RFID for Breath Monitoring

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1 Introduction

Monitoring respiratory function is essential for managing various health conditions. Deep breathing can lower blood pressure, while irregular breathing may signal respiratory issues. Monitoring respiration also aids in evaluating sleep quality and recovery[1].Patients with restrictive or obstructive lung diseases often experience altered respiratory dynamics, a pattern also seen in musculoskeletal conditions like scoliosis and thoracic rheumatological diseases.Additionally, neurological disorders and postoperative states frequently lead to restrictive lung function. Standard lung function assessments include spirometry, which offers key information on lung volume and airflow; however, non-portable methods like body plethysmography, ultrasonography, and CT scans limit their clinical and daily applications.

To overcome these limitations, the Respiratory Movement Measuring Instrument (RMMI) was developed at Sahlgrenska University in Sweden, measuring anterior-posterior chest and abdominal movements. It has proven sensitive in clinical studies, capturing clinically significant respiratory changes in postoperative patients [2].However the RMMI is bulky, its large size makes it hard to move and set up, limiting its use in smaller clinics and mobile situations. The high cost of the technology also makes it difficult for budget-limited practices to afford.It also needs regular maintenance and calibration of its laser sensors.Patients might find the equipment uncomfortable, affecting how well they breathe during tests.Finally, outside factors like lighting and patient movement can disrupt the laser measurements, leading to unreliable results.

Non-contact wireless methods, including Wi-Fi, FMCW radar, LoRa, and RFID, offer non-intrusive alternatives to wearable sensors, yet many face challenges in multi-user settings or require stationary subjects. RFID technology, however, can remotely monitor respiratory motion through phase shifts in backscattered signals caused by chest and abdominal movement.

1.1 State-of-art

Technologies broadly used to measure respiratory parameters in hospital and clinical settings typically rely on pulse oximetry, capnography (end-tidal CO2), and transthoracic impedance (TTI) through echocardiogram electrodes.[3]

Capnography measures carbon dioxide levels in exhaled breath. While it offers high accuracy, its reliance on specific equipment can limit its use in resource-limited settings[4]. Transthoracic Impedance (TTI) provides a non-invasive method for simultaneously monitoring cardiac and respiratory functions, its accuracy can be influenced by factors such as body composition and electrode placement and motion artifacts.[5]

And there are remote and contactless respiration monitoring nowadays: one direct approach involves attaching sensors under the nose to measure human breath[6]. The study in [6] exploits the temperature gradient of the airflow during breathing, allowing for correlation with the rhythm and depth of inhalation and exhalation.

Additionally, the respiration rate, along with respiratory effort and occurrences of apnea, can be derived indirectly from the expansion and contraction of the chest.

By utilizing channel state information (CSI), a sampled version of the channel frequency response (CFR) that can be obtained from commercial wireless NICs, which can able commercial wi-fi devices to estimate vital signs monitoring[7] Acoustic Signals can also be applied to estimate respiration rate by detecting the Doppler effect caused by respiration.[8]

RFID's ability to uniquely differentiate between users has led to its exploration as a viable option for remote vital signs monitoring. Paper[9] presents a multi-person respiratory method by mapping the tag's Electronic Product Code (EPC) to the person's number id and the deployed body part bp. In [10], a pair of RFID tags are employed to mitigate the influence of the user's body movement. By fusing the data from these paired tags, it effectively cancels out the effects of overall body motion, isolating only the displacements caused by the user's respiration. In[11], a COTS RFID tag is attached on the shirt at the abdomen level and interrogated through a fixed reader antenna. In dynamic environment, by transforming a normal respiration cycle into a matched filter, real respiration cycles can be extracted from the noisy RFID signal, and then the respiration rate can be estimated bypeak detection scheme[12].

In conclusion, RFID technology presents a highly feasible solution for respiratory rate detection, offering advantages such as convenience, portability, and low cost. With its diverse potential applications, there remain numerous avenues for exploration and development within this innovative field, making it a promising area for future research and implementation.

