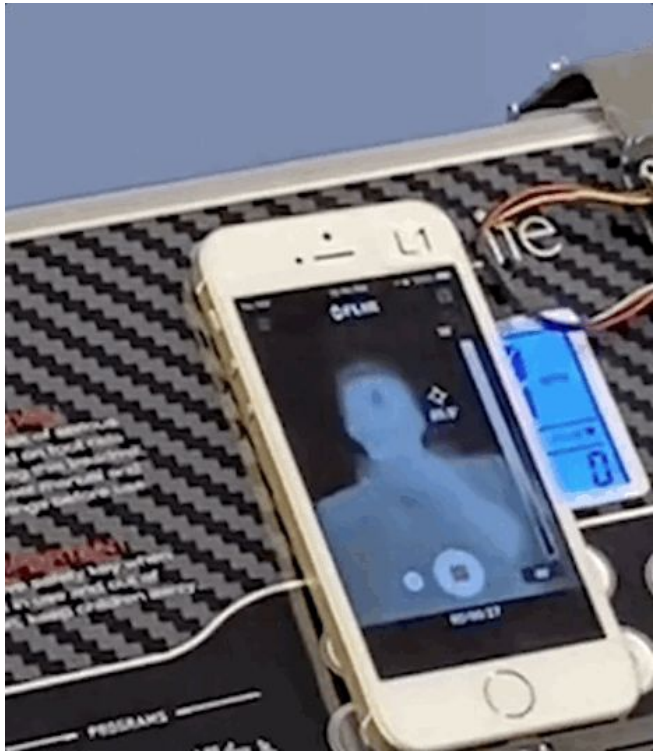
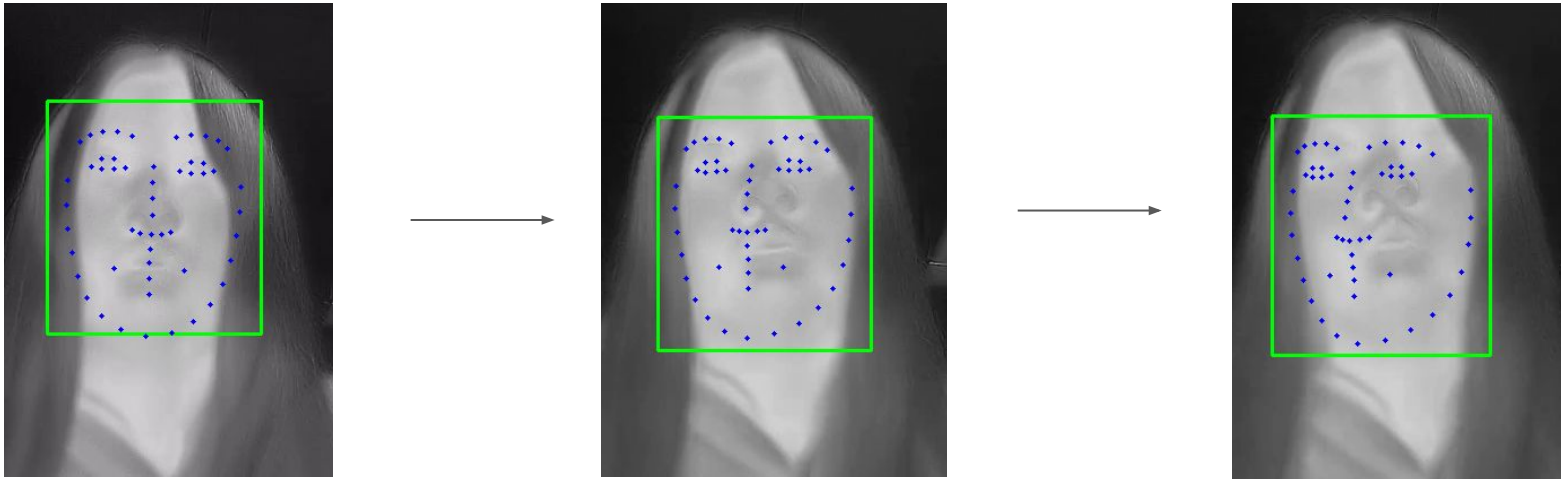


Thermal camera for sensing respiration while exercising

Sensing respiration during vigorous motion is a challenge.

- Localising nostrils does not always work.*



*Kuzdeuov, Askat, et al. "Sf-tl54: A thermal facial landmark dataset with visual pairs." *2022 IEEE/SICE International Symposium on System Integration (SII)*. IEEE, 2022.

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Sensing respiration during vigorous motion is a challenge.

- Optical flow fails in thermal domain.*

*Harley, Adam W., Zhaoyuan Fang, and Katerina Fragkiadaki. "Particle video revisited: Tracking through occlusions using point trajectories." *European Conference on Computer Vision*. Cham: Springer Nature Switzerland, 2022.

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- Discriminative Correlation Filter with Spatial Reliability (DCF)*

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From respiration to energy expenditure

- We first estimate the volume of exhaled air (v) from Respiration Rate.
- Next, we use the estimated volume information (v) to estimate the Energy Expenditure.

JoulesEye: User study

Total Participants	54
Participants who performed cycling on ergometer	41
Participants who performed running on treadmill	13
Female (n, %)	24, (44.4%)
Age (in years) (mean, range)	28.4 (25-54)

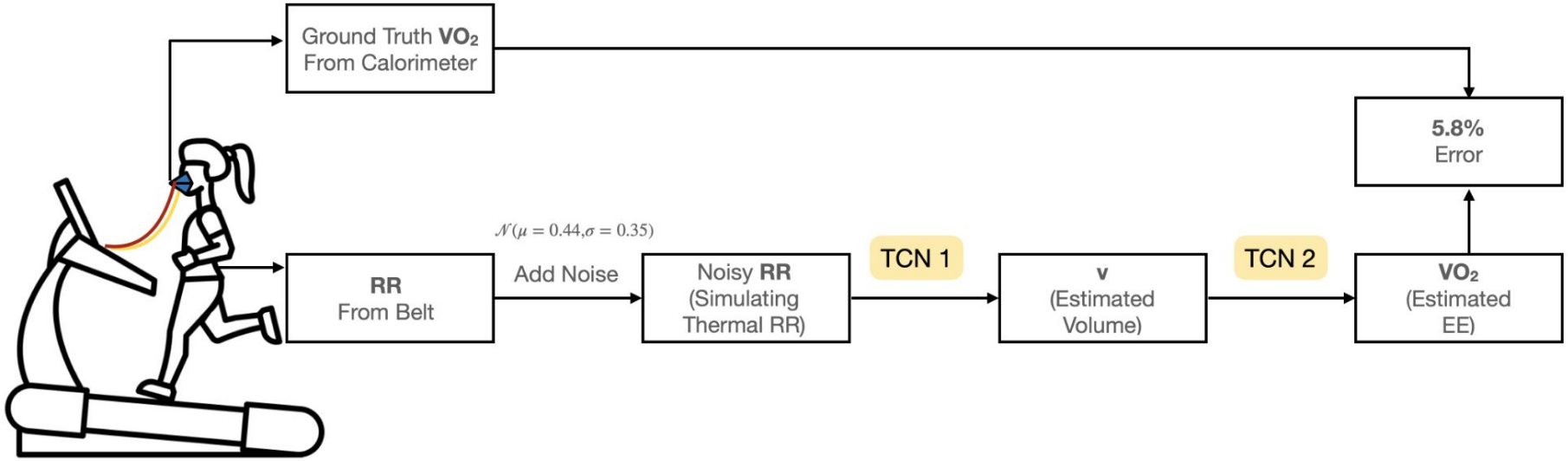
JoulesEye: User study

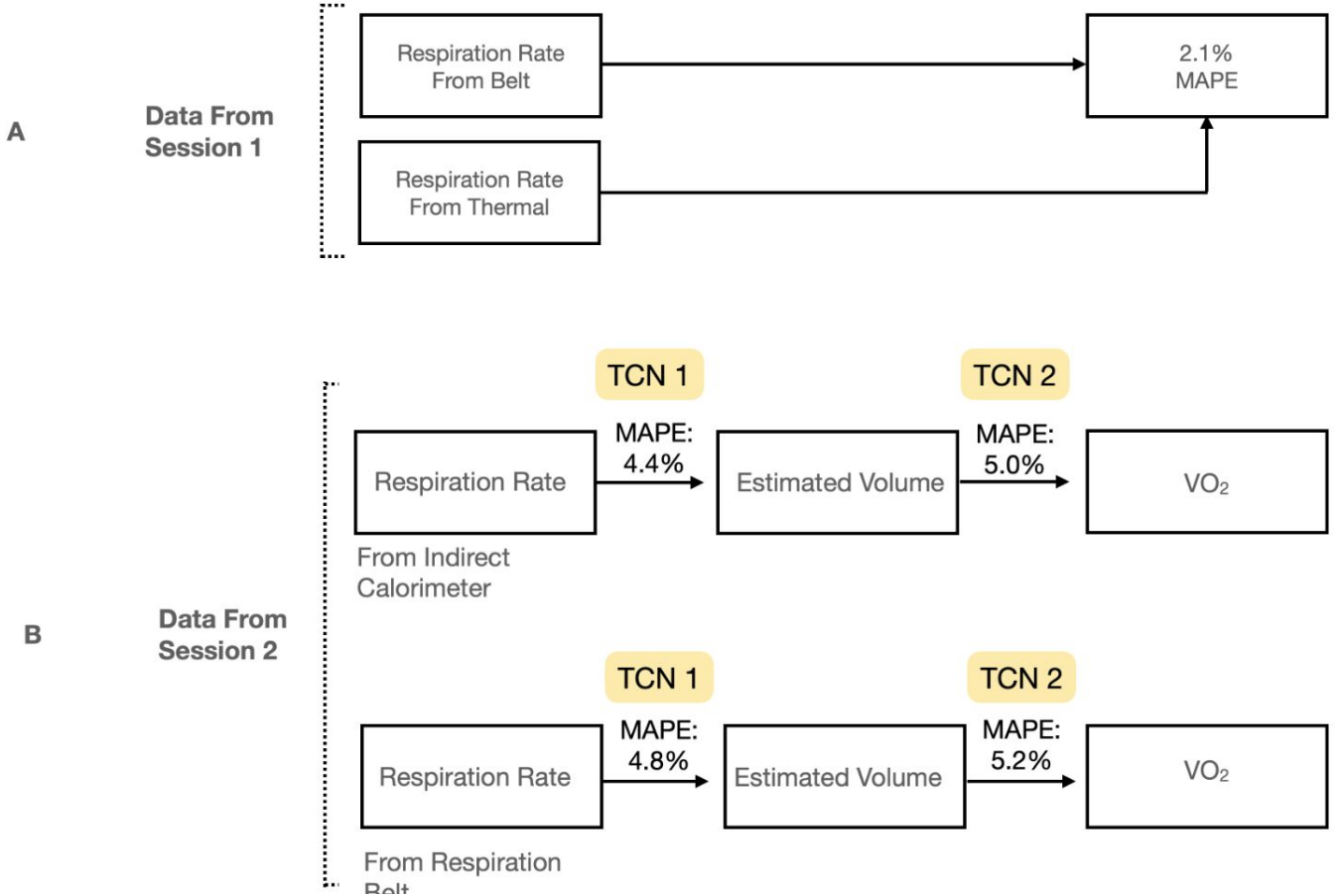
- 2 sessions per user

a)

b)

JoulesEye: User study




A
Data From Session 1
Respiration Rate From Belt
Respiration Rate From Thermal
2.1% MAPE
B
Data From Session 2
TCN 1
TCN 2
Respiration Rate
MAPE: 4.4%
Estimated Volume
MAPE: 5.0%
VO2
From Indirect Calorimeter
TCN 1
TCN 2
Respiration Rate
MAPE: 4.8%
Estimated Volume
MAPE: 5.2%
VO2
From Respiration Belt

JoulesEye: Results

Displayed Energy Expenditure

MAPE: **37.6 %**

- Our observation is similar to prior study.*
- MAPE is Mean Absolute Percentage Error

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JoulesEye: Results

→ **Respiration Rate**

From Thermal Camera

→ ***JoulesEye*** **Model**

→ MAPE: **5.8 %**

JoulesEye performs better for participants with varied Body Mass Index (BMI)

	All Participants	**Participants With Normal BMI**	**Participants With Overweight BMI**
Error (Commercial Smartwatch)	37.6%	29.7%	51.8%
Error (*JoulesEye*) with RR	5.8%	5.2%	6.9%

JoulesEye with low resolution thermal camera

Input Data	**Error on estimated EE**
RR from 256p thermal	5.8%
RR from 24p thermal	15.4%
RR from 24p thermal and HR	10.1%

JoulesEye can be integrated into smartwatches

- 24p resolution thermal camera in a watch prototype.

JoulesEye: Energy Expenditure Estimation and Respiration Sensing from Thermal Imagery While Exercising

Summary

- Respiration Rate combined with heart rate gives a better estimate energy expenditure.

- Conventional fitness trackers may have a poor performance in estimating energy expenditure for people with abnormal BMI. *JoulesEye* performs better when compared to other fitness trackers.

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Wellness

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Diagnosis

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Why attempt to improve the state of diagnosis in India?

- 70% of the rural Community Health Centres (CHCs) lack the full range of specialists.
- 83% of them operating without surgeons.
- **82% are without physicians.**
- Urban CHCs too are facing a 45% shortfall in specialist availability.

