Original Research
Clinical Interventions Following Escalations from a Continuous Respiratory Monitoring Service in Patients With Chronic Obstructive Pulmonary Disease

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Running Head: Escalations from Home Monitoring in COPD

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Abstract

Background:

Continuous respiratory monitoring can support integrated care for chronic obstructive pulmonary disease (COPD) patients, by coupling them with remote clinical personnel who triage patients in coordination with their health care providers. When deploying such services, there remains uncertainty surrounding outcomes when at-risk patients are proactively identified and escalated for provider evaluation. This study presents findings from a service deployed in a real-world COPD cohort by analyzing the clinical interventions made during in-person and telehealth pulmonary outpatient visits following remote escalations.

Methods:

A single-center, retrospective, observational study of real-world COPD patients at a multi-site pulmonary practice was conducted. Patients who were enrolled in a continuous respiratory monitoring service for at least one year and were seen by a provider within seven days of an escalation by the service (N=168) were included. To evaluate the potential impact of these escalations on provider and patient burden, medical charts from outpatient visits were manually reviewed and grouped into six categories based on the clinical action(s) taken by the provider.

Results:

A total of 245 outpatient visits occurred from 168 patients within seven days of escalation. Of the 245 visits, 206 (84.1%) resulted in clinical intervention and 163 (66.5%) resulted in treatment consistent with acute exacerbations of COPD (AECOPDs). 1.6% of the outpatient visits resulted in referral to the emergency room.

Conclusions:

Provider encounters occurring following the escalation of a patient from a continuous respiratory monitoring service consistently resulted in that provider administering a treatment to the escalated patient.

Background

Chronic obstructive pulmonary disease (COPD), the third leading cause of death globally [1], is "a heterogeneous lung condition characterized by chronic respiratory symptoms (dyspnea, cough, expectoration, exacerbations) due to abnormalities of the airways (bronchitis, bronchiolitis) and/or alveoli (emphysema) that cause persistent, often progressive, airflow obstruction" [2]. COPD is punctuated by acute exacerbations of COPD (AECOPDs), a sudden worsening of symptoms, which contribute significantly to disease progression and acute healthcare utilization.

Although earlier treatment of AECOPDs has been shown to reduce their severity and associated acute care utilization [3], care-seeking is often delayed. The reasons for delay are complex and multifactorial, including symptom variability and a lack of awareness of changes in symptoms associated with AECPODs, unwillingness to burden caregivers and providers with potential false alarms, and a desire to minimize the potential significance of changes in symptoms [4-6].

A primary goal for optimal healthcare delivery in COPD is through implementing integrated care, but it often implies greater demand on healthcare resources because of the need for heightened care coordination [7]. This involves information transfer, assessment, monitoring, follow-up, and facilitating transitions across care settings.

Therein lies the potential of leveraging technologies enabling remote clinical professionals to monitor, triage, assess, and interact with patients to improve provider efficiency while minimizing unnecessary burden on providers and patients [8]. Such an approach may employ

some combination of remote monitoring, algorithmic interpretation of physiologic trends, patient-facing digital interfaces, virtual consultation, health coaching, virtual rehabilitation, and others.

Recent advancements in remote physiologic monitoring (RPM) technologies have shown considerable promise in transforming integrated care for COPD. RPM technologies in COPD, which currently encompass a range of commercially available wearable devices (e.g. wristbands [9, 10], armbands [11], vests [12, 13], and rings [14]), have been increasingly studied for their ability to collect real-time physiological data [15]. The integration of artificial intelligence and machine learning algorithms into RPM technologies has begun to offer sophisticated analyses of collected data, increasing the predictability of AECOPDs and facilitating proactive clinical evaluation and intervention [16, 17, 18]. However, research is warranted to systematically evaluate this potential in real-world settings [19-20].

While conceptually appealing, implementing integrated care through RPM technologies in the real world comes with its challenges, such as ensuring long-term adherence among a population that has varying levels of motivation and technological literacy as well as ensuring that equitable access to such technologies is provided. While many of the components of integrated care have been evaluated to meet care goals in COPD [21, 24], the outcomes of escalations from RPM services, where the RPM service prompts a patient to be seen by their provider, have not been reported upon.

The present study evaluates the implementation of a continuous respiratory monitoring service which includes clinical triage that may escalate patients for care from their pulmonary care provider. The service has been previously shown to be associated with reduced acute care utilization [21]. While it was hypothesized that the mechanism for this reduction was more timely outpatient intervention resulting from the service's acute escalations to care providers, no data were provided as to the actions that providers took in outpatient visits during the study period.

This present study aims to address this gap by reporting how frequently COPD patients seen by their pulmonary care provider after being escalated by an RPM service are treated in a manner consistent with them having experienced an AECOPD, providing a comprehensive report of outpatient visits that took place within 7 days of escalations. The results may also help clinicians understand the implications of escalations from remote monitoring on provider and patient burden by evaluating whether providers deemed the resulting outpatient visits clinically necessary. To do this, we employed a framework consistent with prior work [22-23] where treatment-based definitions of COPD exacerbations are used to evaluate the outcomes and clinical relevance of medical escalations.