1.2 Study Setup

The goal of this study is to implement an RFID-based approach for tracking respiratory motion using passive RFID tags. RFID readers emit continuous wave signals that both transmit commands and energize passive tags, enabling data backscatter to the reader. The backscattered signal is modeled as:

$$S(t) = A(t)e^{-j\phi(t)} \tag{1}$$

where $A(t)$ is signal amplitude and $\phi(t)$ is the phase. The phase and Received Signal Strength (RSS) depend on the distance d between reader and tag, with the phase ϕ modeled as:

$$\phi = \left(\frac{2\pi \cdot 2 \cdot d}{\lambda} + \theta\right) \bmod 2\pi \tag{2}$$

where λ is the wavelength, and θ represents hardware offset. Modern RFID readers, like the Impinj R420, detect movements with precision down to 0.0038 mm, suitable for high-sensitivity applications like respiratory monitoring[13].

A C# program was developed to detect and process respiratory data from passive tags. We recognized, named, and positioned the tags. Initial data collection occurred with the patient seated, then lying for improved relaxation and data quality, as advised by a Sahlgrenska supervisor.

Six tags were used in the lying position to measure respiratory patterns under varying conditions: 30 seconds of normal breathing, 30 seconds of deep breathing, and alternating one-minute cycles of each. Millimeter displacements between inhalation and exhalation phases were calculated for each tag, allowing us to evaluate system sensitivity and accuracy in tracking varied respiratory patterns across multiple tags. Despite its potential, the designed study has several limitations. Factors such as interference from loose clothing, variability in tag placement, and the high sensitivity of RFID phase measurements to minimal distance changes can affect data accuracy. Additionally, the stability of the antenna setup and the need for precise alignment between the RFID reader and tags introduce potential sources of error. Further research will be required to optimize these factors and enhance the robustness of the system for practical use in healthcare settings.

2 Methods

2.1 System Setup

I. Fix antenna

Mount the Alien ALR-8698 RFID Antenna using Vulcan RFID HDMNT-100MM Mounting Bracket to a pole that articulates in the vertical plane for sitting posture and in the horizontal plane for lying posture.

II. Power the reader and Connect to the antenna and computer

Connect Impinj Speedway Revolution R420 UHF RFID Reader (4 Port) with +24VDC power supply to the antenna and route an Ethernet cable from the computer to the reader for data transfer.

III. Prepare tag

Select 6 tags from RFID Tag Sample Pack (UHF (860-960 MHz), Passive) for test. Read ranges on tags varying anywhere from 1 m to 16 m. Each tag has a unique Electronic Product Code (EPC).

IV. User interface

a. ItemTest

Impinj provides a simple, easy-to-use Low-Level Reader Protocol (LLRP) application to use to configure and test the basic RF behavior of Speedway. Open a web browser, enter the reader host name and sign into the reader. Then add data source and initiate communications with the reader. Once click “start”, tag data appears on the interface and can be exported into a CSV file.

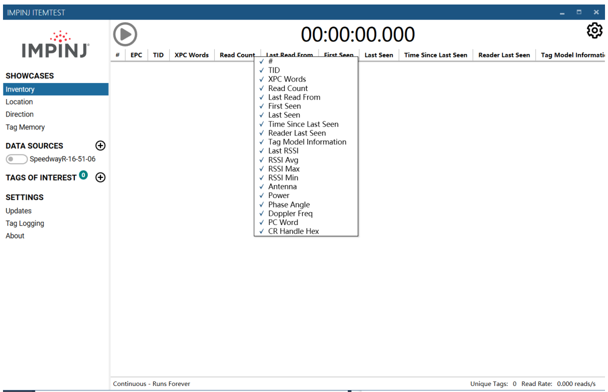


Figure 1: The user interface of ItemTest

b. Octane SDK

The Impinj Octane SDK is a software development kit for developing applications to interact with RFID readers, which provides a set of APIs to help users obtain raw data from readers for tags, as well as perform operations such as tag reading, writing, and programming. The application is built using C# .NET in Visual Studio. The low level data reports raw phase value, RSS, time stamp, and the tag EPC.