Source: Health Dynamics of India (Infrastructure and Human Resources) 2022-23- MoHFW, GoI

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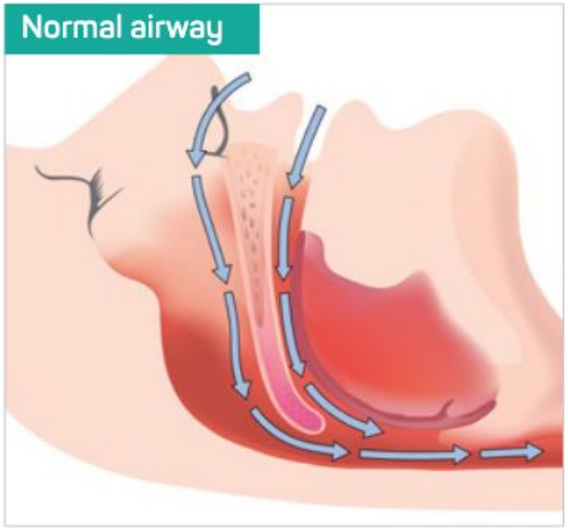


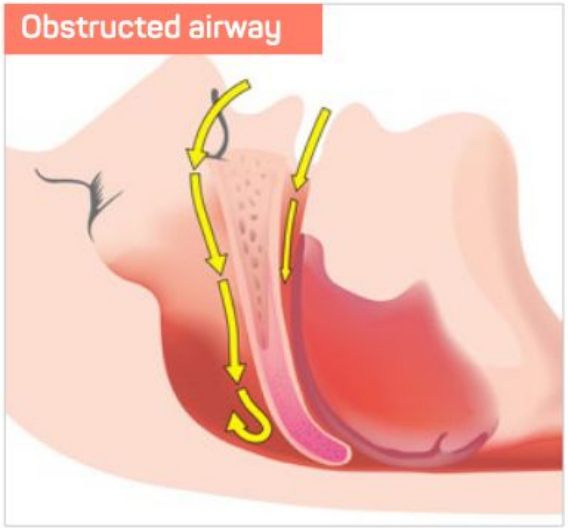
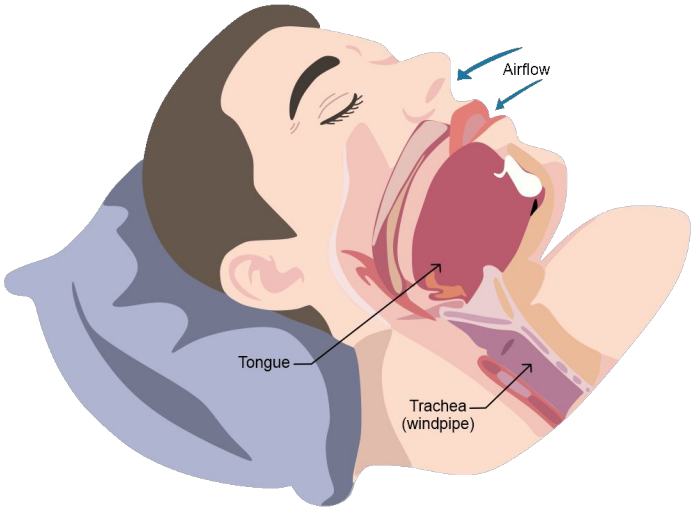


Image Source: SleepEducation.Org

What is sleep apnea?

- Sleep apnea is a disorder characterized by pauses in breathing or shallow breaths during sleep.



Normal Breathing

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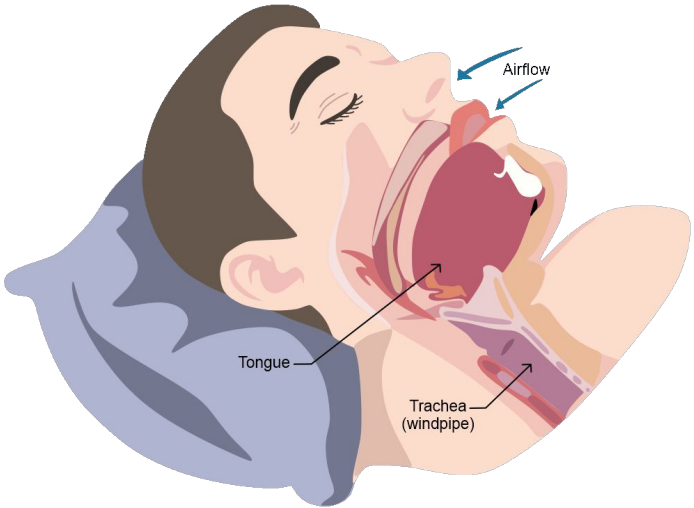

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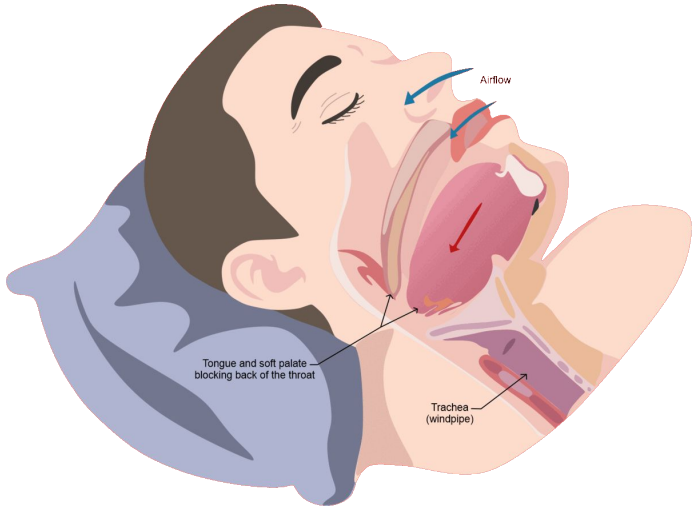
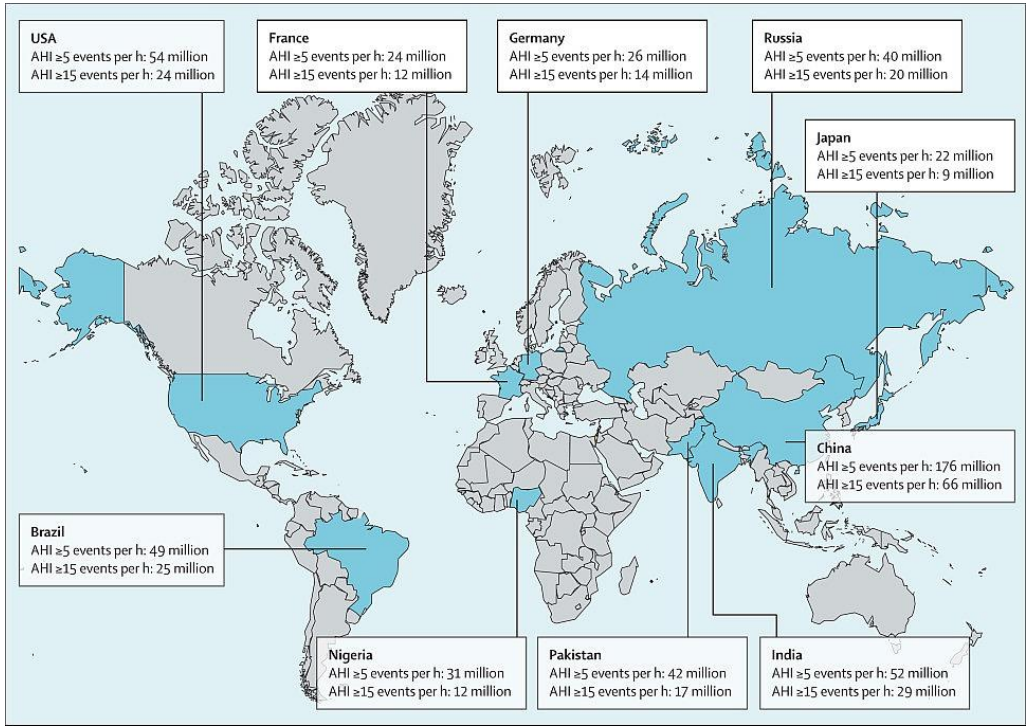


Obstructive Sleep Apnea

Image Source: SleepEducation.Org

Sleep apnea is a global problem

- **One billion people** suffer from sleep apnea.*



Source: "*Estimation of the global prevalence and burden of obstructive sleep apnoea: a literature-based analysis*" - Lancet Respiratory Medicine, 2019

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Sleep apnea is a global problem

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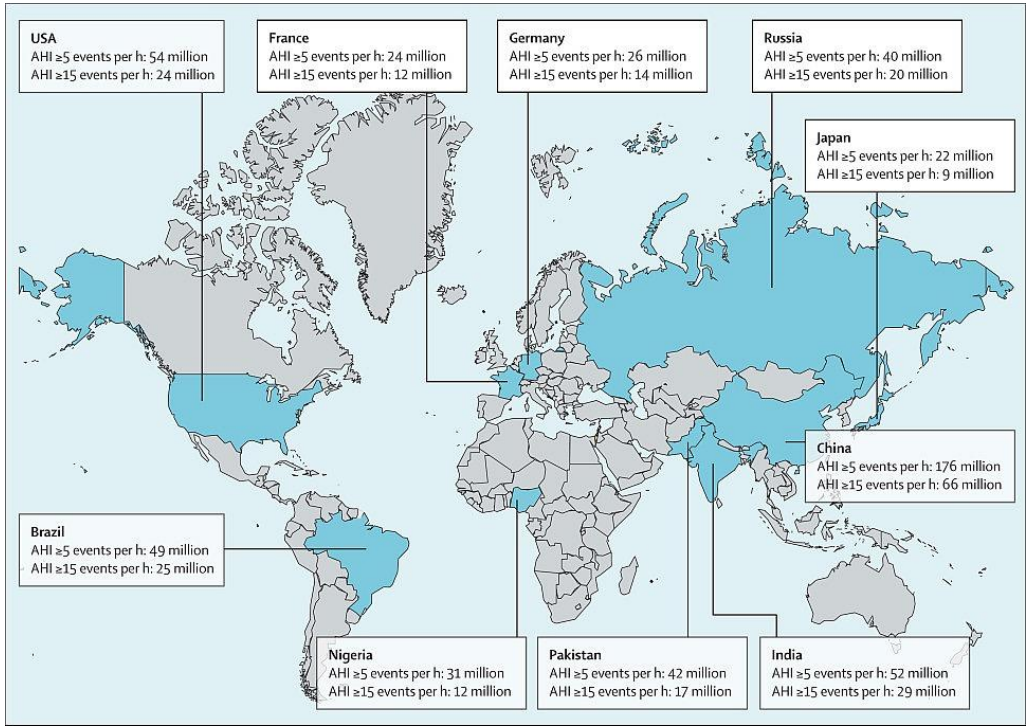
- A vast majority of cases of sleep apnea (more than 80%) remain undiagnosed.*

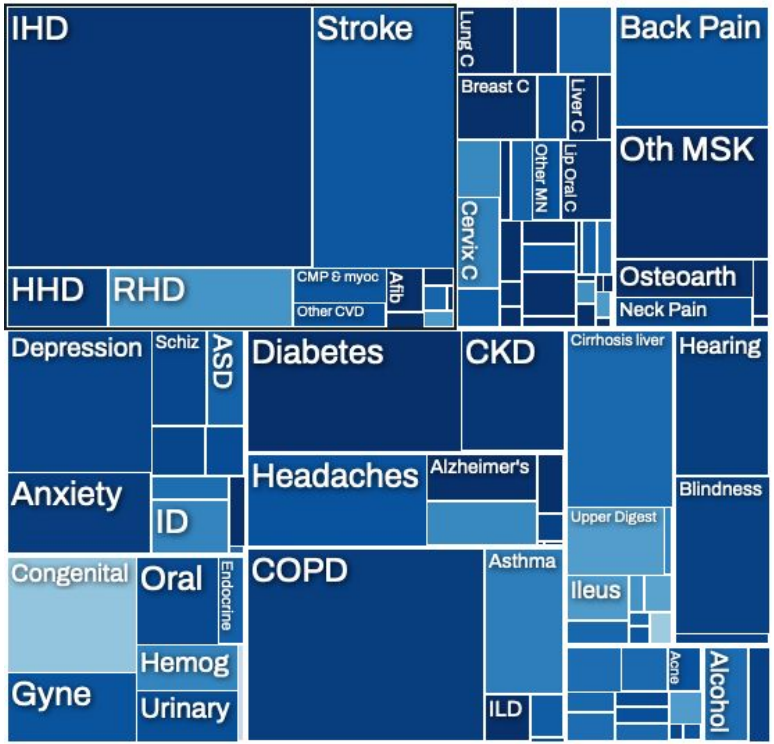


Source: "*Estimation of the global prevalence and burden of obstructive sleep apnoea: a literature-based analysis*" - Lancet Respiratory Medicine, 2019

*Kapur VK, Auckley DH, Chowdhuri S, et al. Clinical Practice Guideline for Diagnostic Testing for Adult Obstructive Sleep Apnea: An American Academy of Sleep Medicine Clinical Practice Guideline. J Clin Sleep Med. 2017;13(3):479-504.

What are the risks associated with not identifying and treating sleep apnea?

- Cardiovascular Disease*
- Metabolic dysfunction
- Impaired brain function
- Depression



Source: Global Burden of Disease, healthdata.org

* Shamsuzzaman, Abu SM, Bernard J. Gersh, and Virend K. Somers. "Obstructive sleep apnea: implications for cardiac and vascular disease." Jama 290.14 (2003): 1906-1914.

How is sleep apnea diagnosed?