Methods

Study Design

This was a retrospective, observational, real-world study of COPD patients at a multi-office pulmonary practice situated in a metropolitan area in the mid-Atlantic region of the United

States. An independent institutional review board (IRB; Western IRB #00000533) approved the study and granted a waiver for documentation of informed consent, given that acquiring such consent would have been impractical and the study entailed no more than minimal risk.

Inclusion Criteria

The patients in this analysis had previously elected to enroll in the service as part of their clinical management. All patients were active at the partnering practice, had been clinician-diagnosed with COPD, and carried at least one of the following ICD-10 classification system codes: COPD (J44), emphysema (J43), chronic bronchitis (J42). They were also continuously enrolled for a period of at least 12 months as of May 1, 2022 and had at least one escalated office visit while enrolled.

Intervention

The intervention consisted of a service with three components: (a) continuous cardio-respiratory monitoring, (b) algorithmic notification of physiologic deterioration, and (c) clinical liaisons who engage patients, respond to algorithmic notifications, triage patients, and "escalate" patients by notifying their provider of the need for further assessment (Figure 1).

Continuous Monitoring

Physiologic monitoring was done through an FDA-cleared, proprietary device called a health tag, which includes sensors for respiratory force (respiration), photoplethysmography (pulse), and tri-axis accelerometers (physical activity or steps). The health tag was designed to minimize patient

burden and social stigma. Patients adhere the health tag to the inner waistband of their undergarment (Figure 2).

Each patient was provided with six health tags, one for each of the patient's undergarments. If a patient requested more health tags, they were given more, up to eight. They are engineered to last over a year as a set without recharging and are for prolonged skin contact. The respiration and accelerometer sensors operate continuously while the pulse sensor takes readings every four minutes. Health tag data are relayed via a dedicated in-home hub to a virtual clinical dashboard shown in Figure 3 and used by a dedicated team of the service's clinical liaisons (CLs).

Algorithmic Notifications

Algorithm-driven notifications are displayed on the clinical dashboard when health tag data indicates deviation from predetermined thresholds. Notifications are triggered by non-adherence (i.e., health tags not worn for at least eight hours in a day for a predefined duration), inactivity (i.e., too few steps taken within a predefined duration), and relative or absolute increases in pulse and respiration rates (Table 1). Within 24 hours of the occurrence of any notification (48 hours on weekends), a CL calls the patient to conduct a risk assessment. (Table 2)

Integrated Clinical Liaisons

The integrated clinical liaison team, which consists of respiratory therapists and nurses experienced in respiratory disease, review algorithmic notifications and data in the dashboard. Though they could be third-party clinicians, the CLs in this analysis are employed by the RPM provider and work 8am-5pm during the weekdays, with a CL on call available on weekends to

address critical RR and PR rates. Upon notification of potential patient deterioration, a CL (usually assigned to that patient) contacts the patient by phone to conduct the standardized clinical risk assessment to assess changes on relevant symptoms.

When a patient fails the risk assessment by answering "yes" to one or more of its questions or they cannot be reached after three attempts over 48 hours, they are 'escalated': notifying a patient's provider to recommend that their patient be evaluated. Multiple notifications may precede an escalation in the case that a patient exceeds multiple physiologic thresholds before failing a risk assessment. Multiple escalations may precede an escalated office visit in the case that escalations persist, and a patient has yet to be seen by their provider.

The service CLs had access to the partnering practice's EMR, where they could schedule either in-person or virtual office visits with the patient's consent. During an escalation, a patient may choose to forego scheduling an office visit. Regardless, a one-page summary of their recent data trends is posted in the EMR for their provider's review. This summary report includes the CL's notes from the phone call, a patient's response to the risk assessment, and a timeline of physiologic data. This workflow is illustrated in Figure 1.

In the absence of notifications, they conduct a monthly 'check-in' call to address any potential patient concerns, support self-management and patient education, and perform a routine patient assessment. While physical activity was monitored by the health tags, and the day's step count was shown to patients, neither explicit activity coaching nor virtual pulmonary rehabilitation were utilized during the observation period.

Data Coding

Manual chart reviews of the practice's electronic medical record (EMR) were performed on escalated office visit records created between the dates of May 2020 and May 2022. Office visits that occurred more than 7 days following an escalation were excluded.

Clinical interventions during office visits were grouped into six categories: an increase or change in oral corticosteroids, antibiotics, inhaled medications, referral for further testing or imaging, other symptomatic treatment, and referral to the emergency room (ER) (Table 3). An office visit was determined to include treatment consistent with the management of an AECOPD if at least one of the codes included corticosteroids, antibiotics, or inhaled medications.

For this analysis, notifications were tied to escalations if they occurred in the three days preceding the escalation. We denote escalations caused by failing a risk assessment during a call within three days after a notification as 'notification-based' or, otherwise, 'check-in-based'.