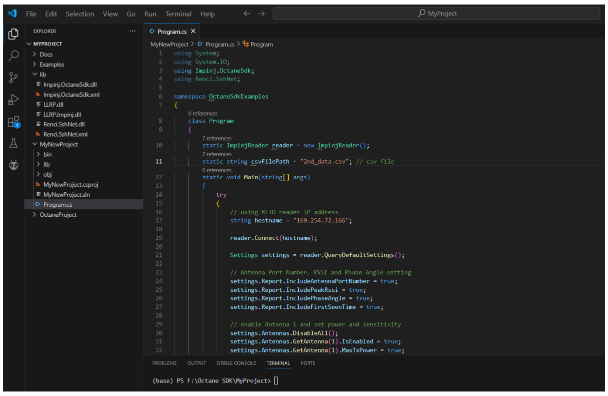


Figure 2: The application developed with Octane SDK in Visual Studio

2.2 Ground truth detection

The sensing element is embedded in the chest strap fabric with adjustable length which measures the overall displacement of the thorax or abdomen. The respiration (RIP) sensor is connected to the 8-Channel biosignalsplux Kit which can record data and communicate with the computer using the OpenSignals (r)evolution application, showing realtime respiration signal as Figure3.

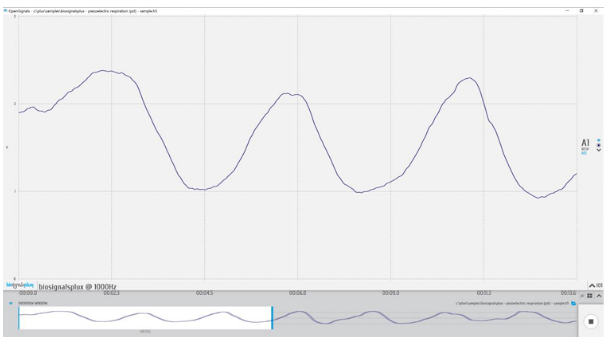


Figure 3: Realtime respiration signal shown by the OpenSignals (r)evolution application

Try to synchronize the data recording of the Octane SDK and the OpenSignals (r)evolution application by making them work at the same time when the test begin.

2.3 Test

Respiratory movements of the chest and abdomen can be different for different people. Normal and deep breathing are different in chest and belly movement pattern. Usually, quiet breathing involves both breathing patterns[14]. Therefore, 6 tags are attatched to the user's cloth at left and right sides of body symmetrically: upper and lower thorax, and abdomen as shown in Figure4, to record the breathing movements of different body parts.

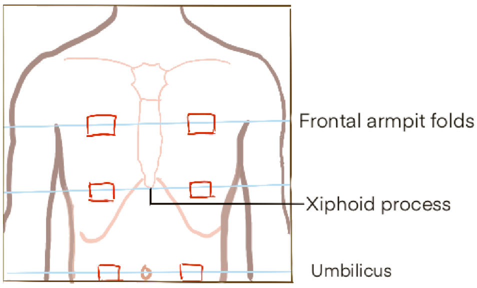


Figure 4: tag deployment

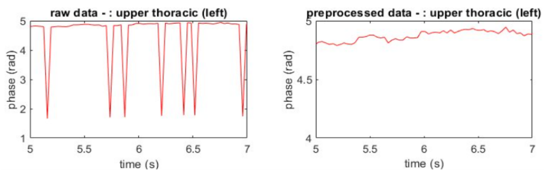
The user naturally breathes lying directly underneath the fixed antenna and stays static during the monitoring process, shown as Figure5 When the user inhales or exhales, his/her abdomen and chest move closer to or further away from the reader antenna, so the distance between the tag and the antenna changes periodically, which can be detected by tracking the changes in phase of the signals backscattered by the tag. Before the test, put the RIP sensor strap on the user's stomach. The users are required to do different breath patterns of normal breath, deep breath and hybird breath (half time for normal breath and half time for deep breath). Each breath monitoring test lasts for 30s or 1min.

Figure 5: Breath monitoring

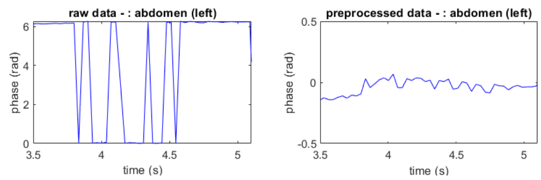
2.4 Data Analysis

2.4.1 Data Pre-Processing

There are two problems of the raw phase data: phase ambiguity and phase transition, which are introduced by the RFID system hardware and the carrier phase winding during signal propagation.
The π radian phase ambiguity is detected when the phase readings of the tag differ by a shift around π at the current moment. The phase wrapping problem refers to the fact that the carrier phase jumps when it reaches the period boundary, for example, the carrier phase jumps from 2π to 0 or from 0 to 2π.