- Polysomnography Test
- Multitudes of Sensor

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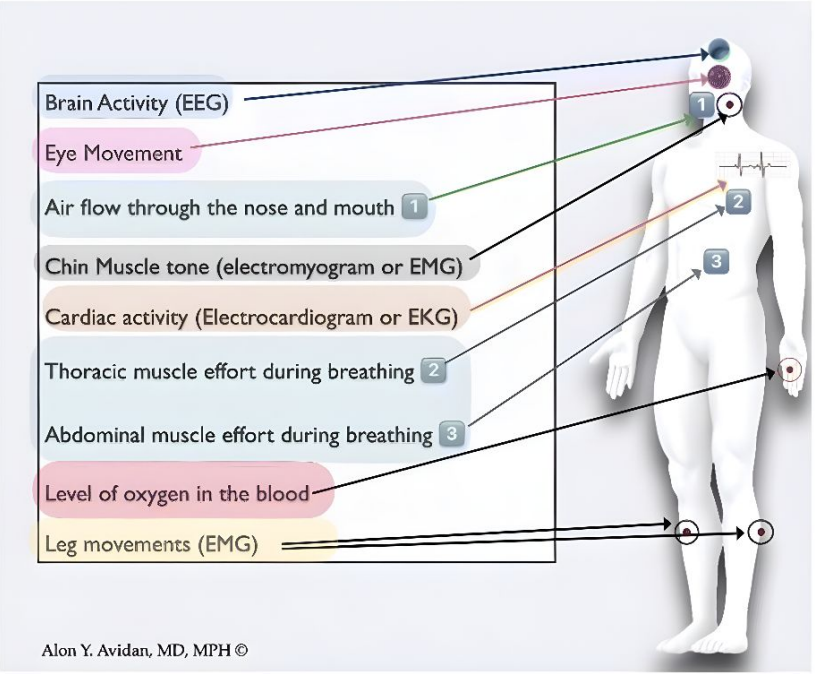

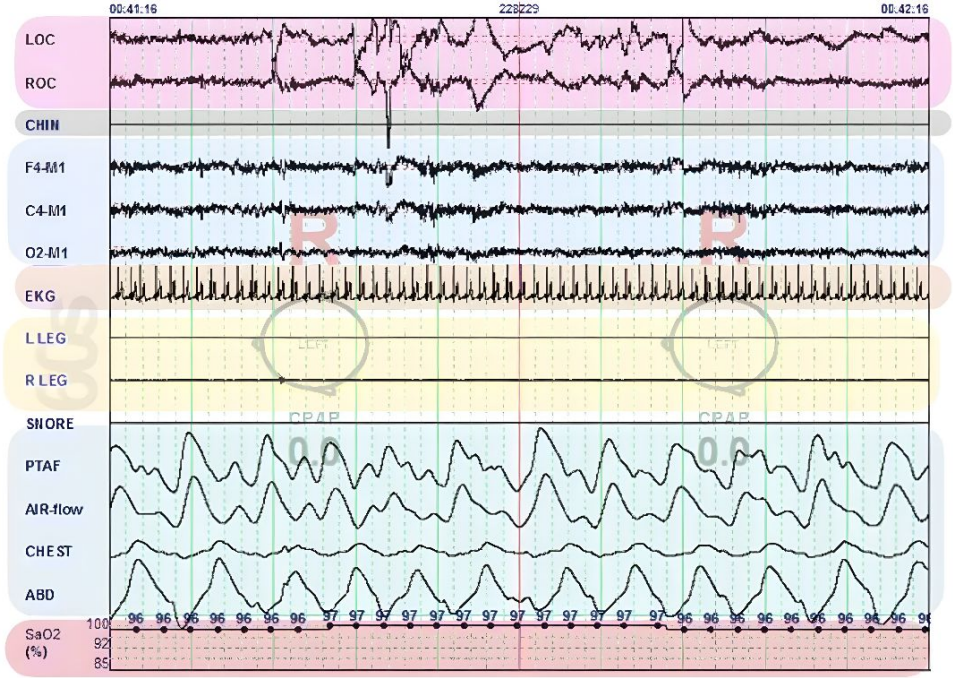

Source: Markun, Leslie C., and Ajay Sampat. "Clinician-focused overview and developments in polysomnography." *Current sleep medicine reports* 6 (2020)

American Association of Sleep Medicine (AASM) Guidelines

Sleep apnea should be diagnosed with

- Nostril airflow signal **and**
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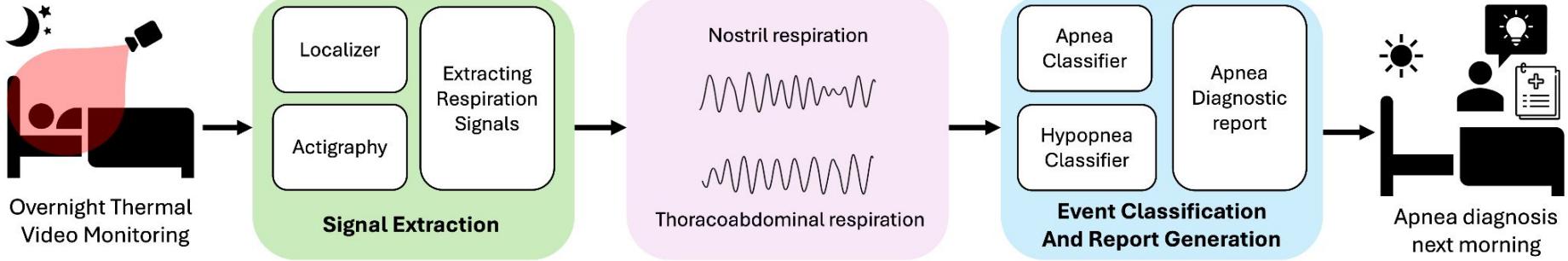

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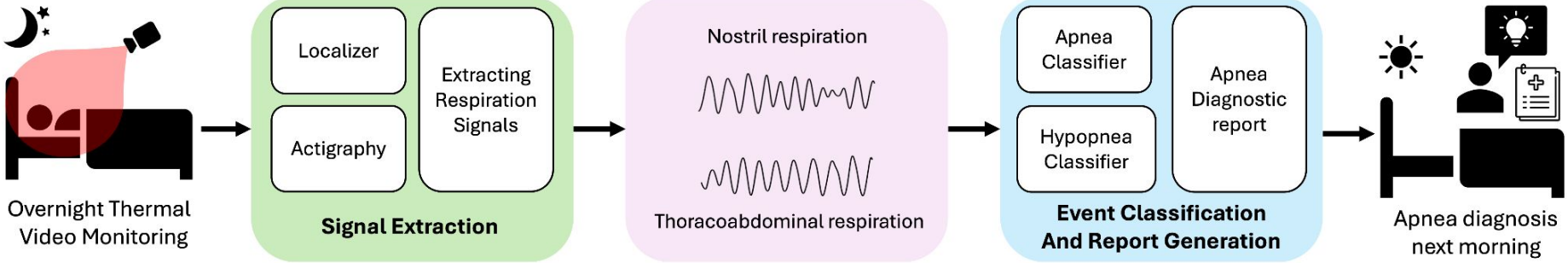
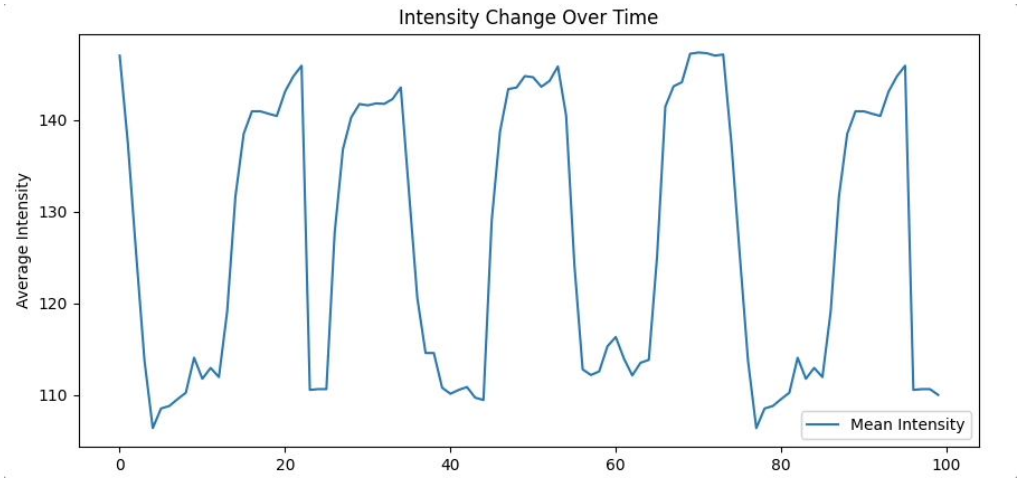
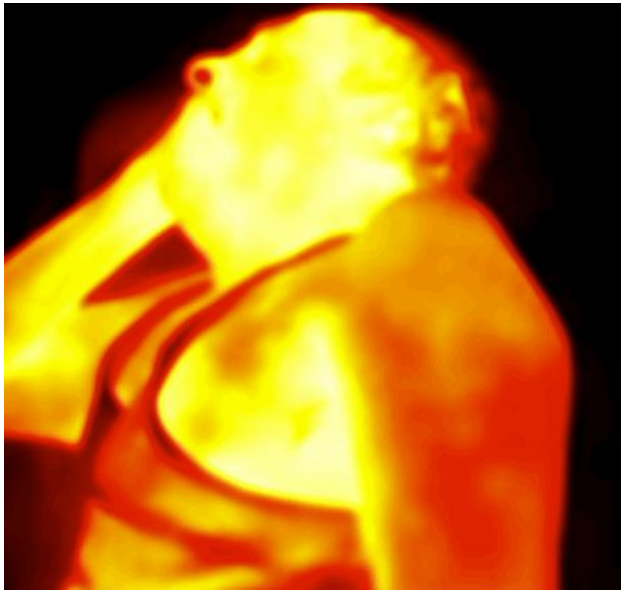


ApneaEye: Thermal Imaging for Lightweight and Accurate Sensing of Sleep Apnea.

Temperature change in nostril is visible in thermal imagery





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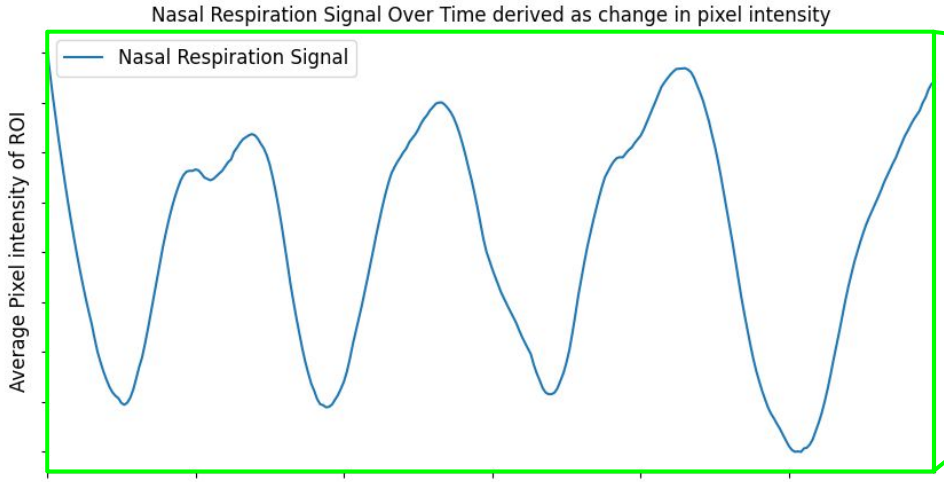

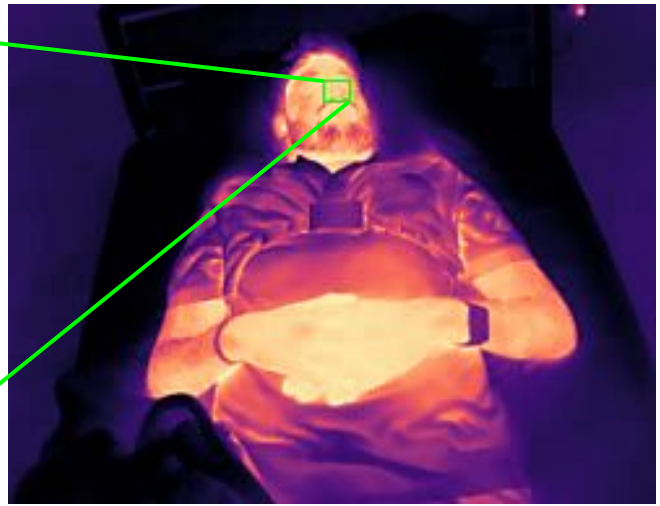

Temperature change in nostril is visible in thermal imagery

Left Position

Supine Position

Right Position

Technical Challenge: Sensing Thorax-Abdomen Movement

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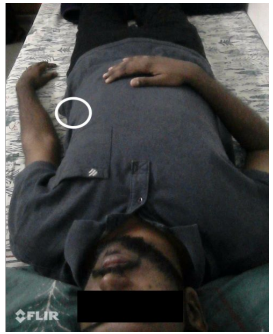

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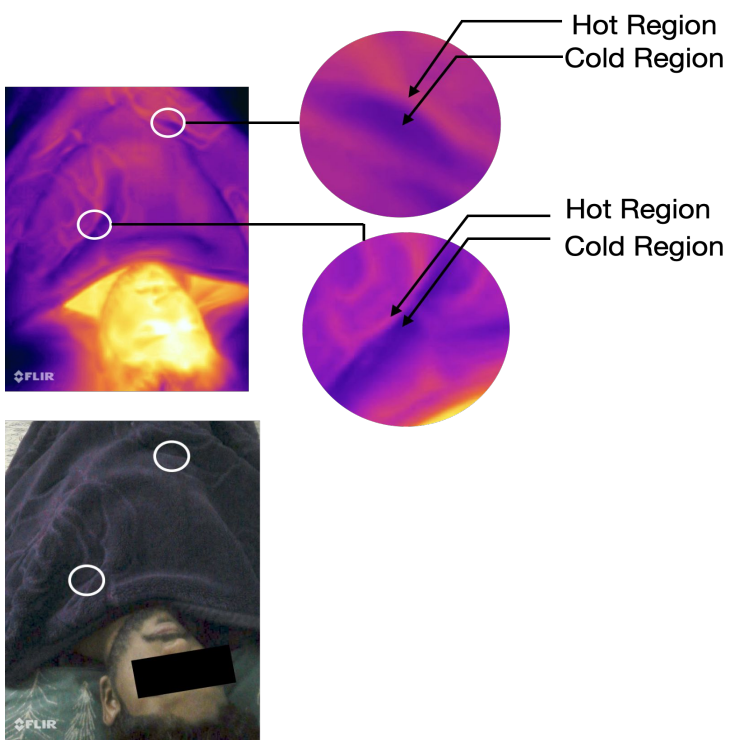