Results

Demographics

The cohort consisted of 168 COPD patients, majority women (54.2%), with a mean age of 73.4 years (SD: 9.0). African Americans comprised 23.8% of the cohort. The cohort exhibited a broad spectrum of comorbidities with a high prevalence of hypertension (64.9%), obesity (BMI ≥ 30; 45.2%), and asthma (38.7%). The cohort was generally comprised of moderate to severe COPD patients, averaging a post-bronchodilator forced expiratory volume in 1 second (FEV_1) of 58.4%

(SD: 19.5%) of predicted, with 83.0% of the cohort having a FEV_1 below 80% of predicted and 37.7% having a FEV_1 below 50% of predicted (Table 4).

Enrollment and Adherence

Across the study period, patients were enrolled for an average duration of 17.5 (SD: 3.2) months. Health tags were worn for at least 8 hours per day on 76.7% of days during the study period (the 8-hour threshold was chosen based on the notification algorithm), with a mean and median of 16.0 (SD: 9.3) and 21.8 hours worn per day, respectively. On average, patients completed 1.5 (SD: 0.3) calls with a CL per month.

Notifications and Escalations

The study recorded 294 escalations that were associated with office visits. 26 (8.8%) were triggered during monthly check-in calls and the remaining 268 (91.2%) by one or more of 524 notifications. 497 (94.8%) of these notifications were cardiorespiratory. Of these, 421 (84.7%) were respiratory (26 absolute and 395 relative) and 76 (15.3%) were pulse (all relative). 27 (10.1%) of the notification-based escalations included both respiratory and pulse notifications in the prior three days. In addition to cardiorespiratory notifications, there were 14 (2.7%) notifications for adherence and 13 (2.5%) activity notifications observed (Table 5).

Office Visits

There were 245 escalated office visits in total, with virtual office visits occurring more frequently (153, 62.4%) than in-person office visits (92, 37.6%). These office visits were

overseen by 33 distinct providers (advanced practitioners or physicians); the mean duration from escalation to office visit ('time to visit') was 2.9 (SD: 2.2) days.

Of the escalated office visits, 163 (66.5%) resulted in treatment consistent with the management of an AECOPD: 116 (47.3%) were coded for "Corticosteroids", 81 (33.1%) were coded for "Antibiotics", and 64 (26.1%) were coded for "Inhaled Medication". Four (1.6%) visits were for "ER referral by the provider", 94 (38.4%) were coded for "Additional Testing, Scan, or Referral", and 31 (12.7%) were coded for "Other Symptomatic Treatment" (see Figure 4 and Table 6).

Overall, 206 (84.1%) visits were coded for at least one clinical intervention, with 78 (31.8%) being coded for one, 79 (32.2%) being coded for two, 42 (17.1%) being coded for three, and 7 (2.9%) being coded for four clinical interventions in the same visit.

All four instances in which providers referred patients directly to the ER resulted in patients presenting there; three of these resulted in hospital admissions. The primary ICD-10 codes for these ER visits were acute on chronic respiratory failure with hypoxia (J96.02), COVID-19 pneumonia (U07.1), and acute COPD exacerbation (J44.1).

Discussion

We present a detailed description of clinical interventions triggered by escalations from a continuous respiratory monitoring and clinical triage service. Of the escalated office visits, 84.1% resulted in clinical intervention and 66.5% in treatment consistent with the management

of an AECOPD. Changes in respiratory rate were the dominant cause for notifications, escalations, and associated clinical interventions (Table S1), mirroring the symptomology of COPD and high prevalence of related respiratory comorbidities in the analyzed population (Table S2). The clinical interventions that were most highly associated with each other were a prescription for corticosteroids and antibiotics, which is in line with a typical intervention for AECOPD (Table S3).

A relatively small proportion (1.6%) of escalated office visits resulted in referral to the ER. It is assumed that these were severe exacerbations. This small proportion lends support to the hypothesis that the system generally identified patients early enough to prevent severe deterioration.

In addition to accurate and prompt clinical detection, remote monitoring services require efficient clinical workflows and expedited clinical assessment for interventions to be swiftly administered. Patients must heed escalations from the service by choosing to go to the office in a timely manner, underscoring the importance of patient engagement in a remote monitoring setting. The observed time to visit of 2.9 days was less than half the average 6-7 day care-seeking delay reported in another study of COPD patients who were on a care management intervention [24]. Furthermore, in another study, the time between symptom onset and treatment was a median of 3.69 days, with 40.1% of exacerbations unreported [3]. This supports the hypothesis that escalations from the service removes obstacles in patient decision-making and enables faster access to care.

Because of the retrospective nature of the study, the 33 providers represented in this analysis were unaware of the study's analytical objectives or goals, bolstering the integrity of the study's results. Access to the practice's EMR by the platform's clinical liaisons allowed for streamlined triaging of escalated patients to their pulmonologist, exemplifying the promise of integrating such platforms into EMR systems and allowing our study to evaluate a mature RPM implementation.