(a) phase ambiguity



(b) Phase transition

Figure 6: Comparison of Phase Monitoring Techniques

2.4.2 Respiratory Rate Extraction

Respiratory rate extraction is divided into three steps: DC (zero frequency) component removal, Butterworth bandpass filtering and Fast Fourier Transform (FFT).
When the reader receives the backscattered signal from the tag, the receiver circuit will introduce a DC component into the respiratory signal. The DC component in the breathing signal is the mean value of the signal sequence. Therefore, it can be removed by subtracting the mean value of the signal sequence from each sample value in the respiratory signal.
A bandpass filter is then applied to eliminate both low- and high-frequency noise from the respiratory signal. Since the human respiratory rate is about 0.2 Hz-0.4Hz [9], the passband range can be set to 0.1 Hz- 1 Hz in order to ensure that the spectrum in the respiratory rate range will not be lost.
One way to estimate the respiration rate is to find the the frequency that corresponds to the maximum power in the frequency spectrum of the filtered signal after fast Fourier transform (FFT). Another way is to count the peaks or valleys of the filtered data.

3 Results

3.1 Data collecting

We collected data under various conditions, using both abdominal and chest breathing techniques. Signals from different body parts are expected to exhibit distinct patterns based on the type of breathing. The collected data are summarized in Table 1. For the sitting data, the breathing type was not specifically labeled, as these measurements were taken at the early stage of the project. Additionally, sitting position detection was later found to be suboptimal for further testing phases.

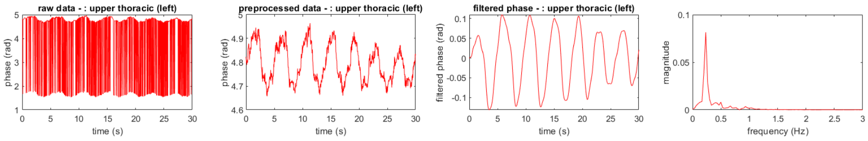
Table 1: Collected Data for Different Breathing Conditions

Collected Data	Abdominal Breath			Chest Breath			Hybrid Breath		
	30s	60s	120s	30s	60s	120s	30s	60s	120s
Lying Data	8	5	3	6	3	3	8	5	3
Sitting Data	16								

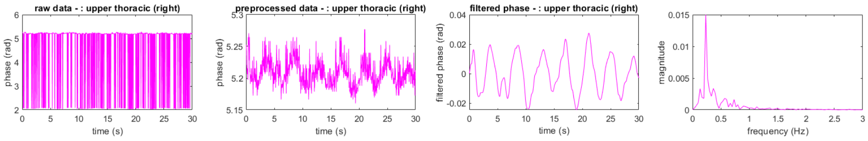
3.2 Result visualization

3.2.1 Normal result

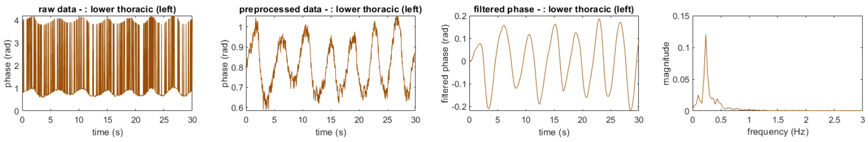
The phase data collected by Reader is the primary focus for data processing in this project. After unwrapping and removing the DC component, the raw data can be transformed back into the original phase data, which can subsequently generate distance data. The result signal can be visualized in 7, separate viewing of signals from different positions can be visualized, making it clearer for the physiotherapists. As shown, there are 7 peaks in 30 seconds, and the dominant frequency resulting from these 6 tags is 0.23 Hz, which is consistent. The graph also clearly shows that different body parts can exhibit different amplitudes during respiration, and the patterns of the left and right pairs should be matched.



