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Remote wearable-based monitoring and environmental exposure for early detection of clinical deterioration in chronic respiratory diseases: a prospective cohort study

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Abstract

Background:

Chronic respiratory diseases (CRDs) are highly prevalent and frequently exacerbated by environmental factors, contributing substantially to morbidity, mortality, and healthcare burden worldwide. Early detection of clinical deterioration remains a major challenge in disease management, particularly in real-world settings. Wearable technologies offer a promising approach for continuous monitoring of physiological parameters and may enable early identification of changes preceding symptom worsening.

Methods:

This prospective cohort study included 30 patients with CRDs, of whom 22 completed a 12-month follow-up in the metropolitan region of São Paulo, Brazil. Participants were monitored using a wearable device (Garmin Venu® SQ) to continuously record heart rate (HR) and peripheral oxygen saturation (SpO_2). Environmental data, including air pollution and climatic variables, were obtained from official monitoring systems, and symptom reports were collected through structured questionnaires. Multivariate logistic regression models were used to identify predictors of cough, while linear regression models were applied to evaluate factors associated with dyspnea and physiological parameters.

Results:

Heart rate was significantly associated with comorbidities, sex, and oxygen therapy use. Peripheral oxygen saturation showed inverse correlations with nitrogen dioxide (NO_2) and ozone (O_3) concentrations. Female sex, lower body mass index, presence of comorbidities, and severe airway obstruction were identified as predictors of cough. Dyspnea was associated with demographic and clinical variables, as well as environmental exposure, particularly morning ozone levels. In addition, environmental and climatic variations were associated with fluctuations in physiological parameters and symptom occurrence throughout the day.

Conclusion:

Wearable-based remote monitoring is a feasible and clinically relevant strategy for early detection of physiological changes associated with clinical deterioration in patients with CRDs. Environmental pollutants, particularly ozone, significantly influence respiratory outcomes, highlighting the importance of integrating digital health technologies with environmental monitoring to support proactive and personalized disease management.

Introduction

Chronic respiratory diseases (CRDs) comprise a heterogeneous group of conditions affecting both the upper and lower airways, among which chronic obstructive pulmonary disease (COPD) is the most prevalent. COPD affects approximately 210 million individuals worldwide and is the third leading cause

of death, accounting for 4.8% of global mortality (1, 2). In Brazil, the population-based PLATINO study conducted in São Paulo reported a COPD prevalence of 15.6% among individuals aged over 40 years, with approximately 25% of smokers being affected (3). It is estimated that around 7.5 million individuals in Brazil live with COPD, resulting in substantial impairment in quality of life, increased disability, and significant economic burden.

In addition to COPD, CRDs include interstitial lung diseases, bronchiectasis, and post-COVID respiratory conditions, which, although less prevalent, contribute considerably to morbidity and healthcare utilization (4–6). These conditions are frequently underdiagnosed, and their true burden may be underestimated due to limited epidemiological data (5, 6).

Recent technological advances have expanded opportunities to improve healthcare delivery, particularly through digital health, telemedicine, and wearable technologies. These tools enable continuous remote monitoring of physiological parameters, supporting early detection of clinical deterioration and facilitating more personalized and preventive care. Evidence suggests that digital health interventions may improve clinical outcomes, reduce complications, and enhance healthcare efficiency in chronic disease management (7–10). In this context, wearable devices have emerged as promising tools for integrating real-time physiological data into clinical decision-making.

Environmental exposure plays a critical role in respiratory health. The metropolitan region of São Paulo, particularly the ABC Paulista area, is characterized by high levels of air pollution due to intense vehicular traffic, industrial activity, and climatic variability (11, 12). Exposure to air pollutants has been consistently associated with increased mortality and morbidity, particularly from respiratory and cardiovascular diseases (13–15). Additionally, environmental factors such as temperature and humidity influence airway reactivity, symptom burden, and exacerbation risk (15–17). Even short-term reductions in pollutant exposure have been shown to improve lung function, highlighting the dynamic interaction between environmental conditions and respiratory health (17).

Despite growing interest in digital health, the use of wearable-based remote monitoring in CRDs remains insufficiently validated in real-world settings, particularly in middle-income countries. Moreover, the integration of continuous physiological monitoring with environmental exposure data to predict early clinical deterioration has not been fully established.