The findings reinforce the potential for this type of service to enable early detection and timely intervention, which can lead to decreased severity of exacerbations, reduced need for acute care, and more efficient resource allocation. Due to the service's goal of identifying deterioration early enough to prevent the need for hospital admission, it is expected to escalate a significant proportion of patients who do not warrant additional intervention. However, a majority of escalations resulted in clinically meaningful actions, supporting the claim that providers found the visits to be clinically relevant. Further research is warranted to fully understand and quantify the potential impact of such platforms on clinical workflow, provider satisfaction, acute care utilization, and successful disease management among COPD patients.

These results have inherent limitations. Though we identified certain interventions during escalated office visits as being consistent with the management of an AECOPD, we lack data to confirm this assessment due to the limitations of clinical documentation. Due to the absence of a suitable control or comparison group, we cannot conclude that a patient being escalated reduced their expected time-to-visit nor can we compare the results to interventions at non-escalated office visits. Thus, we cannot employ a rigorous causal framework to enable us to definitively

attribute these office visits to corresponding escalations. However, we can conclude that service-triggered escalations were associated with actionable medical interventions, which is its purported goal.

Other limitations include that the study did not evaluate patients who declined to see their provider upon escalation. Additionally, that providers had knowledge of when office visits were scheduled via escalations may have influenced their decisions regarding intervention. Finally, this study assessed only one service as described above and was implemented at only a single site.

The goal of this analysis was to evaluate the clinical interventions during office visits triggered by the monitoring service in a COPD cohort. In doing so, the current study contributes to the burgeoning RPM literature by offering a novel evaluation framework for COPD respiratory monitoring programs [15, 21, 25]. We highlight our method to evaluate the impact of the intervention, given the high barriers to conducting large-scale randomized control trials.

These findings support a purported mechanism for remote monitoring to improve patient outcomes, showing that providers are highly likely to intervene in a patient's care following an escalation of care. This contributes to the body of evidence in support of using remote monitoring for the purpose of facilitating early medical intervention, promoting proactive disease management, and enabling advanced clinical decision support systems. In addition, future research should focus on optimizing these systems to capitalize on continuous monitoring data for efficient COPD patient management at scale and improve the risk stratification of patient

populations. Large-scale implementation studies are needed to study the cost-effectiveness of these systems and how clinical workflows can be adapted to maximize respiratory monitoring integration and effectiveness at diverse sites, leading to improved patient outcomes and optimized healthcare delivery.

Conclusions

In a cohort of COPD patients enrolled in a continuous respiratory monitoring service, provider encounters following clinical escalations from the service often resulted in their provider administering a treatment to the escalated patient; treatments administered were consistent with the patient experiencing an AECOPD 66.5% of the time. This finding supports the claimed mechanism for remote monitoring to improve patient outcomes through the timely identification and treatment of AECOPDs.

Acknowledgments

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Declarations of interest

AH, RT, NM, and RM are employees of Spire Health. MP is a consultant to Spire Health. DM had no conflicts of interest.

Availability of data and materials:

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

1. Soriano, Joan B., et al. "Prevalence and attributable health burden of chronic respiratory diseases, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017." The Lancet Respiratory Medicine 8.6 (2020): 585-596.

2. Agustí A, Celli BR, Criner GJ, et al. Global Initiative for Chronic Obstructive Lung Disease 2023 Report: GOLD Executive Summary. European Respiratory Journal 2023;61(4):2300239.

3. Wilkinson, Tom MA, et al. "Early therapy improves outcomes of exacerbations of chronic obstructive pulmonary disease." *American journal of respiratory and critical care medicine* 169.12 (2004): 1298-1303.

4. Adams R, Chavannes N, Jones K, et al. Exacerbations of chronic obstructive pulmonary disease — A patients' perspective. Primary Care Respiratory Journal 2006;15(2):102–109.

5. Langsetmo L, Platt RW, Ernst P, et al. Underreporting exacerbation of chronic obstructive pulmonary disease in a longitudinal cohort. American Journal of Respiratory and Critical Care Medicine 2008;177(4):396–401.

6. MacIntyre, N., & Huang, Y. C. (2008). Acute exacerbations and respiratory failure in chronic obstructive pulmonary disease. Proceedings of the American Thoracic Society, 5(4), 530–535. https://doi.org/10.1513/pats.200707-088ET

7. Hughes G, Shaw SE, Greenhalgh T. Rethinking Integrated Care: A Systematic Hermeneutic Review of the Literature on Integrated Care Strategies and Concepts. Milbank Q. 2020 Jun;98(2):446-492. doi: 10.1111/1468-0009.12459. Epub 2020 May 20. PMID: 32436330; PMCID: PMC7296432.

8. Donner, Claudio F., Richard ZuWallack, and Linda Nici. "The role of telemedicine in extending and enhancing medical management of the patient with chronic obstructive pulmonary disease." *Medicina* 57.7 (2021): 726.