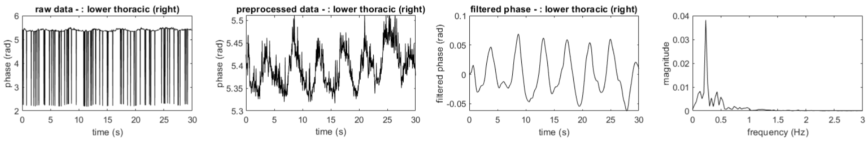
(a) Tag 1



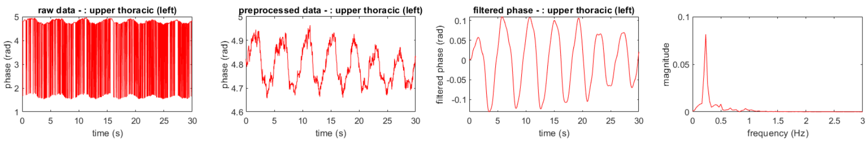
(b) Tag 2



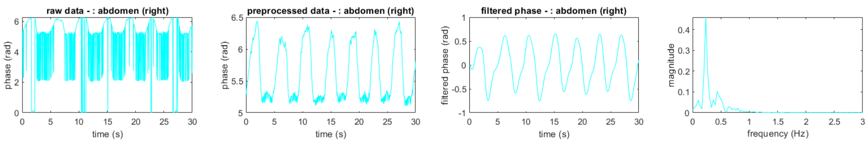
(c) Tag 3



(d) Tag 4



(e) Tag 5



(f) Tag 6

Figure 7: Comparison of Tags 1 to 6

Comparing with the ground reference data from Opensignal (see Fig. 8), to make time synchronize with Octane SDK and allow the system to reach a stable state, the initial 5 seconds of data has been excluded. During the selected data period, 7 peaks were observed in the respiratory signal, aligning with the number of peaks in the processed signal shown in Fig. 7. However, since the ground truth signal is obtained by attaching a belt to the stomach, it is most useful for comparison with the abdominal signals.

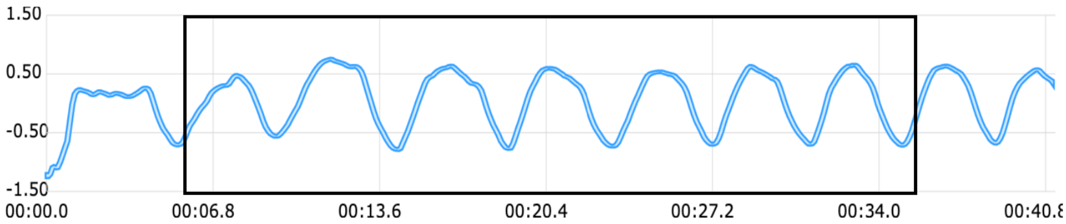
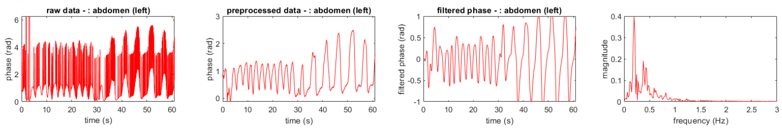


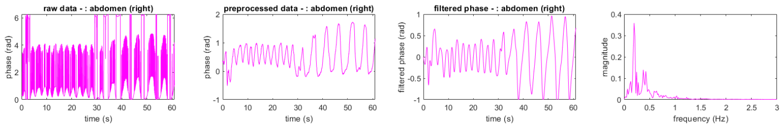
Figure 8: true value

3.2.2 Hybrid result

When the subject switches from normal breath to deep breath, the phase exhibits a significant change, illustrating the movement amplitude of the corresponding body part as in Fig9. The moving distance can also be generated from phase and visualized as in Fig10