Therefore, this study aimed to evaluate the use of a wearable device for home monitoring of heart rate (HR) and peripheral oxygen saturation (SpO_2) in patients with chronic respiratory diseases, in order to detect early signs of clinical deterioration and to investigate the influence of environmental and climatic factors on respiratory outcomes.

Study design and setting

This was a prospective prognostic cohort study including patients with chronic respiratory diseases (CRDs) who were followed at home using a remote monitoring strategy. The study was reported in

accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines.

The study was conducted in municipalities within the Metropolitan Region of São Paulo, Brazil. Participants resided in Diadema, Mauá, Santo André, São Bernardo do Campo, São Caetano do Sul, and São Paulo, and were followed at a pulmonology outpatient clinic. Recruitment and follow-up were carried out between September 2023 and September 2024. Clinical trial number: not applicable.

Participants

Eligible participants were adults with a confirmed diagnosis of CRD under regular follow-up at the pulmonology service.

Inclusion criteria were: confirmed diagnosis of CRD; history of exposure to risk factors (active or passive smoking, environmental pollutants, or other inhalational exposures); and spirometric criteria defined as:

- Obstructive pattern: post-bronchodilator $FEV_1/FVC < 0.70$ or bronchodilator response ≥ 200 mL, consistent with COPD (18);
- Restrictive pattern: $FEV_1/FVC \geq 0.70$ with $FVC < 80\%$ and $FEV_1 < 80\%$, compatible with fibrosing interstitial lung diseases.

Exclusion criteria included: absence of maintenance pulmonary treatment, hospitalization within the previous month, or exacerbation within the previous 15 days.

Participants were stratified according to the risk of exacerbation and hospitalization using the Global Initiative for Chronic Obstructive Lung Disease (GOLD) classification (groups A, B, or E) (18). For standardization, this classification was adapted to other interstitial lung diseases included in the sample. Each stage was defined based on spirometric findings, symptom burden, and exacerbation risk.

Data collection and monitoring

Participants were monitored using a wearable device (Garmin smartwatch, Venu® SQ model) integrated with the HumanITCare® platform, which continuously recorded heart rate (HR) and peripheral oxygen saturation (SpO_2).

A structured questionnaire assessing respiratory symptoms and their association with climatic variations was also administered.

All participants underwent an initial clinical assessment, during which detailed instructions on device use and the 12-month monitoring protocol were provided. When abnormal physiological parameters were detected by the platform, patients were contacted and received clinical guidance.

Clinical deterioration was defined a priori as the occurrence of worsening respiratory symptoms (cough, dyspnea, or increased sputum production) associated with either a ≥ 20% increase in baseline HR or a ≥ 4% decrease in baseline SpO_2.

Environmental data

Environmental variables, including air humidity, temperature variation, and air pollution parameters, were collected daily from official monitoring systems, including CETESB (Companhia Ambiental do Estado de São Paulo) and Climatempo (12, 19, 20).

Pollutants measured included particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), ozone (O_3), and carbon monoxide (CO).

Outcomes

The primary outcome was clinical deterioration, defined as an increase of ≥ 20% in baseline HR and/or a decrease of ≥ 4% in baseline SpO_2, associated with worsening respiratory symptoms.

These thresholds are supported by previous evidence indicating that physiological changes precede clinical exacerbations in chronic respiratory diseases.

The secondary outcome was the occurrence of clinical worsening (cough, dyspnea, or healthcare utilization) in relation to environmental exposure, defined as:

- Relative humidity < 60%;
- Temperature variation > 3°C;
- Increased levels of air pollution, according to World Health Organization thresholds (19):
    - $PM_{2.5}$: annual mean 5 μg/m³; 24-hour mean 15 μg/m³
    - PM_{10}: annual mean 15 μg/m³; 24-hour mean 45 μg/m³

Symptom occurrence (cough and dyspnea), reported in the questionnaires, was also considered as outcome variables.(Supplementary Material)

Predictor variables

Predictor variables included:

- Demographic variables: age, sex
- Clinical variables: body mass index, comorbidities, oxygen therapy use, disease severity
- Environmental variables: temperature, humidity, pollutant levels, wind speed

- Physiological variables: heart rate (HR) and peripheral oxygen saturation (SpO_2)

This was an observational study; therefore, it was not registered as a clinical trial.

Statistical analysis

All data were expressed as mean ± standard deviation (SD) for continuous variables and as absolute and relative frequencies for categorical variables. The distribution of continuous variables was assessed for normality using the Shapiro–Wilk test. Parametric or non-parametric methods were applied as appropriate.