9. Grzesiak E, Bent B, McClain MT, Woods CW, Tsalik EL, Nicholson BP, et al.. Assessment of the feasibility of using noninvasive wearable biometric monitoring sensors to detect influenza and the common cold before symptom onset. JAMA Netw Open. (2021) 4:e2128534. doi: 10.1001/jamanetworkopen.2021.28534

10. Lubitz SA, Faranesh AZ, Selvaggi C, Atlas SJ, McManus DD, Singer DE, et al.. Detection of atrial fibrillation in a large population using wearable devices: the fitbit heart study. Circulation. (2022) 146:1415–24. doi: 10.1161/CIRCULATIONAHA.122.060291

11. Lahham A, McDonald CF, Mahal A, Lee AL, Hill CJ, Burge AT, et al.. Participation in physical activity during center and home-based pulmonary rehabilitation for people with COPD: a SECONDARY ANALYSIS OF a RANDOMIZED CONTROLLED TRIAL. J Cardiopulm Rehabil Prev. (2019) 39:e1–4. doi: 10.1097/HCR.0000000000000373

12. Abdallah S, Wilkinson-Maitland C, Waskiw-Ford M, Abdallah I, Lui A, Smith B, et al.. Validation of Hexoskin biometric technology to monitor ventilatory responses at rest and during exercise in COPD. Eur Respir J. (2017) 50:PA 1359. doi: 10.1183/1393003.congress-2017.PA1359

13. Hawthorne G, Greening N, Esliger D, Briggs-Price S, Richardson M, Chaplin E, et al.. Usability of wearable multiparameter technology to continuously monitor free-living vital signs in people living with chronic obstructive pulmonary disease: prospective observational study. JMIR Hum Factors. (2022) 9:e30091. doi: 10.2196/30091

14. de Zambotti M, Rosas L, Colrain IM, Baker FC. The sleep of the ring: comparison of the ŌURA sleep tracker against polysomnography. Behav Sleep Med. (2019) 17:124–36. doi: 10.1080/15402002.2017.1300587

15. Shah SA, Velardo C, Farmer A, et al. Exacerbations in Chronic Obstructive Pulmonary Disease: Identification and Prediction Using a Digital Health System. Journal of Medical Internet Research 2017;19(3).

16. Polsky MB, Moraveji N. Early identification and treatment of COPD exacerbation using remote respiratory monitoring. Respiratory Medicine Case Reports 2021;34:101475.

17. Hayes CJ, Dawson L, McCoy H, et al. Utilization of Remote Patient Monitoring Within the United States Health Care System: A Scoping Review. Telemedicine and e-Health 2022;29(3).

18. Cooper CB, Sirichana W, Arnold MT, et al. Remote Patient Monitoring for the Detection of COPD Exacerbations. International Journal of Chronic Obstructive Pulmonary Disease 2020;Volume 15:2005–2013.

19. Walker RC, Tong A, Howard K, Palmer SC. Patient expectations and experiences of remote monitoring for chronic diseases: Systematic review and thematic synthesis of qualitative studies. International Journal of Medical Informatics. 2019 Apr;124(124):78–85.

20. Farias FAC de, Dagostini CM, Bicca Y de A, et al. Remote Patient Monitoring: A Systematic Review. Telemedicine and e-Health 2019;26(5).

21. Polsky M, Neema Moraveji, Hendricks A, et al. Use of Remote Cardiorespiratory Monitoring is Associated with a Reduction in Hospitalizations for Subjects with COPD.

International Journal of Chronic Obstructive Pulmonary Disease 2023;Volume 18:219–229.

22. Rodriguez-Roisin R. Toward a Consensus Definition for COPD Exacerbations. Chest 2000;117(5):398S401S.

23. Putcha N, Wise RA. Medication Regimens for Managing COPD Exacerbations. Respiratory Care 2018;63(6):773–782.

24. Fan VS, Gaziano JM, Lew R, et al. A Comprehensive Care Management Program to Prevent Chronic Obstructive Pulmonary Disease Hospitalizations. Annals of Internal Medicine 2012;156(10):673.

25. Noah B, Keller MS, Mosadeghi S, et al. Impact of remote patient monitoring on clinical outcomes: an updated meta-analysis of randomized controlled trials. npj Digital Medicine 2018;1(1).

Tables

Table 1. Types of daily notifications generated by the system. A description of the types of notifications threshold types, cadence of calculation, and descriptions of what type of deviation causes the notification to be fired. Each notification type is separate and multiple notifications can be generated in a single day/hour.

Notification Type	Threshold Type	Cadence	Description
Low Activity	Absolute	Daily	Too few steps are taken over a predefined period.
Low Adherence	Absolute	Daily	The tags are not worn over a predefined period.
Respiration	Relative	Daily	Respiration rates exceed a threshold relative to a patient's learned baseline.
Respiration	Absolute	Hourly	Respiration rates exceed an absolute threshold.
Pulse	Relative	Daily	Pulse rates exceed a threshold relative to a patient's learned baseline.
Pulse	Absolute	Hourly	Pulse rates exceed an absolute threshold.

Table 2. The 'clinical risk assessment' script. The questions asked of patients by clinical liaisons upon notification. A patient that answers "Yes" to any of these questions is escalated to their provider.

