mmFlow: Facilitating At-Home Spirometry with 5G Smart Devices

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Respiratory Diseases: A Global Health Challenge

➢ Respiratory Diseases:

- Asthma
- Chronic Obstructive Pulmonary Disease (COPD)
- COVID-19

➢ Worldwide Cases++:

<table>
<thead>
<tr>
<th>Disease</th>
<th>Cases (Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asthma</td>
<td>262 M (2019)</td>
</tr>
<tr>
<td>COPD</td>
<td>384 M (2019)</td>
</tr>
<tr>
<td>COVID-19</td>
<td>178 M (2019-)</td>
</tr>
</tbody>
</table>

➢ United States Cases++:

<table>
<thead>
<tr>
<th>Disease</th>
<th>Cases (Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asthma</td>
<td>25 M (2019)</td>
</tr>
<tr>
<td>COPD</td>
<td>14.8 M (2019)</td>
</tr>
<tr>
<td>COVID-19</td>
<td>33.5 M (2019-)</td>
</tr>
</tbody>
</table>

++: WHO: [https://www.who.int/health-topics/chronic-respiratory-diseases#tab=tab_1](https://www.who.int/health-topics/chronic-respiratory-diseases#tab=tab_1)
Spirometry: Lung Function Test

Spirometry: Common Lung Function Test

Spirometry Setup

Spirometry Procedure

Step 1: Breathe through your mouth

Step 2: Full Inhalation

Step 3: Exhale hard and fast

Step 4: Exhale until lung is empty
Spirometry: Lung Function Test

Flow – Volume Graph with Lung Function Indicators

Doctors use both lung function indicators and graph to assess the condition
Available Spirometry Solutions

- Daily In-Clinic Spirometers
  - Bulky
  - High-Cost
  - Availability of Doctors

- Portable Spirometers
  - Accurate but Expensive (> $1200)
  - Cheap but Error-Prone

- Research Works
  - Requires Extra Hardware
  - High Hardware Cost
  - Susceptible to Noise
mmFlow Overview

In-Clinic Spirometry

Key Enabling Technology: Millimeter-wave

Opportunity: Extremely sensitive to device movement

Machine Learning Algorithms
mmFlow: At-Home Spirometry

- Utilizes built-in **millimeter-wave technology** in ubiquitous millimeter-wave based mobile devices to perform at home-spirometry

1. Hold a phone in front
2. Inhale
3. Exhale Forcibly

Output

- PEF
- FEV1
- FVC
- FEF25
- FEF50
- FEF75
- MMEF
Challenge 1

➢ When user exhales in-front of the 5G mobile device, phase change should only be from airflow vibrations
Challenge 2

- Predicting lung function from vibration signal requires modeling non-linear relationship
mmFlow Design: Airflow Vibration Estimator

1. A person blows into phone

2. Airflow creates tiny vibrations

3. Vibrations directly affect the phase of reflected mmwave signal
mmFlow Design: Airflow Vibration Estimator

Distinct Vibratory Signal
mmFlow Design: Airflow Vibration Estimator

Reflection from multiple objects \(\rightarrow\) Frequency Modulated Continuous-Wave (FMCW) \(\rightarrow\) Single strongest reflector

Hand or body motion

Change in device relative location w.r.t. the reflector
Beamforming and Reflector Tracking

Measures reflected signals from multiple antennas

Scans nearby region to find the strongest reflector

\[ \{r^*, \Theta^*\} = \arg\max \{|BF(r, \Theta)|\} \]

Updates based on shortest Euclidean distance

Beamforming and Reflector Tracking
mmFlow Design: Vibration to Spirometry Predictor
Input Vibrations

CNN-Feature Extraction

LSTM-Regression

Output

PEF
FEV1
FVC
FEF25
FEF50
FEF75
MMEF

4 antennas + Beamformed

Conv + LeakyRelu + Maxpooling

LSTM

FC Layer with Linear

mmFlow Design: Vibration to Spirometry Predictor
mmFlow Design: Deep Residual Decoder

Input

Stacked Fully Connected Layers

Output

Experimental Platform

- 77-81GHz mmWave device TI IWR 1443BOOST
- 4 receive antennas in mmWave device
- Flow-Volume Calibrator, Jones Medical FVC-3000
90th percentile error of mmFlow is 1.28 L/s, which is similar to in-clinic spirometers.
Impact of Device Distance

mmFlow works very well for device distance upto 35 cm
Deep Residual Decoder

mmFlow produces accurate graphs for both healthy and diseased patients.
Comparison with MIR Portable Spirometer

mmFlow produces results similar to clinically-validated commercial spirometers
mmFlow Summary

System summary

➢ mmFlow is a first-of-a-kind mmWave based spirometry solution
➢ mmFlow employs beamforming, reflector tracking, and machine learning to perform spirometry
➢ mmFlow generalizes well under real conditions
➢ mmFlow is developed as software-only solution to 5G mobile devices
➢ In the post-COVID era, mmFlow can transform 5G smartphones into at-home spirometers for non-intrusive lung function monitoring