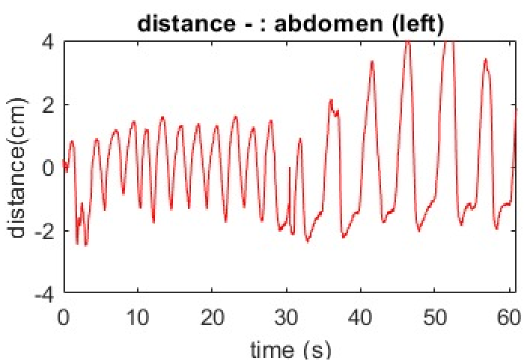


(a) Hybrid breathing tag1

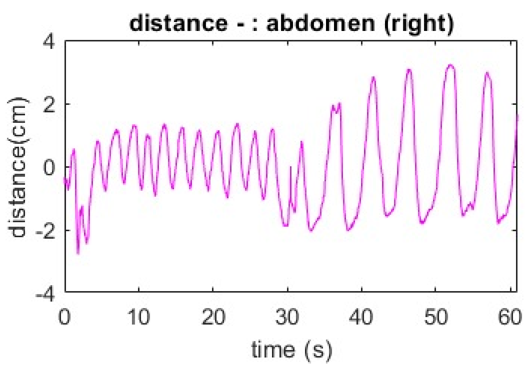


(b) Hybrid breathing tag2

Figure 9: Comparison of two tags results of hybrid breath



(a) Movement distance (left)



(b) Movement distance (right)

Figure 10: Comparison of breath movement

4 Discussion

4.1 Implications of the Results

The results show that RFID technology can effectively track respiratory movements. Calculations from the six tags in the lying position produced clear and consistent readings, highlighting respiratory behavior, especially when the body position and tag placement are carefully optimized. These findings suggest that RFID systems could be reliable,non-intrusive option for continuous respiratory monitoring. Notably, the amplitude of signals from different sides of the body varies significantly, which is expected due to the natural asymmetry in human physiology.

4.2 Limitations of the Study

Several factors limited the accuracy and consistency of our results. First, the patient's clothing had a notable effect: a loose T-shirt caused extra shifts in phase measurement, which affected the calculated displacement between inhalation and exhalation. A tighter, well-fitted T-shirt would likely reduce this variability by minimizing extra movement that interferes with phase measurements. Another limitation was the antenna setup. Without a stable structure, the antenna was placed on two chairs, which made aligning it with the tags challenging. This setup sometimes led to inconsistent data for tags not fully within the antenna's range, resulting in occasional missed or incorrect readings. Additionally, each tag collected a different number of samples, which may have impacted the accuracy of the displacement measurements. Finding the best placement for the tags was also essential but difficult. Tags placed inconsistently affected data accuracy, especially when monitoring different breathing conditions. The close proximity of multiple tags created interference, making it harder to separate data from individual tags. To address this, we removed other tags from the environment to focus solely on respiratory monitoring

4.3 Future work

Future studies could address these limitations through several improvements. Using a stretchable, well fitted T-shirt with integrated tags would likely to enhance data consistency by minimizing phase changes due to loose fabric. While different patient sizes present a challenge, exploring flexible fabrics could accommodate various body types while ensuring secure tag placement.

A structured setup with a well-positioned antenna would also improve data capture. In a controlled environment with reduced interference, signal quality would likely improve, leading to more reliable results. Expanding the study to include more participants with different body types and breathing patterns would further strengthen the system's reliability.

As it is still challenging to synchronize the start time of both the Opensignal and our C programto obtain a more precise ground truth, a dummy could be used to simulate the movement of the human body.

Incorporating adaptive algorithms could improve RFID monitoring by accounting for slight body movements, distinguishing respiratory patterns across multiple users, and reducing signal interference. Real-time plotting would enable immediate visualization of breathing patterns, providing valuable insights for clinical assessments and at-home monitoring. These advancements could make RFID-based respiratory monitoring a dependable and scalable solution for a range of applications.