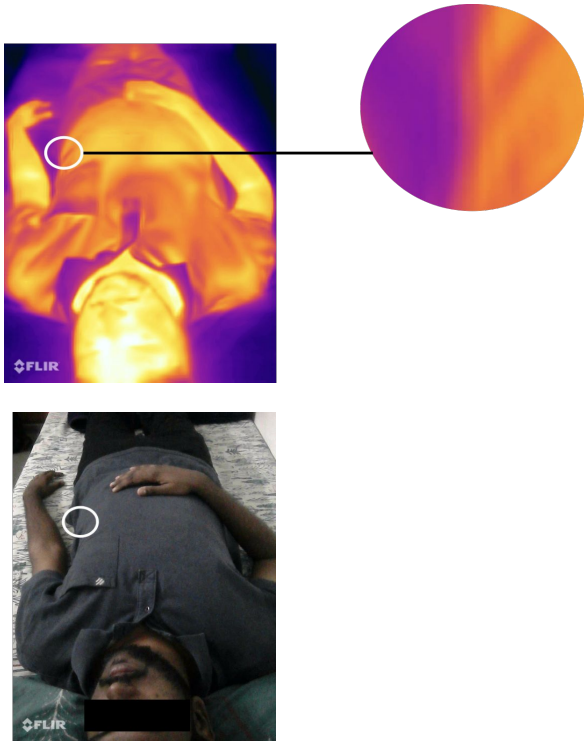

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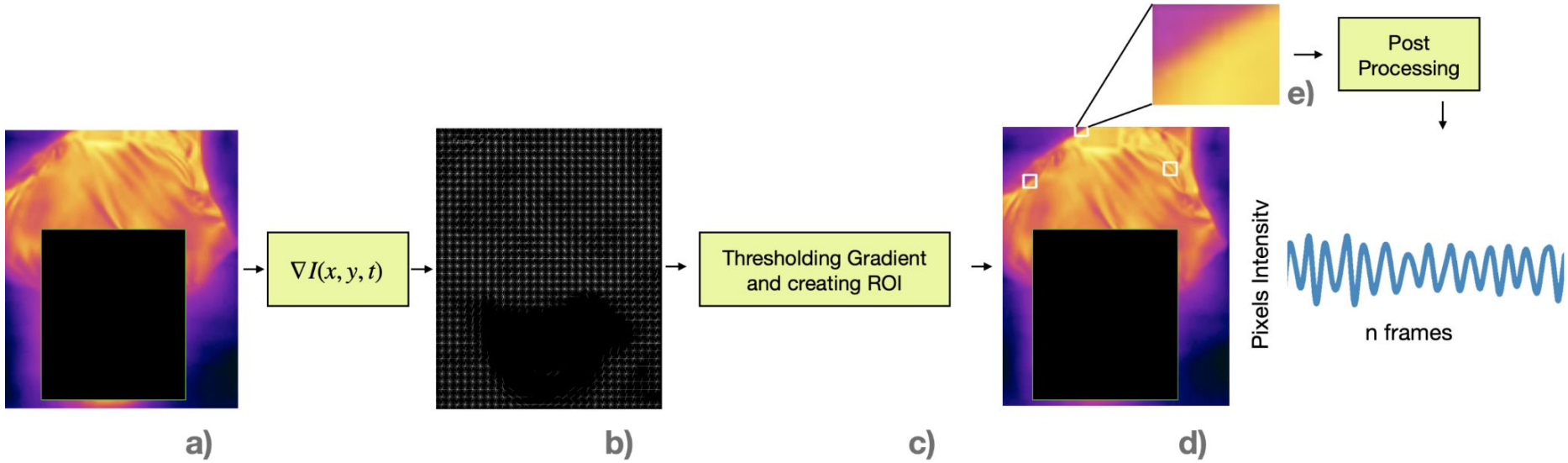

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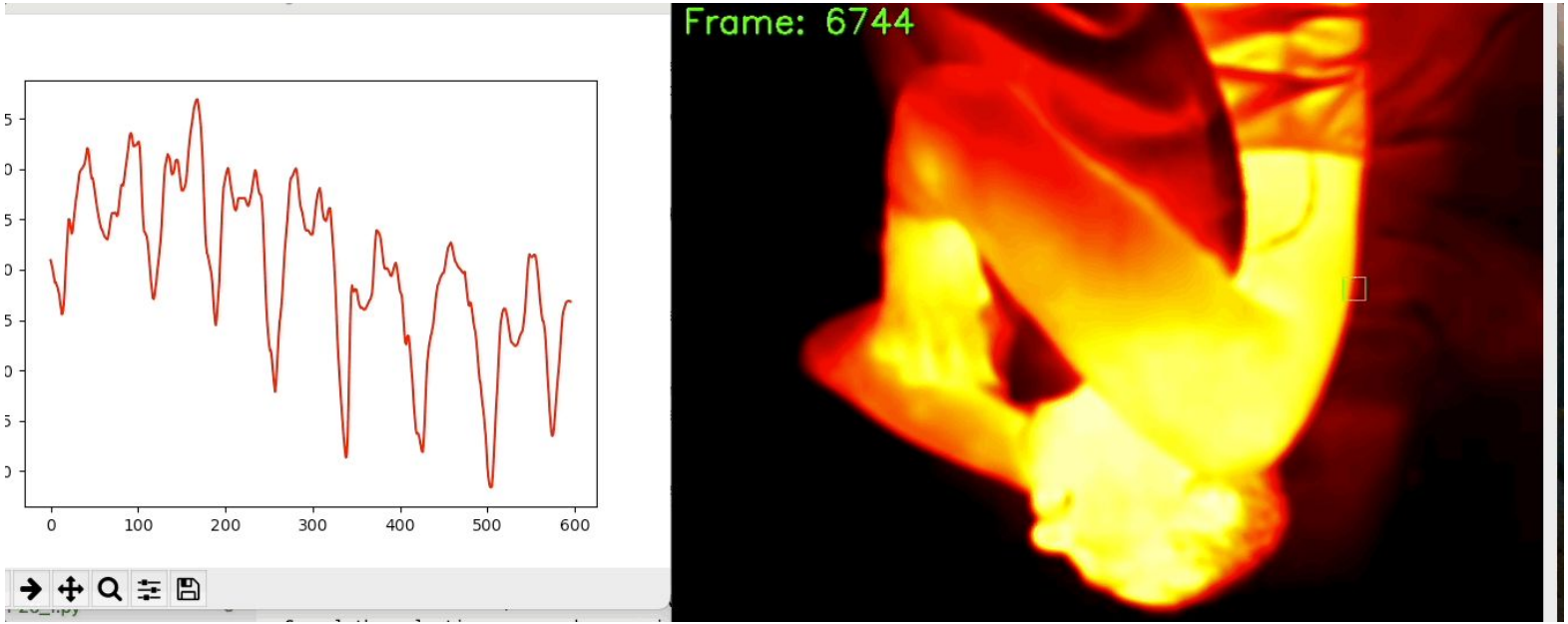

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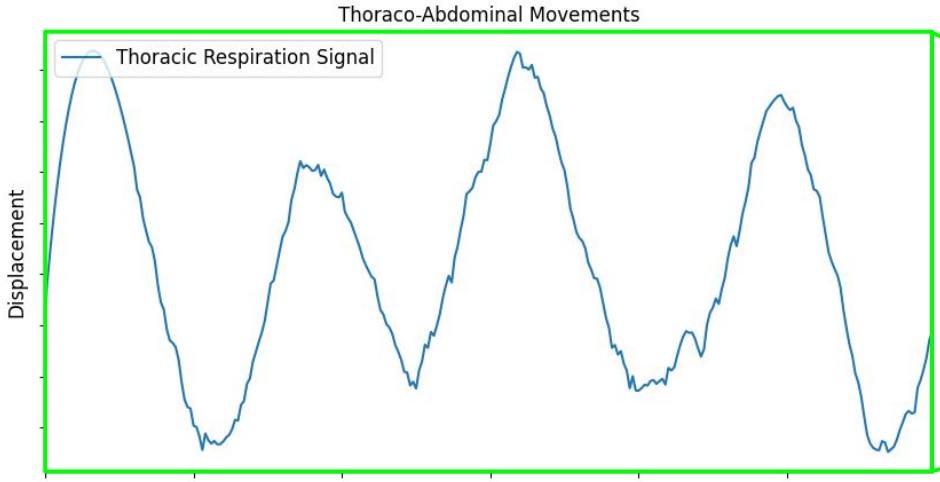

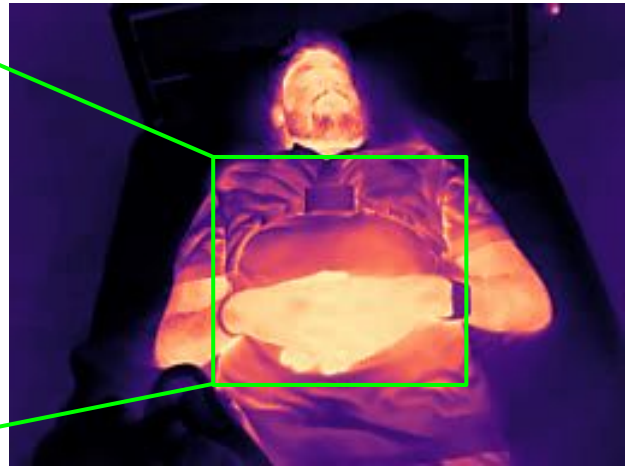

Sensing Thorax-Abdomen Movement using Optical Flow

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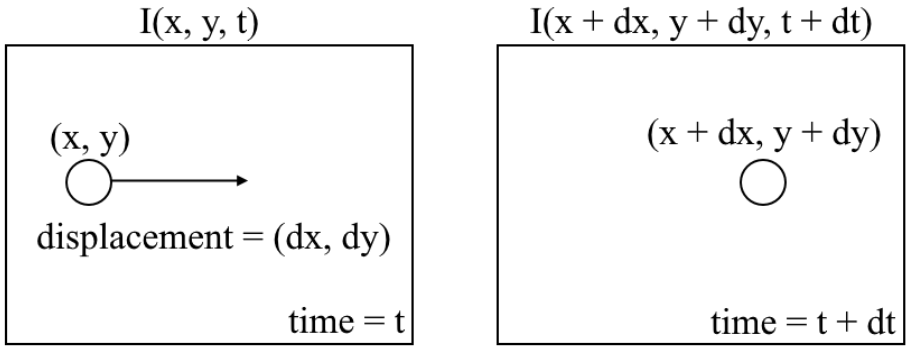

