Longitudinal Respiratory Rate Monitoring Using Wearable Devices Reveals Cardiorespiratory Coupling and Circadian Physiological Patterns

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Background

Why did we choose respiratory rate?
Respiratory rate (RR) is one of the four classic vital signs and a sensitive early marker of physiological stress, illness, and autonomic dysfunction. We chose this biomarker due to the clean RR signal nightly acquisition from Apple Watch.

Why does respiratory rate measure physiologically?
Respiratory rate measures breaths per minute and reflects the body's metabolic demand for oxygen exchange. It is tightly regulated by brainstem respiratory centers, making deviations from baseline potential indicators of physiological stress or illness.

How do wearables measure RR?
Photoplethysmography (PPG) sensor emits light (ex. green LED) into vascularized tissue and detects the reflected light with a photodetector, capturing beat-to-beat blood volume changes in the blood vessels to continuously estimate respiratory parameters.

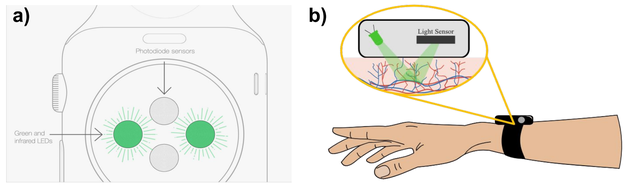


Fig 1. *(a) Apple Watch PPG Sensor Design, (b) PPG Sensor Reflective Mechanism.*

RR is estimated from periodic breathing-induced fluctuations in the PPG waveform via respiratory-induced amplitude variation (RIAV).

Cases:
Early detection of respiratory infections, Sleep monitoring and detection of sleep-related breathing disturbances, Monitoring physiological recovery and stress

Research Question:
Can longitudinal wearable respiratory rate data reveal physiological patterns and deviations associated with cardiovascular activity and circadian regulation?

Hypothesis: Respiratory rate will remain relatively stable over time but will increase during periods of elevated heart rate, reflecting shared autonomic regulation between the respiratory and cardiovascular systems.

Methods

Dataset Overview: Wearable physiological data from **one female pregnant participant** were analyzed, including: The dataset contained:~33,000 respiratory rate observations and ~485,000 heart rate observations

Preprocessing: To synchronize signals across modalities: 1) Timestamps were converted to datetime format. 2) Both signals were resampled to hourly averages. 3) Respiratory and heart rate measurements were aligned by timestamp. 4) Observations with missing values were removed. This produced N ≈ 1,400 paired observation

Analysis: 1) Respiratory baseline deviation analysis: Respiratory rate time series were compared to the individual's mean and standard deviation to identify physiological deviations.
2) Cardiorespiratory coupling: The relationship between heart rate and respiratory rate was evaluated using correlation and density visualization.
3) Circadian physiological patterns: Mean heart rate and respiratory rate were computed for each hour of the day to examine circadian trends.

Results

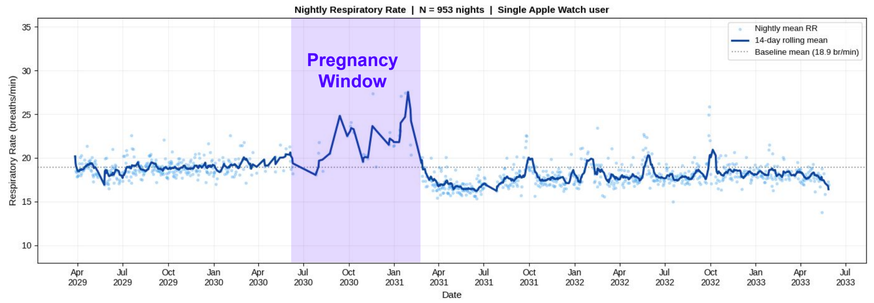


Fig 2. *Nightly RR time series (N = 792 nights). Dotted line = baseline mean.*

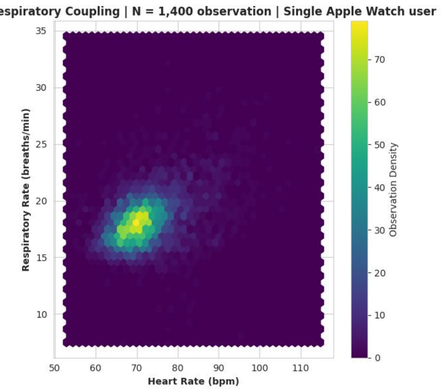


Fig 3. *Cardiorespiratory coupling evaluated using correlation and density visualization (N = 1400 nights).*

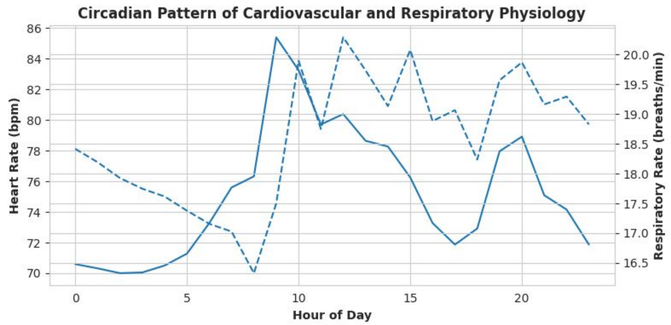


Fig 4. *Circadian physiological patterns computed for each hour of the day.*

Table 1. *Key Signal Parameters for Single User of Apple Wearable Device*

N (Nights)	Mean RR	CV (RR)	RR - HR
792	18.4 ± 1.5 breath/min	5.5 %	r = 0.51, p<0.001

Discussion

Results Interpretation

- Respiratory rate remained relatively stable across the observation period (with the exception of the period between July 2030-Feb 2031) supporting that respiratory rate exhibits low variability in healthy individuals.
- RR elevated from 18.9 to 21.5 br/min (+2.6 br/min) between July 2030-Feb 2031, consistent with pregnancy-related diaphragm elevation and increased metabolic demand, with a return to baseline consistent with delivery.
- Respiratory rate showed a positive association with heart rate, reflecting cardiorespiratory coupling mediated by autonomic nervous system regulation.
- Both physiological signals exhibited clear circadian trends consistent with normal daily autonomic rhythms.

Interpretation guide

Higher HR + Higher RR → exercise or physiological stress
Higher HR, Stable RR → emotional stress or postural changes
Higher RR Spikes → illness, exertion, or sensor noise

Alternative explanations & confounders
PPG-derived RR is susceptible to motion artifacts and irregular cardiac rhythms, especially with a user that showcases pregnancy. Additionally, sleep stages were not taken into consideration when decoupling RR

Practical implication
Rather than fixed clinical thresholds (>20 br/min), a wearable could flag deviations exceeding 2 SD above the user's personal longitudinal mean (i.e. >21.0 br/min) providing a more sensitive and individualized early warning for illness or physiological stress.

Class Insight

This class taught us about all the different types of sensors within wearable devices and all the potential biomarker data that can be extrapolated using advanced algorithms. The most insightful experience was getting to use a Oura ring wearable device for the first time for both of us and look at our data in detail :)



Fig 5. First wearable device!