The association between peripheral oxygen saturation (SpO_2) and environmental variables obtained from CETESB monitoring stations was evaluated using correlation analysis (Pearson or Spearman, as appropriate) and linear regression models. Similarly, the relationship between heart rate (HR) and environmental variables was assessed using the same approach.

To estimate the association between selected predictors and the occurrence of respiratory symptoms, logistic regression models were used to identify predictors of cough, and linear regression models were used to evaluate factors associated with dyspnea and physiological variables. Results from logistic regression analyses were expressed as odds ratios (OR) with 95% confidence intervals (95% CI), while results from linear regression analyses were expressed as β coefficients with 95% confidence intervals.

Initially, univariate logistic regression analyses were performed. Variables with $p \leq 0.25$ were considered eligible for inclusion in the multivariate model to avoid the exclusion of potentially relevant predictors.

Multivariate logistic regression models were constructed using a forward stepwise selection approach, with sequential inclusion of variables based on statistical significance and improvement in model fit, assessed using maximum likelihood estimation. This approach was used for exploratory purposes.

Potential multicollinearity among independent variables, particularly environmental parameters, was assessed using variance inflation factors (VIF).

A two-tailed significance level of $p < 0.05$ was adopted for all analyses.

All statistical analyses were performed using Stata version 16 (StataCorp LLC, College Station, TX, USA).

Results

Study population

A total of 33 patients were initially recruited. After exclusions due to device incompatibility (n=4), allergy to the watch strap (n=2), device-related issues (n=2), and non-adherence or withdrawal (n=3), 22 participants completed the 12-month follow-up and were included in the final analysis. All participants were enrolled in a pulmonary rehabilitation program at Centro Universitário FMABC, Santo André, Brazil.

As shown in Table 1, the majority of participants were female and aged over 60 years. Approximately 50% were former smokers. Comorbidities were present in 62% of the sample, including systemic arterial hypertension (40.9%), diabetes mellitus (18%), and hypothyroidism (13.6%). Most participants were overweight or obese (68%). COPD was the predominant diagnosis (71%), with moderate airway obstruction in 48% and severe obstruction in 29% of cases. Most participants were not receiving home oxygen therapy.

Table 1. Baseline demographic and clinical characteristics of patients with chronic respiratory diseases

Variable	Adjusted OR	95% CI	p-value
Gender			
Female	4.129	2.985 – 5.711	<0.001
Age	1.008	0.998 – 1.019	0.108
Presence of comorbidities			
Yes	2.738	2.002 – 3.745	<0.001
Body Mass Index (BMI)	0.939	0.914 – 0.964	<0.001
Use of oxygen therapy			
Yes	1.991	1.354 – 2.927	<0.001
Spirometric classification of COPD severity			
GOLD 1 (mild obstruction)	1.000	—	—
GOLD 2 (moderate obstruction)	2.682	1.556 – 4.624	<0.001
GOLD 3 (severe obstruction)	2.024	1.090 – 3.760	0.026
GOLD 4 (very severe obstruction)	4.963	2.202 – 11.188	<0.001
Heart rate	1.012	1.001 – 1.024	0.046
Oxygen saturation	0.809	0.755 – 0.866	<0.001
NO_2 concentration at 6 AM	1.001	0.987 – 1.014	0.922
Ozone concentration at 6 AM	0.994	0.986 – 1.003	0.191
Particulate matter at 6 AM	1.005	0.992 – 1.018	0.441
Relative humidity at 6 AM	0.999	0.987 – 1.013	0.997

Monitoring data and clinical events

During the follow-up period, 13 participants underwent continuous monitoring using the Garmin Venu® SQ smartwatch, generating a total of 152 clinical alerts recorded by the platform. Of these, 94 were related to heart rate (HR) alterations and 62 to peripheral oxygen saturation (SpO_2) reductions. In several cases, both parameters changed simultaneously.

A total of 59 cough episodes were recorded, frequently associated with concurrent changes in HR and/or SpO_2. No episodes of fever were reported. Four emergency department visits occurred, and no hospitalizations were observed.

Environmental and climatic conditions

Table 2 presents environmental and meteorological parameters according to time of day. At 6 a.m., ozone concentrations averaged 29 μg/m³, exceeding the World Health Organization (WHO) recommended 1-hour limit of 25 μg/m³, and decreased to 23 μg/m³ later in the day. Carbon monoxide levels remained within acceptable limits throughout the observation period, while nitrogen dioxide (NO_2) levels were higher in the morning.