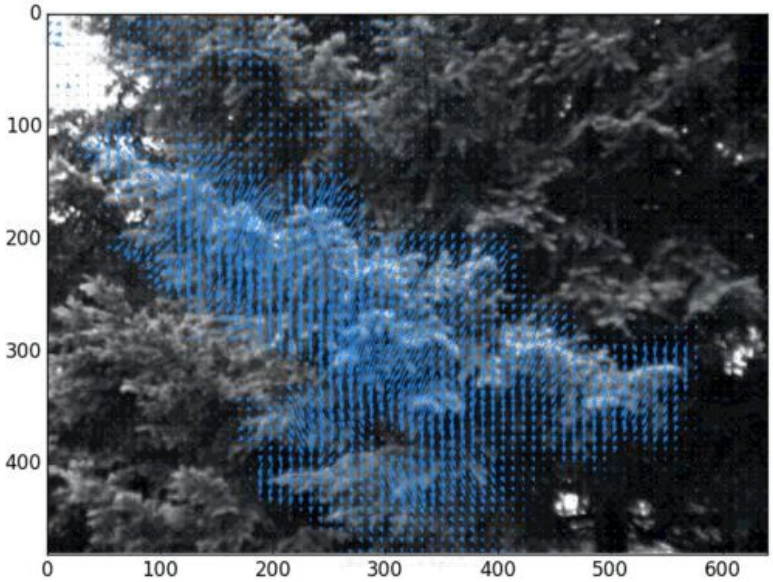

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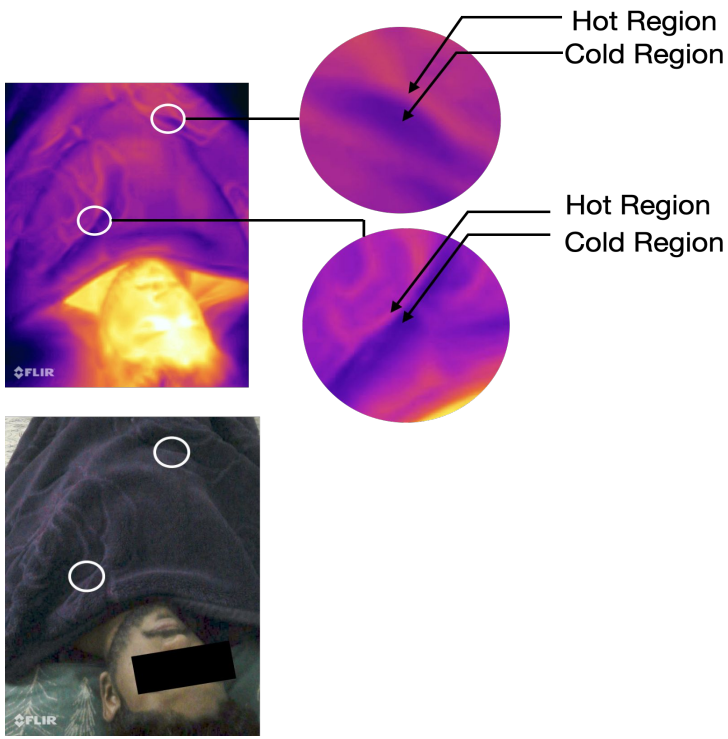
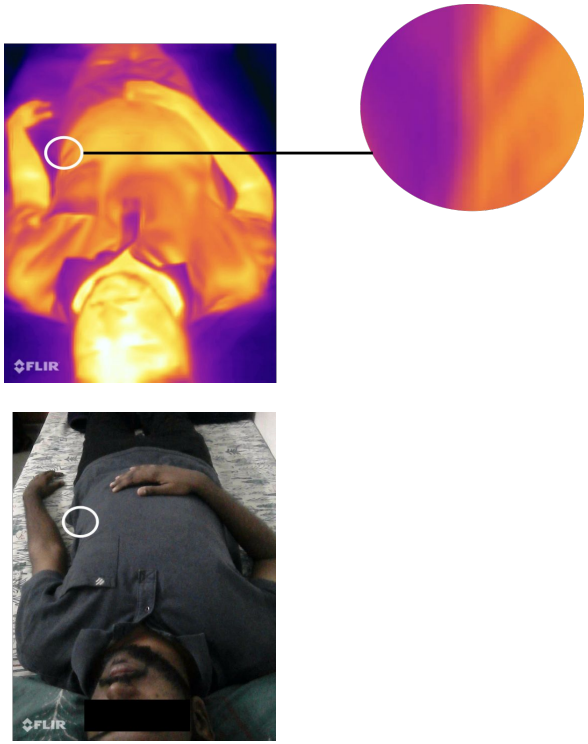
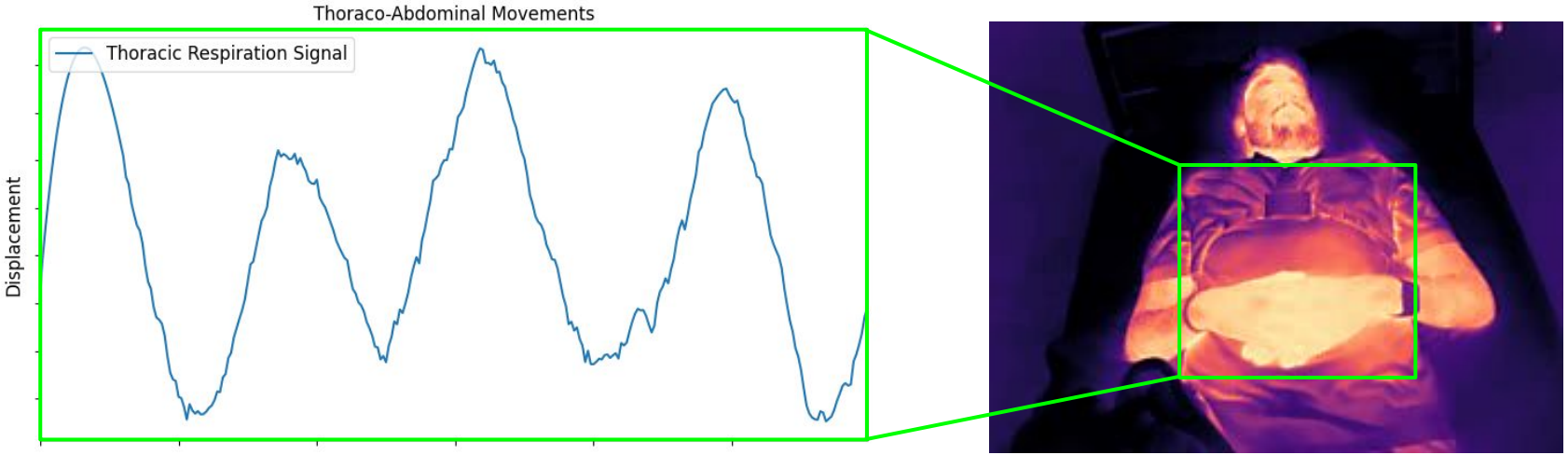




Sensing Thorax-Abdomen Movement using Optical Flow

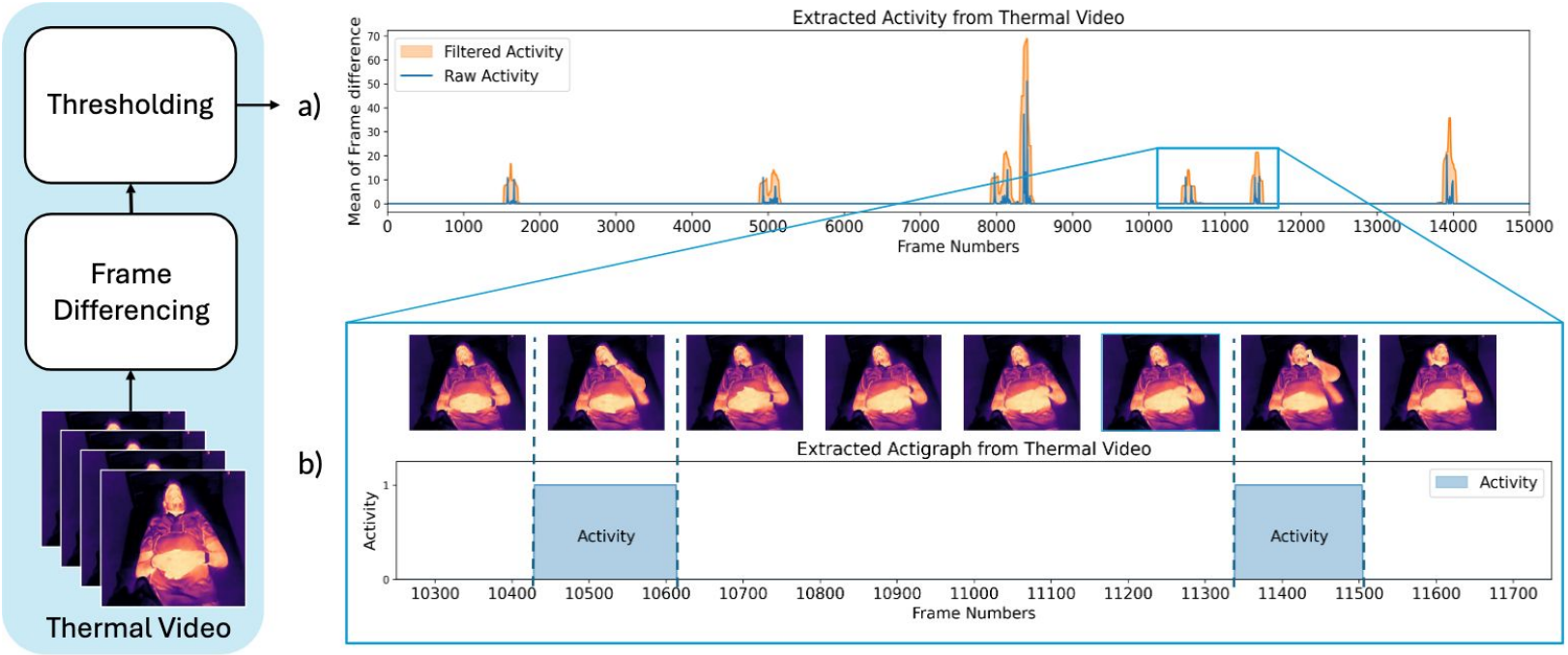


Technical Challenge: Generalizability across different sleeping positions and activity.

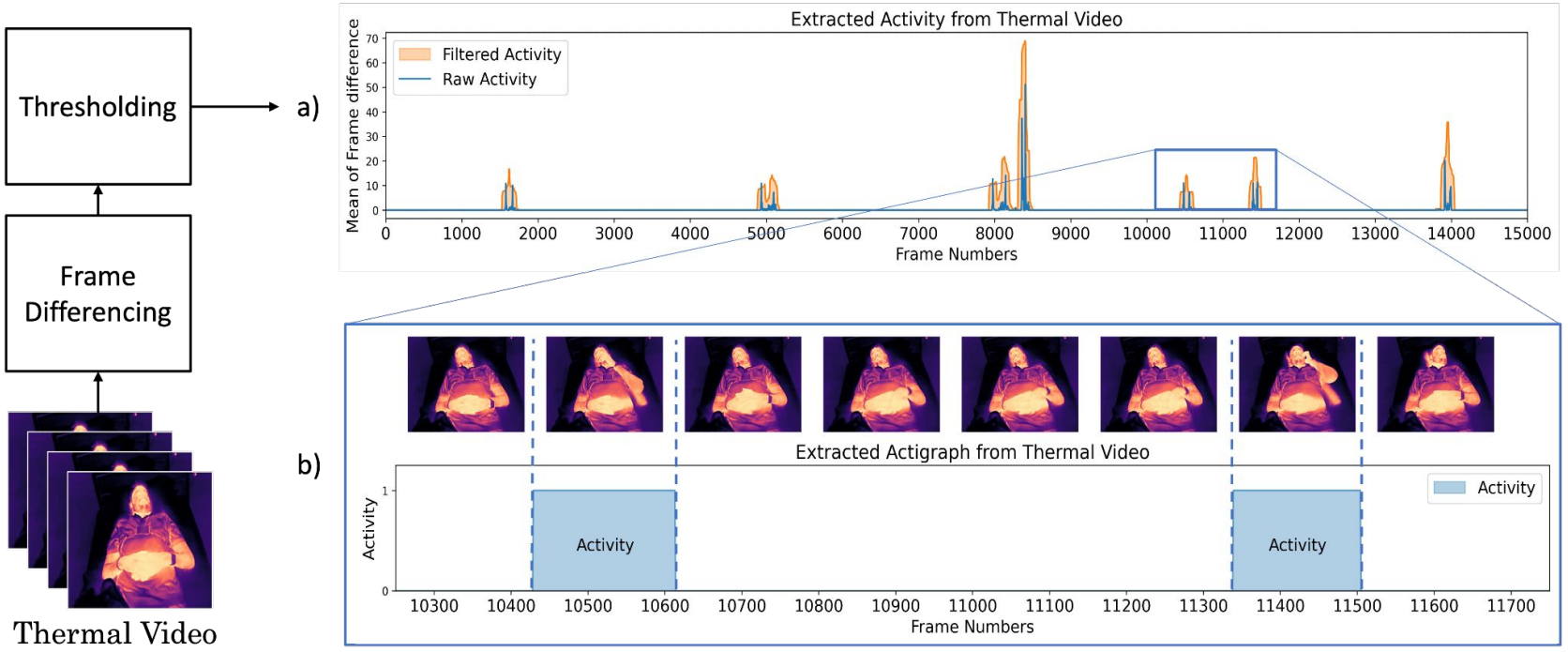
- How do we keep track of nostril and abdomen at different sleeping positions?
  - Solution: We use Region of Interest (ROI) localiser.

- Movement during sleep introduces noise in the signal of interest.
  - Remove signal which contains activity.

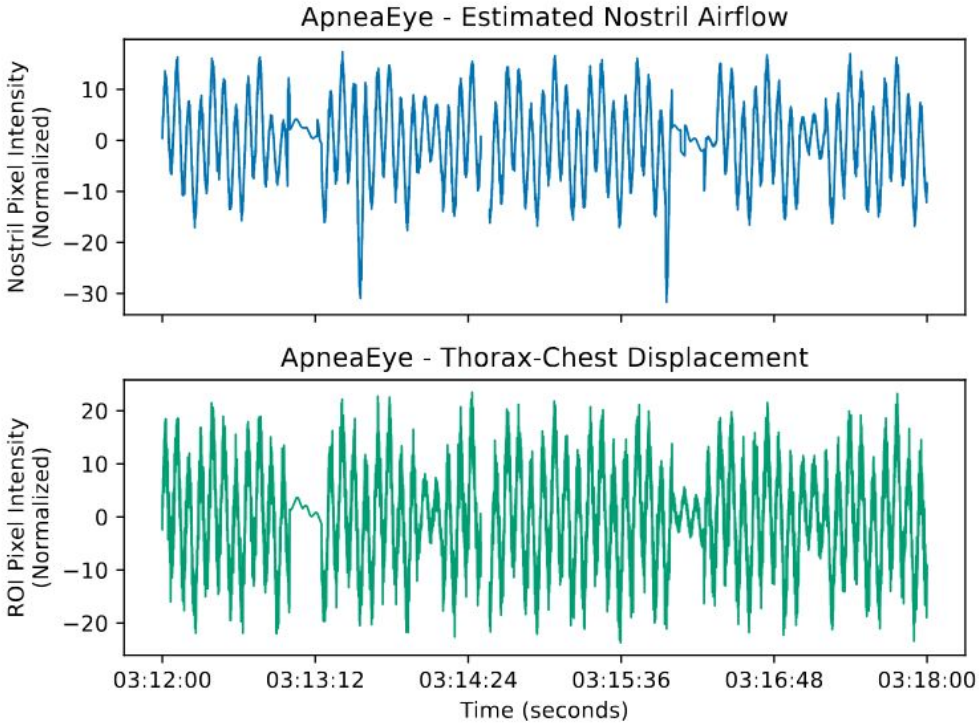
Technical Challenge: Generalizability across different sleeping positions and activity.



Technical Challenge: Generalizability across different sleeping positions and activity.