1	These past two days, are you more short of breath than usual?
2	These past two days, are you having more sputum than usual?
3	These past two days, have you noticed any changes in the color of your sputum?
4	Do you have any new concerns about your breathing?
5	Would you like me to make an appointment with your doctor?

Table 3: Labels used to code clinical interventions in escalated office visits

Code	Definition	Consistent with the management of an AECOPD
Corticosteroids	A new order, escalation of dosage, or increase in frequency of oral corticosteroids (e.g., prednisone).	True
Antibiotics	A new order, escalation of dosage, or increase in frequency of oral antibiotics (e.g., ciprofloxacin, azithromycin, tetracycline).	True
Inhaled Medication	A new order, escalation of dosage, or increase in frequency of inhaled corticosteroids, nebulizers, and other inhaled medication such as anticholinergic inhalers, Beta-agonist inhalers, and combination inhalers. (e.g., Ipratropium, Arformoterol, Budesonide).	True
Other Symptomatic Treatment	A new order, escalation of dosage, or increase in frequency of medication that did not fit into the categories of corticosteroids, antibiotics, or inhaled medications (e.g., Oxycodone, Lasix, and psychiatric medication).	False
Additional Testing, Scan, or Referral	A new order of a test such as pulmonary function test (PFT), a new order of a scan including chest x-ray (CXR), or echocardiogram (ECHO). Referrals included those to a sleep lab, pulmonary rehabilitation, cardiologist, or otherwise.	False
ER Referral by Provider	A note in the patient's chart by the provider saying that the patient was advised or recommended to present to the emergency room.	False

Table 4: Cohort demographics and clinical characteristics

Parameter	Value
Demographics	
Age, years (SD)[A]	73.4 (9.0)
BMI, kg/m2; mean (SD)[B]	29.5 (7.9)
Women, n (%)	91 (54.2)
African American, n (%)	40 (23.8)
Comorbidities[C]	
Hypertension, n (%)	109 (64.9)
Obesity, n (%)	76 (45.2)
Supplemental Oxygen Use, n (%)	74 (44.1)
Sleep apnea, n (%)	66 (39.3)
Asthma, n (%)	65 (38.7)
Depression, n (%)	43 (25.6)
Diabetes, n (%)	41 (24.4)
CAD (coronary artery disease), n (%)	37 (22.0)
Atrial fibrillation, n (%)	24 (14.3)
CHF (Congestive heart failure), n (%)	21 (12.5)
Stroke or cerebrovascular accident, n (%)	20 (11.9)
Thyroid disease, n (%)	17 (10.1)
ILD (interstitial lung disease), n (%)	7 (4.2)
PVD (peripheral vascular disease), n (%)	6 (3.6)
Cardiomyopathy, n (%)	5 (3.0)
Lung Function[D]	

	FEV1 (% Post FEV1 Predicted), mean (SD)	58.4 (19.5)
	GOLD 1: Mild (FEV1 >= 80% Predicted), n (%)	18 (17.0)
	GOLD 2: Moderate (50% <= FEV1 < 80%), n (%)	48 (45.3)
	GOLD 3: Severe (30% <= FEV1 < 50%), n (%)	33 (31.1)
	GOLD 4: Very Severe (FEV1 < 30%), n (%)	7 (6.6)
	Patients with lung function data available, n (%)	106 (63.1)

A: Age was calculated based on age at time of onboard on the RPM service.

B: Body mass index (BMI) was calculated as the most recent BMI at time of analysis.

C: Comorbidities were coded based on ICD-10 codes from the EMR.

D: GOLD grades are taken from the GOLD 2023 report

Table 5: Escalations triggered by the intervention and their associated notifications

Parameter			Value
Total escalations resulting in escalated office visit			294
	Escalations (notification-related)		268
	Escalations (via monthly check-ins)		26
Cardiorespiratory notifications			497
	Respiratory Rate (total)		421
	Respiratory Rate (relative)		395
	Respiratory Rate (absolute)		26
	Pulse Rate (total)		76
	Pulse Rate (relative)		76
	Pulse Rate (absolute)		0
Step Count (Activity)			13
Non-Adherence			14

Table 6: Coded clinical interventions that occurred during office visits

Clinical Interventions	n (%)
At least one clinical intervention	206 (84.1%)
Clinical intervention consistent with management of an AECOPD	163 (66.5%)
Corticosteroids	116 (47.3%)
Additional Testing, Scan, or Referral	94 (38.4%)
Antibiotics	81 (33.1%)
Inhaled Medication	64 (26.1%)
Other Symptomatic Treatment	31 (12.7%)
ER Referral by Provider	4 (1.6%)