Table 2 Environmental and meteorological parameters according to time of day.

Environmental Variable	Mean	Min Value	Max Value
Nitrogen dioxide concentration at 6 AM	29,47	4	110
Carbon monoxide concentration at 6 AM	0,43	0,1	5
Ozone concentration at 6 AM	27,41	1	87
Particulate matter concentration at 6 AM	15,05	0	88
Wind speed at 6 AM	1,28	0,5	9,9
Relative humidity at 6 AM	83,77	45	98
Nitrogen dioxide concentration at 2 PM	23,49	7	89
Carbon monoxide concentration at 2 PM	0,36	0,1	0,8
Ozone concentration at 2 PM	94,49	0,5	229
Particulate matter concentration at 2 PM	18,66	0	81
Wind speed at 2 PM	2,49	0,9	4,6
Relative humidity at 2 PM	56,55	17	94

Ozone concentrations increased substantially during the day, rising from 27 μg/m³ in the morning to 94 μg/m³ in the afternoon, reaching levels classified as moderate and potentially associated with respiratory effects.

Data from Climatempo® monitoring systems demonstrated clear diurnal variation, with lower temperatures (17–18°C) and higher relative humidity (80–85%) in the morning, compared to higher temperatures (27–28°C) and lower humidity (40–50%) in the afternoon.

Physiological responses and symptom patterns

As shown in Table 3, heart rate was significantly higher in the afternoon compared to the morning (82 ± 6 bpm vs 72 ± 5 bpm; $p < 0.05$), while SpO_2 remained relatively stable (95.0 ± 0.9% vs 94.1 ± 1.3%; $p > 0.05$). Cough and dyspnea episodes were more frequent during morning periods ($p < 0.05$).

Table 3. Diurnal variation of environmental conditions, physiological parameters, and respiratory symptoms

Variable	Morning (6:00 a.m.)	Afternoon (2:00 p.m.)	p-value
Temperature (°C)	17.6 ± 0.8	27.9 ± 1.2	< 0.01
Relative humidity (%)	83.2 ± 4.5	45.6 ± 6.3	< 0.01
Heart rate (bpm)	72 ± 5	82 ± 6	< 0.05
SpO_2 (%)	94.1 ± 1.3	95.0 ± 0.9	0.12
Cough episodes (n)	39	20	< 0.05
Dyspnea episodes (n)	35	18	< 0.05

Data are presented as mean ± standard deviation unless otherwise indicated. P-values refer to comparisons between morning and afternoon measurements.

Predictors of cough

Table 4 presents the results of the multivariate logistic regression model for cough. Significant predictors included female sex (OR 4.13), body mass index (OR 0.94), presence of comorbidities (OR 2.74), SpO_2 (OR 0.81), oxygen therapy use (OR 2.00), severity of airway obstruction (OR up to 4.90), and HR (OR 1.01). Environmental variables were not significantly associated with cough.

Table 4. Multivariate logistic regression analysis for predictors of cough

Variable	Adjusted OR	95% CI	p-value
Gender			
Female	4.129	2.985 – 5.711	<0.001
Age	1.008	0.998 – 1.019	0.108
Presence of comorbidities			
Yes	2.738	2.002 – 3.745	<0.001
Body Mass Index (BMI)	0.939	0.914 – 0.964	<0.001
Use of oxygen therapy			
Yes	1.991	1.354 – 2.927	<0.001
COPD severity (spirometric classification)			
GOLD 1 (mild obstruction)	1.000	—	—
GOLD 2 (moderate obstruction)	2.682	1.556 – 4.624	<0.001
GOLD 3 (severe obstruction)	2.024	1.090 – 3.760	0.026
GOLD 4 (very severe obstruction)	4.963	2.202 – 11.188	<0.001
Heart rate	1.012	1.001 – 1.024	0.046
Oxygen saturation	0.809	0.755 – 0.866	<0.001
NO_2 concentration at 6 AM	1.001	0.987 – 1.014	0.922
Ozone concentration at 6 AM	0.994	0.986 – 1.003	0.191
Particulate matter at 6 AM	1.005	0.992 – 1.018	0.441
Relative humidity at 6 AM	0.999	0.987 – 1.013	0.997

Predictors of dyspnea

Table 5 shows predictors of dyspnea. female sex, age, comorbidities, BMI, oxygen therapy, COPD severity, heart rate, and ozone concentration at 6 a.m. were associated with dyspnea.