Detecting Apnea Events

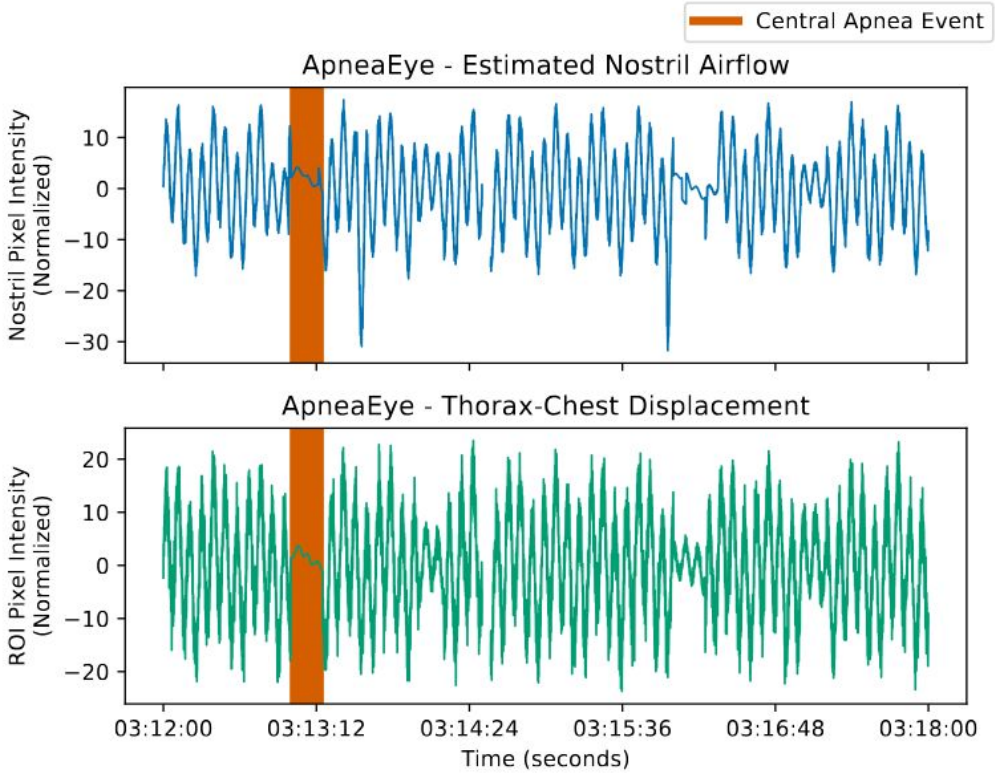


Detecting Apnea Events

Central Apnea

- Nasal Airflow drops by 80%
- Thoracoabdominal movements stops

This occurs because the central nervous system temporarily stops sending the necessary signals to activate the thoracoabdominal muscles.

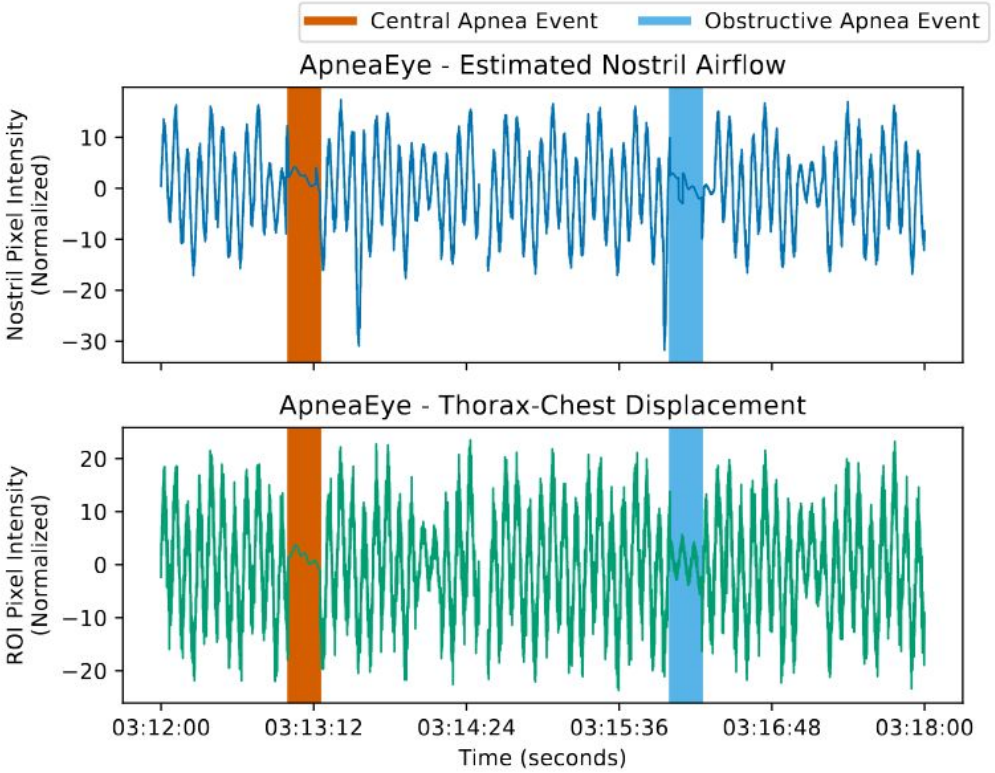


Detecting Apnea Events

Obstructive Apnea

- Nasal Airflow drops by 80%
- Thoracoabdominal movements persists.

This occurs when there is a blockage in the airway causing the nasal airflow to drop.

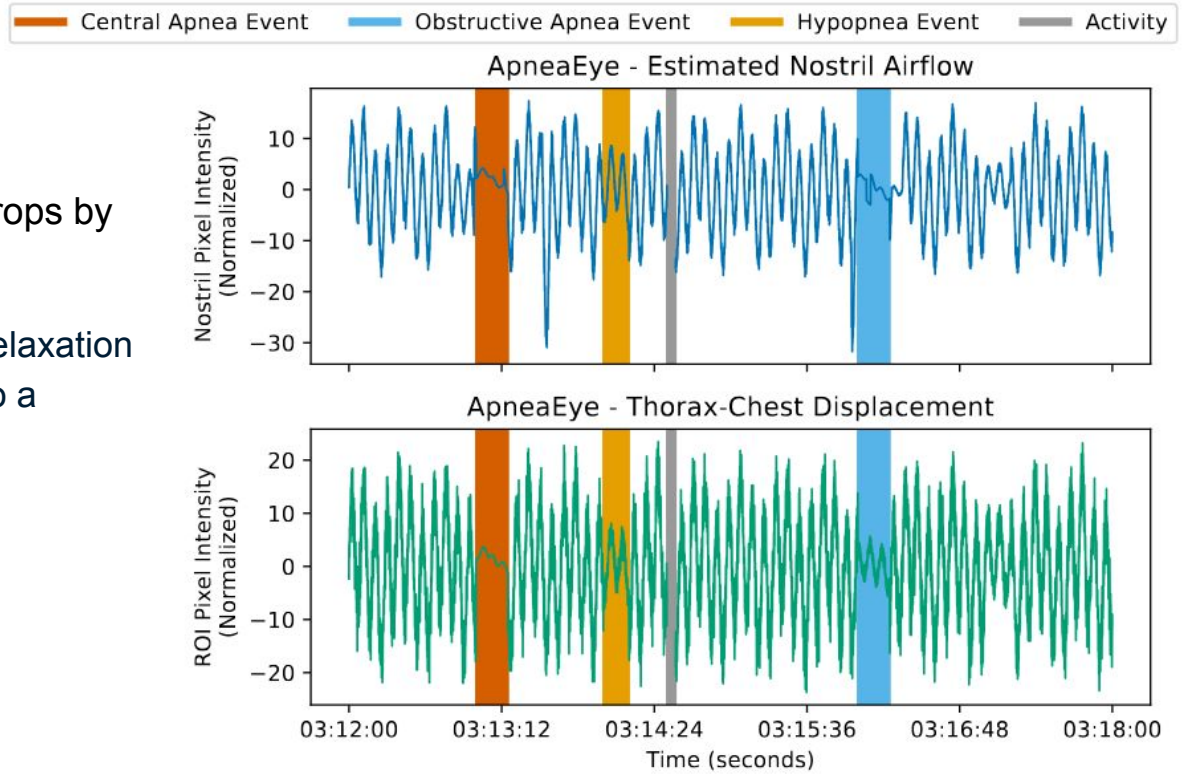


Detecting Apnea Events

Hypopnea

- Nasal Airflow drops by 30%
- Thoracoabdominal movements drops by 30%

Hypopneas are frequently linked to the relaxation of throat muscles during sleep, leading to a narrower airway.



Evaluating ApneaEye

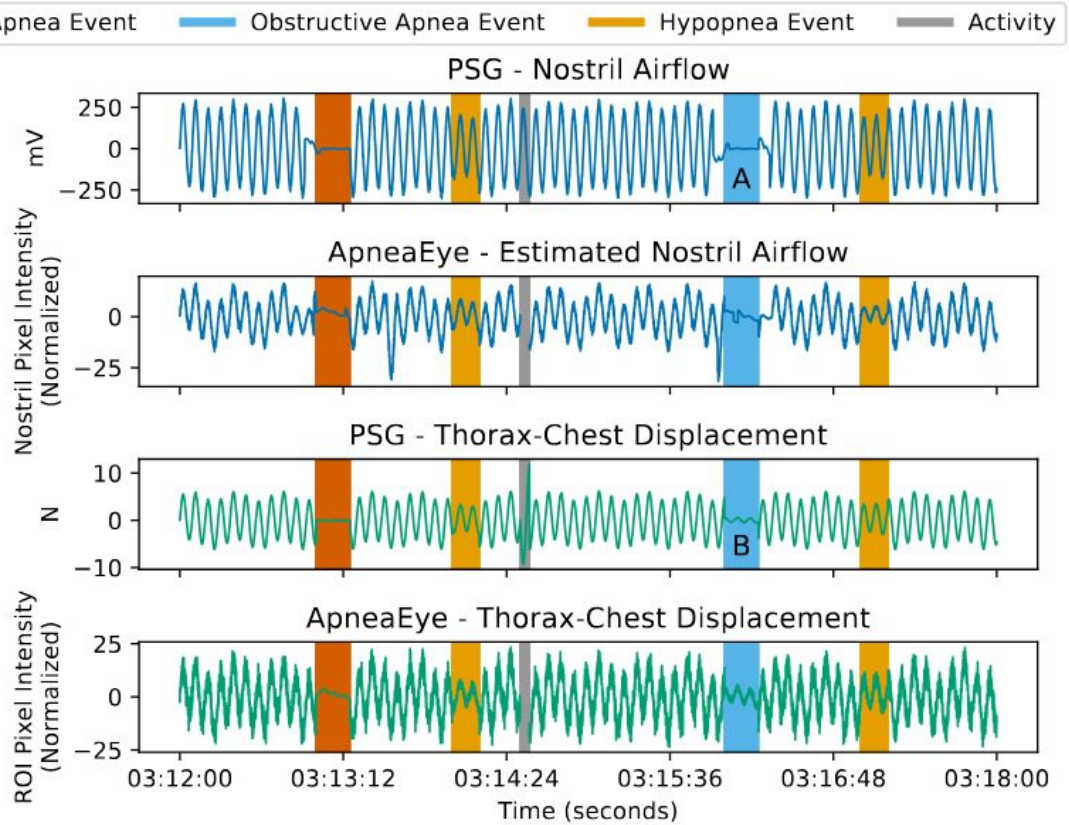
Study Site:	• AIIMS, New Delhi, • IIT Gandhinagar • Home test
Total participants	44
Participants diagnosed with apnea	24
Female participants	21
Age (in years) (mean, range)	45.19 (18-76)
Total apnea events	3805
Data recorded in hours (mean, range)	7.51 (5-9.83)

Evaluating ApneaEye

Evaluating ApneaEye

ApneaEye installation at Sleep Lab along side Polysomnography kit

Evaluating ApneaEye against Polysomnography



Evaluating ApneaEye

	Precision	Sensitivity	Specificity
Apnea	0.71	0.72	0.99
Hypopnea	0.74	0.92	0.97

Precision: The proportion of predicted positives that are actually correct.
Precision = True Positives / (True Positives + False Positives)

Sensitivity (also called Recall): The proportion of actual positives that are correctly identified.
Sensitivity = True Positives / (True Positives + False Negatives)

Specificity: The proportion of actual negatives that are correctly identified.
Specificity = True Negatives / (True Negatives + False Positives)

Evaluating ApneaEye

	Precision	Sensitivity	Specificity
Apnea	0.71	0.72	0.99
Hypopnea	0.74	0.92	0.97

- How good are these results ?
  - Solution: Use metric that doctors rely on

PID	Total time (in mins)	Excluded time (in mins)	Excluded time (in percentage)	Reason for exclusion (as % of entire sleep duration)			
				Blanket Overhead	CPAP Mask	Activity	ROI Failure
AP20	428	45	10.6	0.1	0.0	10.3	0.4
AP19	430	407	94.7	90.5	0.0	12.6	0.1
AP18	436	130	29.9	1.0	0.0	28.8	1.1
AP17	484	154	31.8	9.2	0.0	8.6	12.6
AP16	369	215	58.3	41.7	0.0	18.5	0.1
AP15	429	193	45.0	0.2	33.1	14.1	1.7
AP14	501	212	42.3	0.1	0.0	13.9	25.0
AP13	336	198	58.9	4.8	26.4	12.5	14.0
AP12	441	131	29.7	0.2	0.0	27.2	2.8
AP11	495	446	89.9	46.9	24.9	7.5	3.3
AP10	410	117	28.5	2.0	0.0	24.0	0.7
AP09	496	79	15.9	0.1	0.0	6.1	7.0
AP08	400	114	28.6	2.1	0.0	24.1	0.7
AP07	415	62	14.9	1.2	0.0	11.0	2.7
AP06	458	191	41.8	0.0	21.5	20.5	1.6
AP05	368	99	26.9	1.6	0.0	11.3	7.8
AP04	469	26	5.5	0.0	0.0	3.9	0.2
AP03	410	117	28.5	2.0	0.0	24.0	0.7
AP02	473	51	10.9	0.0	0.0	9.9	0.6
AP01	479	60	12.6	0.0	0.0	5.3	7.5
			Avg	**10.2**	**5.3**	**14.7**	**4.5**