Figures

Figure 1: Process diagram illustrating the remote physiologic monitoring service. Health tags are worn by patients, the data of which populates the clinical dashboard, which is monitored 7 days a week by Spire clinicians. Upon seeing notifications, clinicians contact patients by phone and conduct risk assessments. Based on the results, they determine whether the patient should be seen by their provider, where a change in prescription can be administered if deemed necessary.
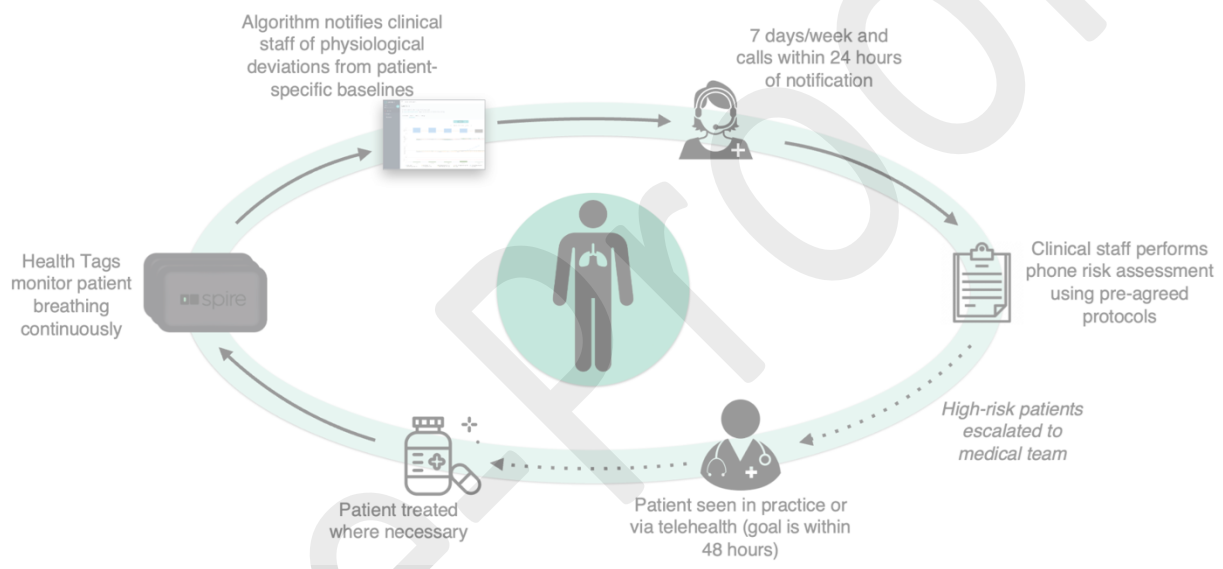
Figure 2: Health tags are adhered by patients to their undergarments (one health tag is adhered to each undergarment). Patients were also provided a data capture and display hub, which passively and automatically collects data from the sensors and securely uploads it to the cloud for display to clinical personnel.

Figure 3: Screenshot of the healthcare portal from the intervention. This view, for clinicians, provides a timeline of the patient's physiologic data. The patient did not wear the sensor during March 17, as evidenced by the missing data.

Figure 4: A graphical representation of all clinical interventions taken during escalated office visits. Each vertical line represents one office visit, with rows corresponding to each action remaining blank if that action was not taken during that office visit. Office visits are sorted from most treatments administered during a single visit on the left to those with no actions taken on the right. Office visits with the same combination on treatments administered are grouped together.
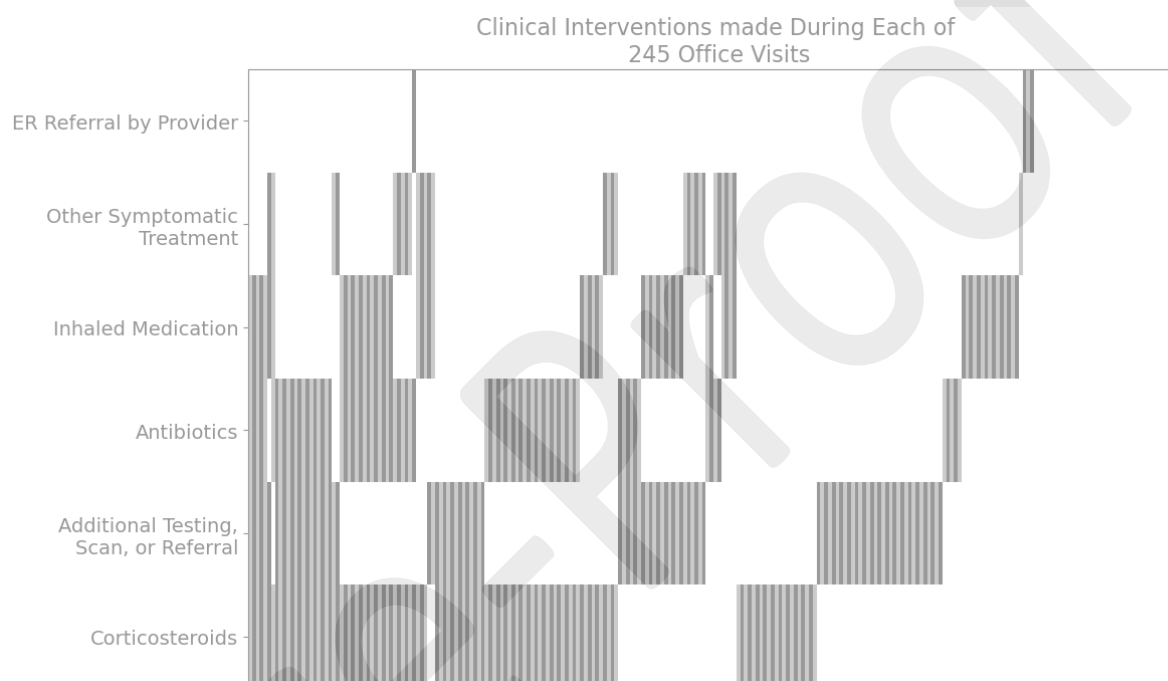
Online Supplement

Table S1: Frequency of notification types associated with specific clinical interventions in outpatient visits resulting from escalations.