Table 5. Multivariate linear regression analysis of factors associated with dyspnea

Variable	Adjusted OR	95% CI	p-value
Female sex	3.09	2.17–4.39	<0.001
Age (years)	0.98	0.97–0.99	<0.001
Comorbidities (yes)	1.80	1.26–2.58	0.001
BMI (kg/m²)	0.92	0.90–0.94	<0.001
Oxygen therapy (yes)	3.69	2.49–5.49	<0.001
GOLD 1 (reference)	1.00	—	—
GOLD 2	1.76	0.98–2.17	0.060
GOLD 3	1.61	0.83–3.12	0.155
GOLD 4	18.29	6.98-31.16	<0.001
HR (bpm)	1.04	1.03–1.05	<0.001
SpO_2 (%)	0.99	0.92–1.06	0.745
NO_2 (6 a.m.)	0.996	0.982–1.001	0.548
Ozone (6 a.m.)	0.989	0.980–0.998	0.019
$PM_{2.5}$ (6 a.m.)	1.004	0.989–1.017	0.610
Relative humidity (6 a.m.)	0.989	0.975–1.002	0.099

Associations between physiological and environmental variables

Table 6 demonstrates associations between HR and clinical variables. HR showed a positive association with comorbidities and oxygen therapy use, and a weak inverse association with age.

Table 6. Multivariate linear regression analysis of factors associated with heart rate

Variable	β coefficient (95% CI)	p-value
Female sex	6.96 (6.26–7.66)	<0.001
Age (years)	-0.10 (-0.12–-0.08)	<0.001
Comorbidities (yes)	3.42 (2.77–4.08)	<0.001
Oxygen therapy (yes)	2.17 (1.42–2.93)	<0.001
COPD severity (GOLD)	-0.36 (-0.75–0.03)	0.071
NO_2 (6 a.m., μg/m³)	-0.002 (-0.038–0.033)	0.894
CO (6 a.m., μg/m³)	0.88 (-1.76–3.51)	0.514
Ozone (6 a.m., μg/m³)	-0.005 (-0.028–0.017)	0.647
$PM_{2.5}$ (6 a.m., μg/m³)	-0.001 (-0.037–0.036)	0.976
Wind speed (6 a.m., m/s)	-0.35 (-0.76–0.07)	0.099
Relative humidity (2 p.m., %)	-0.03 (-0.05–-0.01)	0.002

Table 7 presents correlations between SpO_2 and clinical and environmental variables. Female sex showed an inverse association with SpO_2. NO_2 levels at 6 a.m. and ozone levels at 2 p.m. demonstrated weak inverse correlations with SpO_2. Carbon monoxide showed a strong positive correlation with SpO_2 (r = 0.98), while wind speed showed a weak inverse correlation.

Table 7. Multivariate linear regression analysis of factors associated with SpO_2

Variable	β coefficient (95%CI)	p-value
Female sex	-0.42 (-0.54–-0.29)	<0.001
Age (years)	0.001 (-0.004–0.005)	0.837
Oxygen therapy (yes)	0.59 (0.45–0.73)	<0.001
COPD severity (GOLD)	-0.01 (-0.08–0.06)	0.770
NO_2 (6 a.m., μg/m³)	-0.004 (-0.007–-0.001)	0.048
CO (2 p.m., μg/m³)	0.99 (0.43–1.55)	0.001
Ozone (2 p.m., μg/m³)	-0.003 (-0.008–-0.001)	0.006
Wind speed (2 p.m., m/s)	-0.09 (-0.18–-0.003)	0.044
Relative humidity (2 p.m., %)	-0.001 (-0.005–0.003)	0.643

Discussion

This study provides evidence that wearable-based remote monitoring is a feasible and clinically relevant strategy for continuous assessment of physiological parameters in patients with chronic respiratory diseases. Both heart rate (HR) and peripheral oxygen saturation (SpO_2) were significantly associated with the occurrence of cough and dyspnea, supporting the ability of wearable technology to detect early physiological changes preceding symptom worsening.

Regarding environmental exposure, higher concentrations of carbon monoxide (CO) and ozone (O_3) were associated with lower SpO_2 levels. A weaker inverse correlation between nitrogen dioxide (NO_2) and SpO_2 also reinforces the contribution of pollutant exposure to transient desaturation, consistent with previous findings (21).