Evaluating ApneaEye With **Apnea Hypopnea Index (AHI)**

AHI = (Number of apnea Events + Number of Hypopnea Events)/ Duration of sleep (in hours)

AHI rule for classification	
Severe Apnea	AHI: > 30
Moderate Apnea	AHI: 15-30
Mild Apnea	AHI: 5-15
Normal	AHI: < 5

Evaluating ApneaEye With **Apnea Hypopnea Index (AHI)**

$$\text{AHI} = \frac{\text{Number of Apnea Events} + \text{Number of Hypopnea Events}}{\text{Sleep duration(in hours)}}$$

AHI rule for classification	
Severe Apnea	AHI: > 30
Moderate Apnea	AHI: 15-30
Mild Apnea	AHI: 5-15
Normal	AHI: < 5

PID	Ground Truth - AHI	Ground Truth - Severity	Estimated by ApneaEye - AHI	Estimated by ApneaEye - Severity
AP01	14.6	Mild	15.2	Moderate
AP02	13.8	Mild	19.2	Moderate
AP03	93.3	Severe	114	Severe
AP04	45.3	Severe	49	Severe
AP05	40.2	Severe	51.9	Severe
AP07	50.8	Severe	63.1	Severe
AP08	30.6	Severe	38.4	Severe
AP09	29.7	Moderate	36.2	Severe
AP10	32.7	Severe	41.6	Severe
AP12	1.5	Normal	2.32	Normal
AP14	7.8	Mild	10	Mild
AP15	87	Severe	79.3	Severe
AP16	48.4	Severe	46.4	Severe
AP17	29.4	Moderate	33.8	Severe
AP18	3.8	Normal	7.1	Mild
AP20	21.2	Moderate	21.3	Moderate

ApneaEye Summary

- ApneaEye, a cost-effective, privacy-aware, robust system that uses a low-resolution thermal camera to monitor nasal airflow and thoracoabdominal movements during sleep **without on-body instrumentation**.
- ApneaEye accurately classified sleep apnea severity in **89%** of cases.
- The remaining misclassifications were conservatively assigned to a higher severity class, effectively avoiding under-diagnosis.

We investigated techniques to sense breathing and using that information for **wellness** and **diagnosis**.

Wellness

- **JoulesEye:** Energy Expenditure Estimation and Respiration Sensing from Thermal Imagery While Exercising [ACM IMWUT'24]

Diagnosis

- **ApneaEye:** Thermal Imaging for Lightweight and Accurate Sensing of Sleep Apnea. [Under Review, Nature Communications]
- **Spiromask:** Measuring Lung Function Using Consumer Grade Mask [ACM HEALTH'23]

Why do we need systems for lung health diagnosis?

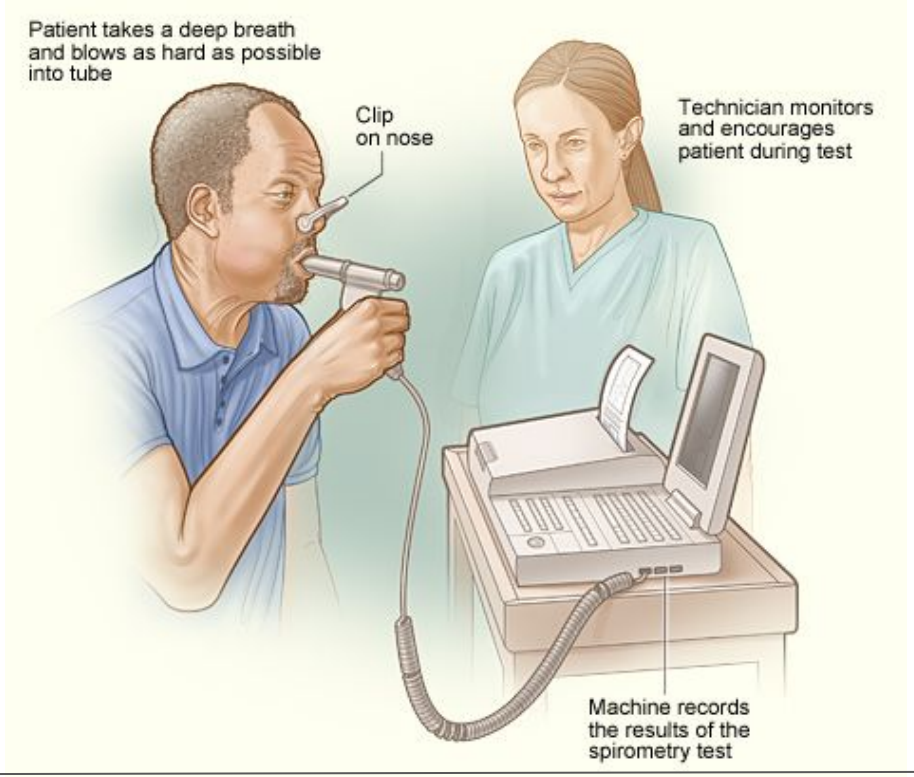
- **235 million** people suffer from Asthma. More than 3 million people die each year from Chronic Obstructive Pulmonary Disease (COPD).*
- More than **90%** COPD death, occur in low-income and middle income countries.*

* FYañez, Aina M., et al. "Monitoring breathing rate at home allows early identification of COPD exacerbations." *Chest* 142.6 (2012): 1524-1529.

Clinical diagnosis of lung health

- **Pulmonary Function Test**: a test designed to measure the working of the lungs.

- PFT works by monitoring the <u>forced</u> and <u>normal</u> breathing.



Clinical diagnosis of lung health

1. Forced Breathing:
   a. The **Flow Volume Curve** gives us a number of information

2. Normal Breathing:
   a. Respiratory Rate (RR). This is the amount of air exhaled forcefully and quickly after inhaling as much as you can.

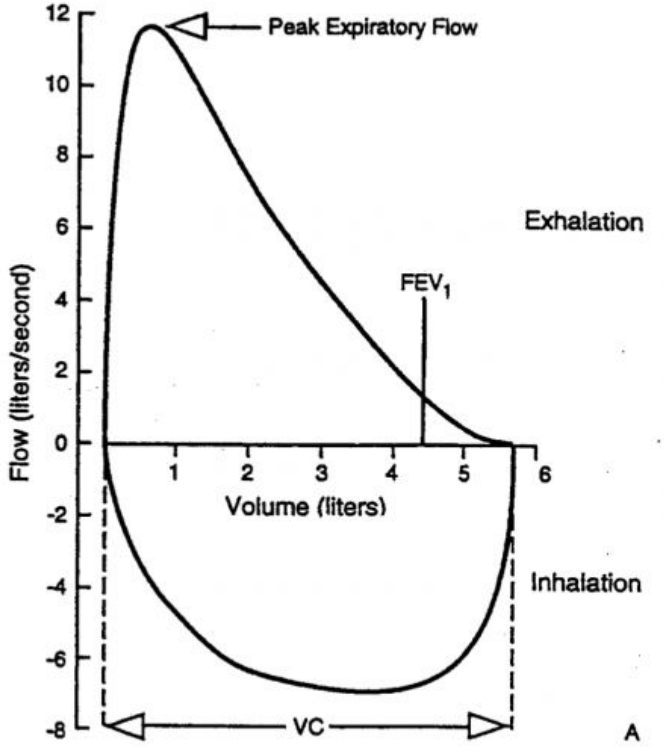


Figure: Parameters of forced breathing.

Clinical diagnosis of lung health

1. Forced Breathing:
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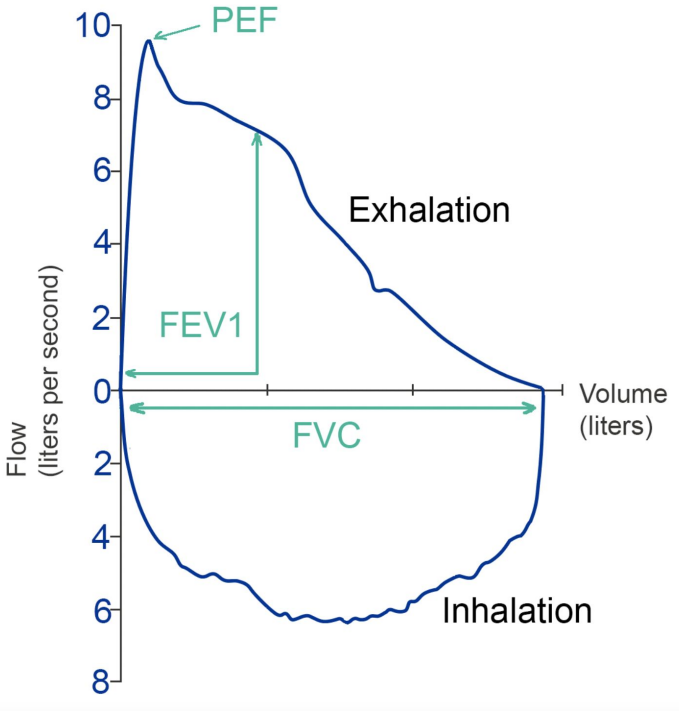


Figure: Parameters of forced breathing.

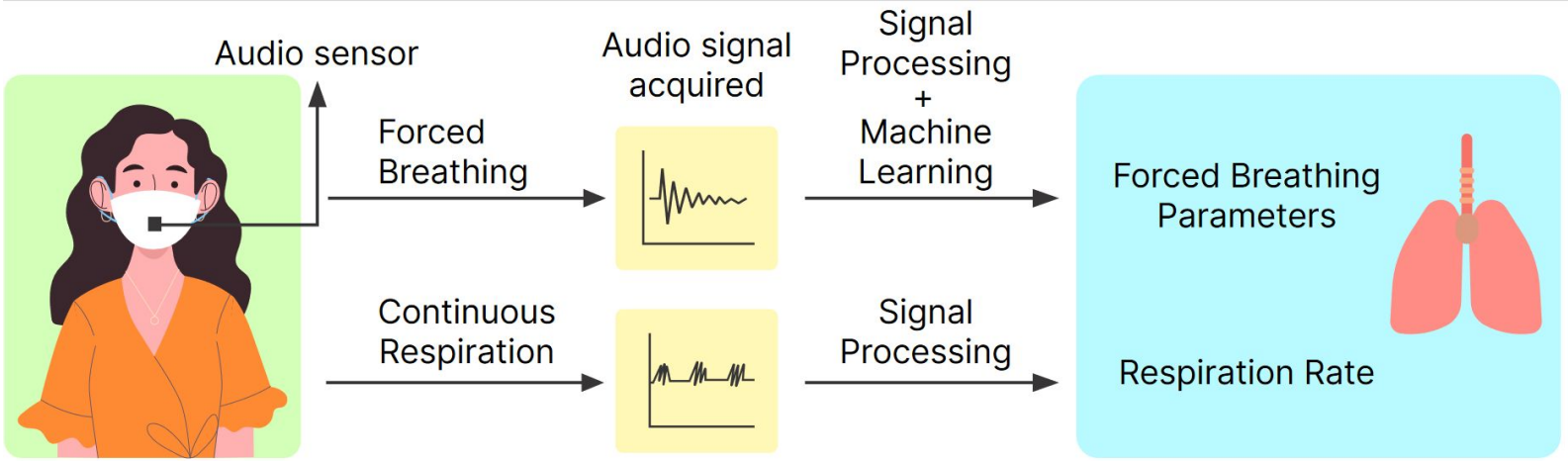
source : https://www.medikro.com/understanding-your-spirometry-test-results

Prior work

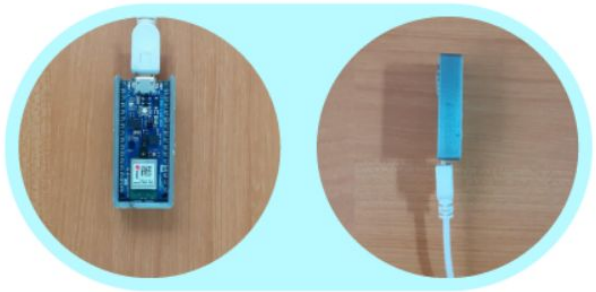
1. Smartphone Spirometry*:
    a. Smartphone heterogeneity is a challenge.
    b. Not suited for sensing tidal breathing

*Larson, Eric C., et al. "SpiroSmart: using a microphone to measure lung function on a mobile phone." *Proceedings of the 2012 ACM Conference on ubiquitous computing*. 2012.