5 Conclusion

In conclusion, this study demonstrates the potential of RFID technology as a reliable, non-intrusive solution for respiratory monitoring, addressing limitations found in traditional respiratory assessment methods. Using passive RFID tags to track respiratory motion, we could effectively capture the periodic chest and abdominal movements associated with breathing. Calculations based on phase shifts from multiple tags positioned on the thorax and abdomen yielded consistent measurements of inhalation and exhalation displacement, indicating a high sensitivity to even millimeter-scale movements. This approach overcomes several limitations associated with conventional methods, such as the need for stationary setups or invasive contact. By developing a custom C# application to capture raw phase data, we increased the sensitivity and robustness of data collection. This method shows promise for clinical and home settings, particularly in monitoring patients with restrictive or obstructive pulmonary diseases, neurological conditions, and postoperative respiratory challenges. While the results are promising, challenges remain, including minimizing the interference from loose clothing, refining antenna alignment, and optimizing tag placement. The precision of phase data also makes it sensitive to minimal shifts, which introduces complexities but underscores the capability of RFID technology in detecting subtle respiratory patterns. Future work could involve improving setup stability, enhancing data filtering techniques, and conducting further tests with various breathing patterns and postures. These advancements may help establish RFID-based respiratory monitoring as a standard practice in non-invasive patient monitoring, with broad applications in healthcare and wellness monitoring.

References

[1] Z. Cao, R. Zhu, and R.-Y. Que, "A wireless portable system with microsensors for monitoring respiratory diseases," *IEEE Transactions on Biomedical engineering*, vol. 59, no. 11, pp. 3110–3116, 2012.

[2] M. Fagevik Olsén and K. Romberg, "Reliability of the respiratory movement measuring instrument, rmmi," *Clinical Physiology and Functional Imaging*, vol. 30, no. 5, pp. 349–353, 2010. DOI: 10.1111/j.1475-097X.2010.00951.x.

[3] K. Van Loon, B. van Zaane, E. J. Bosch, C. J. Kalkman, and L. M. Peelen, "Non-invasive continuous respiratory monitoring on general hospital wards: A systematic review," *PLoS One*, vol. 10, no. 12, e0144626, 2015.

[4] B. S. Kodali, "Capnography outside the operating rooms," *The Journal of the American Society of Anesthesiologists*, vol. 118, no. 1, pp. 192–201, 2013.

[5] L. Nilsson, A. Johansson, and S. Kalman, "Monitoring of respiratory rate in postoperative care using a new photoplethysmographic technique," *Journal of clinical monitoring and computing*, vol. 16, pp. 309–315, 2000.

[6] C. Occhiuzzi, C. Caccami, S. Amendola, and G. Marrocco, "Breath-monitoring by means of epidermal temperature rfid sensors," in *2018 3rd International Conference on Smart and Sustainable Technologies (SpliTech)*, IEEE, 2018, pp. 1–4.

[7] J. Shang and J. Wu, "Fine-grained vital signs estimation using commercial wi-fi devices," in *Proceedings of the Eighth Wireless of the Students, by the Students, and for the Students Workshop*, 2016, pp. 30–32.

[8] T. Wang, D. Zhang, L. Wang, *et al.*, "Contactless respiration monitoring using ultrasound signal with off-the-shelf audio devices," *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 2959–2973, 2019. DOI: 10.1109/JIOT.2018.2877607.

[9] X. Zang and C. Li, "A multi-person rfid-based respiratory monitoring system," *IEEE Transactions on Biomedical Engineering*, vol. 69, no. 7, pp. 1763–1774, 2022.

[10] W. Zhang and L. Chen, "Accurate respiration monitoring with paired rfid tags," *IEEE Transactions on Mobile Computing*, vol. 19, no. 5, pp. 1168–1179, 2020.

[11] A. Hussain and Y. Fang, "Cost-effective rfid monitoring of respiratory cycles in dynamic environments," *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 3245–3256, 2019.

[12] Y. Yang, J. Cao, and Y. Wang, "Robust rfid-based respiration monitoring in dynamic environments," *IEEE Transactions on Mobile Computing*, vol. 22, no. 3, pp. 1717–1730, 2023. DOI: 10.1109/TMC.2021.3106954.

[13] L. Yang, Y. Chen, X.-Y. Li, C. Xiao, M. Li, and Y. Liu, "Tagoram: Real-time tracking of mobile rfid tags to high precision using cots devices," in *Proceedings of the 20th Annual International Conference on Mobile Computing and Networking*, 2014, pp. 237–248.

[14] M. Higashino, K. Miyata, and K. Kudo, "Coordination dynamics of thoracic and abdominal movements during voluntary breathing," *Scientific Reports*, vol. 12, no. 1, p. 13 266, 2022. DOI: 10.1038/s41598-022-17473-9.