These results align with previous literature showing that continuous exposure to nitrogen dioxide may trigger pulmonary inflammation, bronchoconstriction, and increased airway reactivity, leading to reduced respiratory capacity and hypoxemia (21). Similarly, studies have demonstrated a direct correlation between air pollution and hospital admissions for respiratory diseases, particularly among older adults and children (22).

The observed relationship between CO, HR, and SpO_2 reveals a complex and potentially hazardous pathophysiological interaction. However, the strong correlation observed between CO and SpO_2 (r = 0.98)

should be interpreted with caution, as it may reflect temporal co-variation with environmental factors (e.g., temperature and time of day) rather than a direct causal relationship(24).

Environmental factors are well-recognized modulators of respiratory stability (25–27). Air quality and humidity are crucial determinants of clinical balance in patients with CRD (25, 26). Low humidity impairs mucociliary clearance, predisposing patients to infection and exacerbation (27). The association between pollutant exposure and increased respiratory symptoms observed in this study is consistent with previous findings demonstrating that urban pollutants induce airway inflammation and exacerbate symptoms in vulnerable individuals (28).

Continuous monitoring via wearable devices proved to be a sensitive and practical tool for identifying early physiological alterations related to environmental fluctuations. This approach is consistent with modern trends in personalized and proactive respiratory care, allowing healthcare professionals to detect risk patterns and intervene before symptom escalation.

Temperature variation also played an important role in the physiological responses observed. Lower temperatures were associated with transient reductions in SpO_2 and increased cough and dyspnea, often accompanied by mild tachycardia. In contrast, higher temperatures were related to elevated HR without significant desaturation, likely reflecting thermoregulatory adaptation.

Physiologically, low temperatures promote bronchial vasoconstriction, impair mucociliary clearance, and increase airway resistance, resulting in transient desaturation. Conversely, high temperatures favor ozone formation, intensifying airway inflammation and oxidative stress (29, 30). The interaction between temperature and pollutants appears synergistic, amplifying clinical effects. Epidemiological data corroborate these findings, showing increased respiratory exacerbations associated with temperature extremes and climatic variability (29–31).

These results reinforce the need to incorporate meteorological data into remote monitoring protocols, as temperature and humidity fluctuations can precipitate respiratory instability even before patients perceive symptoms.

Female patients exhibited more frequent dyspnea, cough, higher HR, and lower SpO_2 than males. Previous studies have shown that women experience greater dyspnea despite similar airflow limitation and may develop more pronounced cardiopulmonary stress responses (32–34). Biological sex differences, including inflammatory pathways, may contribute to airway remodeling and heightened symptom perception.

In this study, the most frequent comorbidities were hypertension, diabetes, and hypothyroidism, whereas the literature commonly reports higher rates of cardiovascular disease in CRD populations. Previous studies have demonstrated that conditions such as heart failure and pulmonary hypertension share pathophysiological pathways with COPD, including sympathetic overactivation and chronic hypoxemia (35, 36).

Dyspnea and cough intensity correlated with both HR and comorbidities, suggesting autonomic dysfunction as a contributing mechanism. Previous evidence has shown that HR variability and SpO_2 fluctuations are sensitive markers of disease severity and cardiovascular involvement (28). Monitoring these parameters may aid in risk stratification and individualized therapeutic planning, especially in multimorbid patients.

The integration of wearable monitoring with environmental data represents a promising strategy for precision management of chronic respiratory diseases. Real-time alerts and trend analyses may enable early interventions in primary care and home-based rehabilitation.

However, the small sample size and the geographic limitation to a single region restrict the generalizability of findings. In addition, the observational nature of the study precludes causal inference, and the associations identified should be interpreted as temporal relationships.

Future studies with larger cohorts and broader geographic representation are needed to validate these findings and develop predictive models for exacerbation risk.

In summary, this study provides evidence that wearable-based monitoring can identify early physiological and environmental patterns associated with clinical deterioration in patients with chronic respiratory diseases. The integration of digital health technologies with environmental surveillance represents a promising approach for improving risk stratification and proactive disease management.

Declarations

Ethics approval and consent to participate

This study was approved by the Research Ethics Committee of Centro Universitário FMABC, Brazil (protocol number 6.214.530) and was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants prior to inclusion in the study.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated and/or analysed during the current study are not publicly available due to privacy restrictions but are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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The authors received no specific funding for this research.

Authors' contributions

All authors contributed to the study conception and design, data collection, analysis, and manuscript preparation. All authors read and approved the final manuscript.

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