SpiroMask measures Forced Breathing and *Continuous* Normal Breathing Parameters Using Commodity-Grade Mask

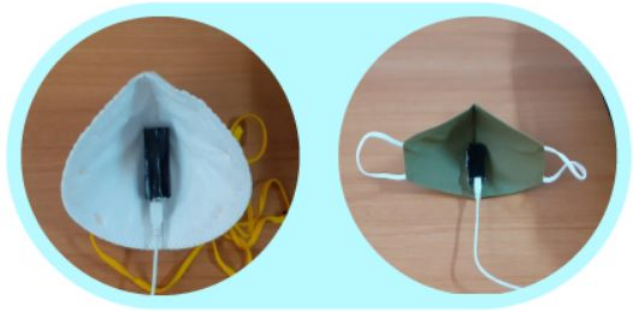


Microphone inside mask



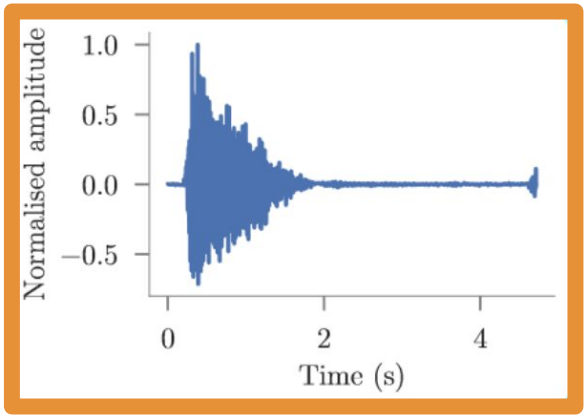
i)

ii)



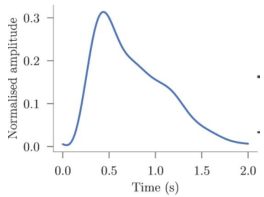
iii)

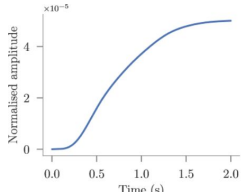
From audio to spirometry

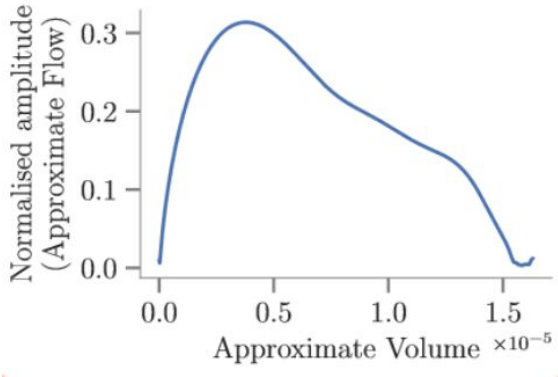


1. Mel Frequency Cepstral Coefficient
2. Mel Frequency Energy

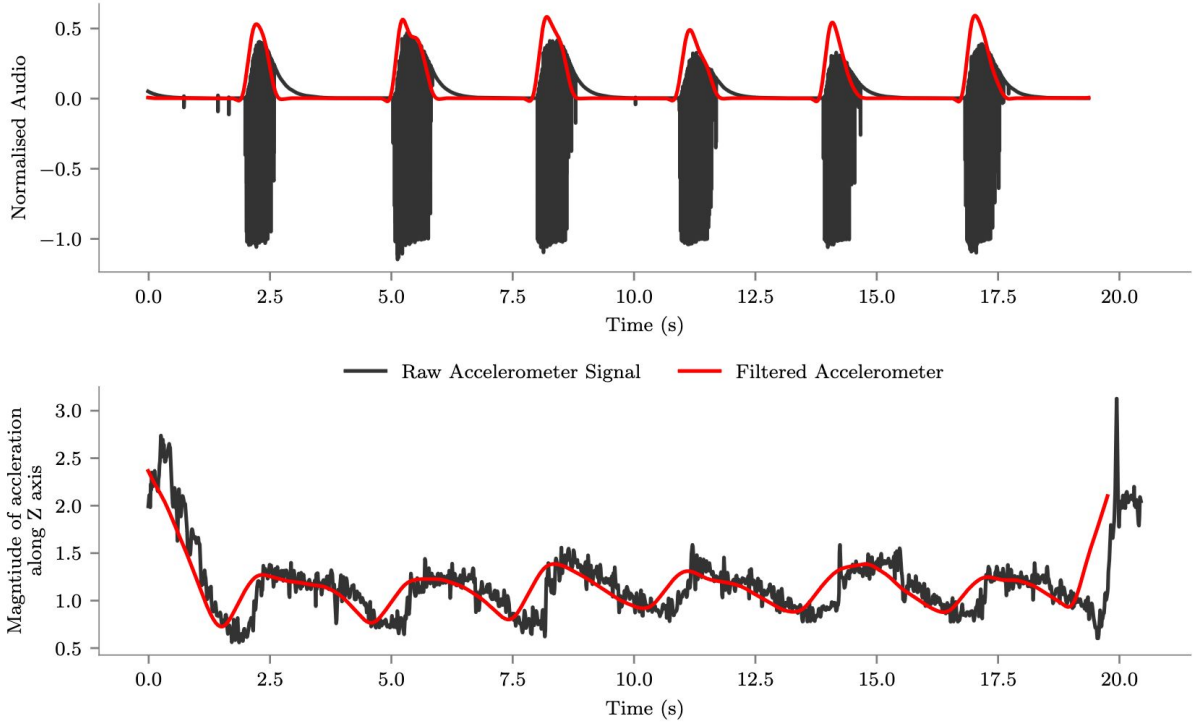
Hilbert Envelope



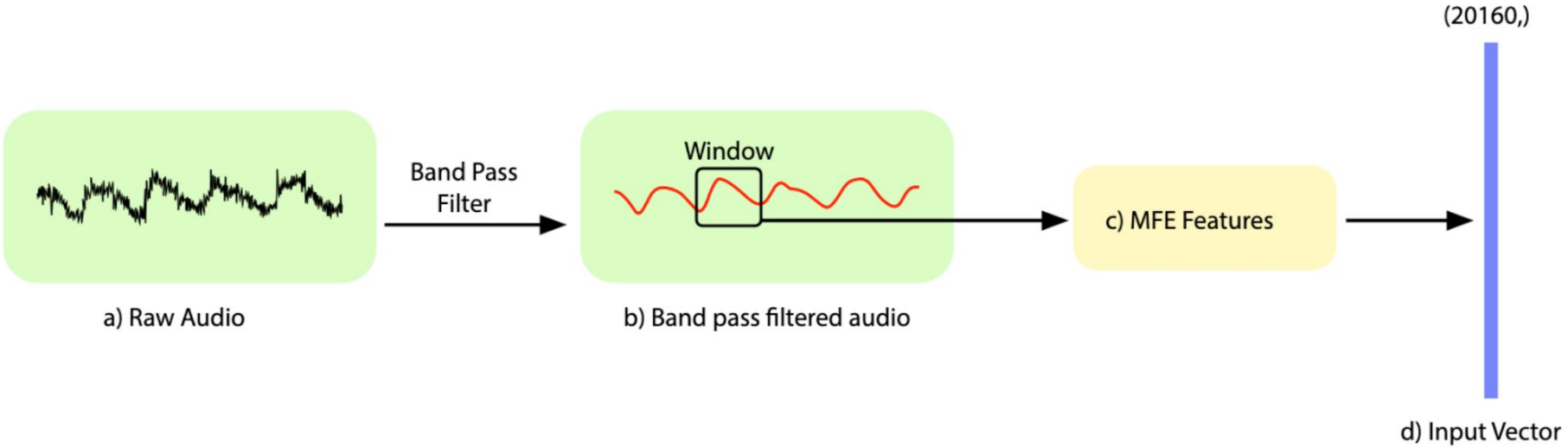




From audio to breathing rate



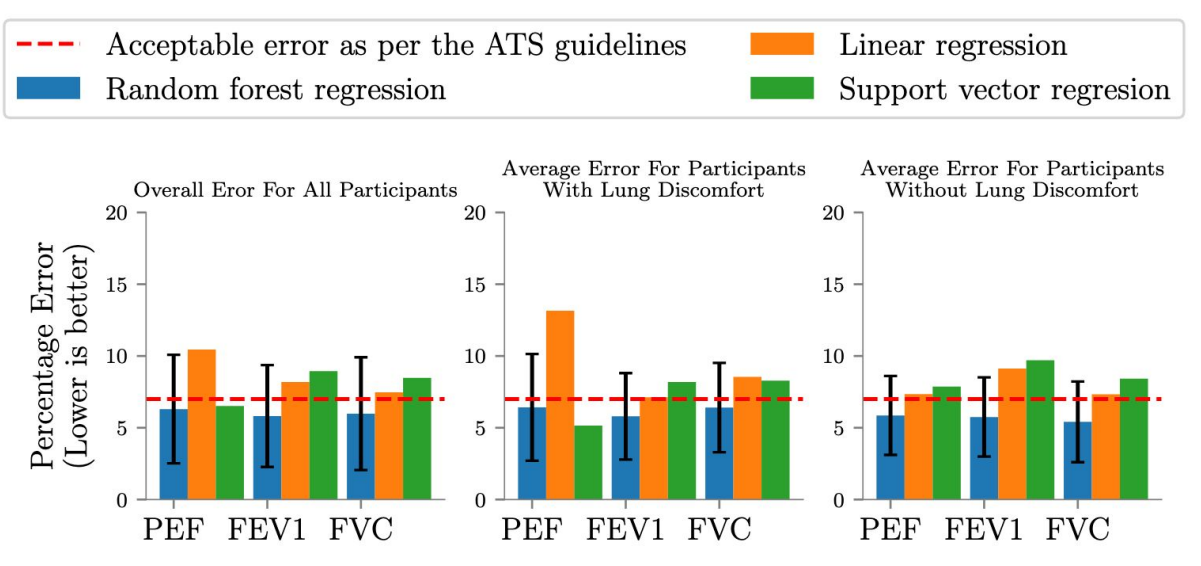
Dealing with noise and speech



User study

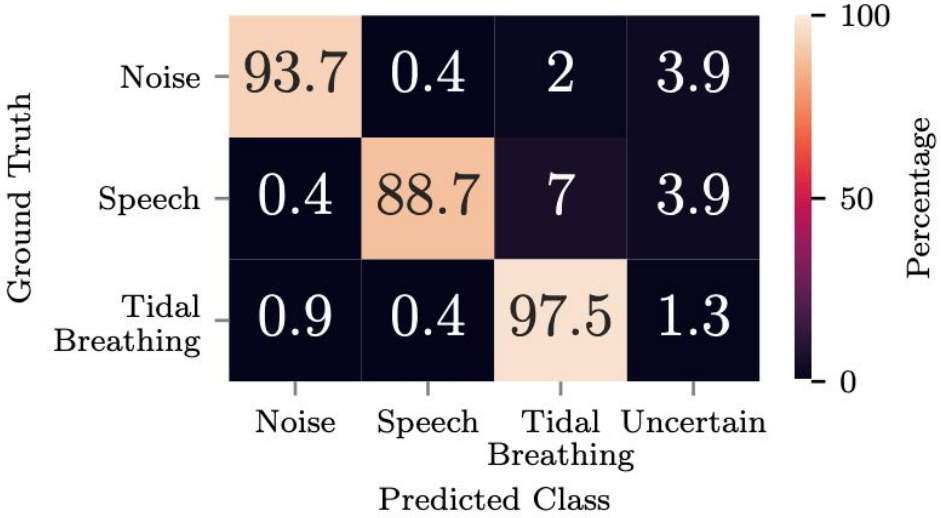
Total participant	37
Participants with lung ailments	14 (37.8%)
Females	13 (35.1%)
Age	20-32

From audio to spirometry



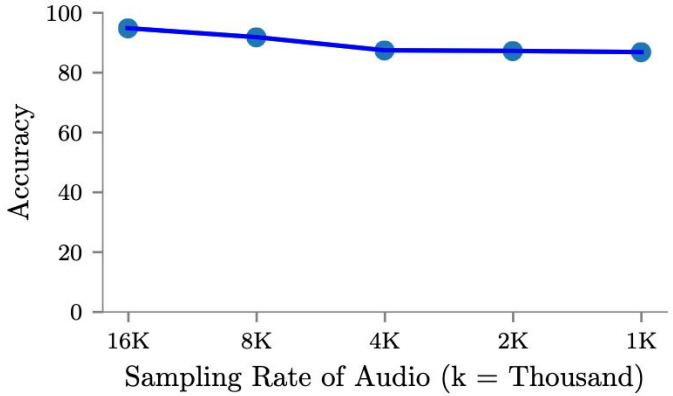
The result of SpiroMask is acceptable as per ATS criteria, both for healthy and unhealthy participants.

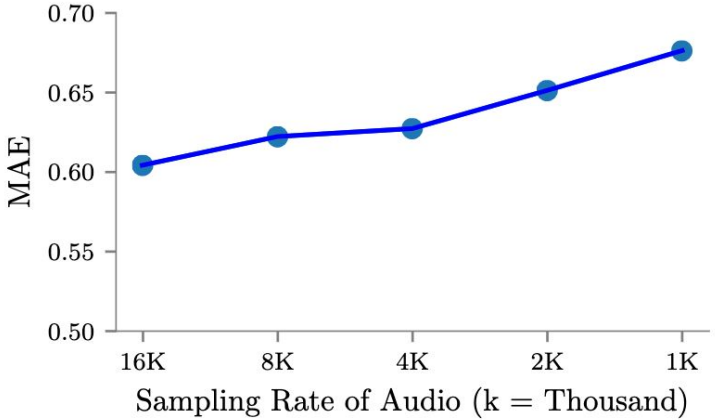
Differentiating breathing from other signals



For respiration rate monitoring, we achieved a Mean Absolute Error (MAE) of 0.47 on the N95 mask. The MAE on the cloth mask was 0.36

Effect of sampling rate





Reducing the sampling rate had little effect on the performance of our system.

SpiroMask Summary

- *SpiroMask* senses both forced breathing and normal breathing and can diagnose people with lung ailments.

- *SpiroMask* works for both N95 and cloth mask.

Challenges

- Real-world deployment of health sensing systems is a challenge.
- Given the multi-disciplinary nature of health sensing devices, negotiating with professionals, like doctors, as well as potential participants requires much time.
- For instance, it took 6-7 months and negotiations with 7-8 doctors to deploy the ApneaEye system.

Summary

- Thermal cameras can unlock potential health application. We showed how we can extract accurate energy expenditure and diagnose sleep apnea using thermal imagery data.

- Lung ailment can be diagnosed by retrofitting microphone inside face mask.

Future Research Work

- Sensing and **intervention**
- Scaling sensing devices