	Respiratory Rate (Relative)	Respiratory Rate (Absolute)	Pulse Rate (Relative)	Pulse Rate (Absolute)	Non-Adherence	Step Count (Activity)
Total Distinct Office Visits Associated with Notification Type	177	11	46	0	14	11
Corticosteroids	50.8%	45.5%	39.1%	N/A	50.0%	45.5%
Antibiotics	34.5%	18.2%	43.4%	N/A	28.6%	27.2%
Inhaled Medication	25.4%	9.1%	23.9%	N/A	28.6%%	0.0%
Additional Testing, Scan, or Referral	39.5%	36.3%	30.4%	N/A	42.9%	18.1%
Other Symptomatic Treatment	13.5%	0.0%	8.7%	N/A	0.0%	9.1%
ER Referral by Provider	2.3%	0.0%	0.0%	N/A	2.3%	0.0%
Clinical intervention consistent with management of an AECOPD	70.2%	45.5%	61.7%	N/A	71.4%	54.5%

The likelihood of an office visit coded as having been positively coded for each of the categories defined in Table 3 conditional on that office visit being preceded by a notification of a certain type.

Table S2: Escalated office visits and notifications per year by sex, GOLD status, and comorbidities

Category	Value	N	Escalated Office Visits per Year, mean (SD)	Escalated Notification per Year, mean (SD)
Sex Assigned at Birth				
	Female	91	1.07 (0.61)	2.04 (2.47)
	Male	77	1.00 (0.55)	2.47 (3.09)
GOLD Status				
	GOLD 1: Mild (FEV1 >= 80% Predicted)	18	0.94 (0.40)	2.16 (2.13)
	GOLD 2: Moderate (50% <= FEV1 < 80%)	48	1.01 (0.58)	2.38 (2.60)
	GOLD 3: Severe (30% <= FEV1 < 50%)	33	1.00 (0.55)	1.92 (1.71)
	GOLD 4: Very Severe (FEV1 < 30%)	7	1.27 (0.81)	0.92 (1.08)
	Patients without lung function data available	62	1.09 (0.62)	2.47 (3.55)
Comorbidities				
	Hypertension	109	1.03 (0.54)	2.15 (2.39)
	Obesity	76	1.11 (0.63)	2.01 (2.34)
	Supplemental Oxygen Use	74	1.02 (0.53)	1.95 (2.41)
	Sleep apnea	66	1.10 (0.69)	2.03 (2.46)
	Asthma	65	1.10 (0.52)	1.88 (1.79)
	Depression	43	1.06 (0.53)	1.76 (1.57)
	Diabetes	41	1.16 (0.59)	2.62 (2.82)
	CAD (coronary artery disease)	37	0.95 (0.52)	1.59 (1.24)
	Atrial fibrillation	24	1.12 (0.63)	3.71 (4.10)
	CHF (Congestive heart failure)	21	1.04 (0.59)	2.13 (2.31)
	Stroke or cerebrovascular accident	20	1.04 (0.57)	2.35 (3.83)
	Thyroid disease	17	1.08 (0.55)	3.11 (4.13)
	ILD (interstitial lung disease)	7	1.02 (0.40)	2.89 (5.57)
	PVD (peripheral vascular disease)	6	1.18 (0.78)	2.33 (1.08)
	Cardiomyopathy	5	1.07 (0.55)	2.52 (3.27)

Table S3: Correlation matrix of clinical interventions made in escalated office visits

Variable		Corticosteroids	Additional Testing, Scan, or Referral	Antibiotics	Inhaled Medication	Other Symptomatic Treatment	ER Referral by Provider
Corticosteroids							
	r	1	-0.143	0.480	-0.006	0.033	-0.058
	P-value	---	.025	<.001	.930	.612	.369
Additional testing, Scan, or Referral							
	r	-0.143	1	-0.091	-0.106	-0.023	-0.102
	P-value	.025	---	.157	.097	.752	.113
Antibiotics							
	r	0.480	-0.091	1	0.017	-0.059	-0.022
	P-value	<.001	.157	---	.796	.360	.731
Inhaled Medication							
	r	-0.006	-0.106	0.017	1	0.081	-0.077
	P-value	.930	.097	.796	---	.206	.232
Other Symptomatic Treatment							
	r	0.033	-0.023	-0.059	0.081	1	-0.049
	P-value	.612	.752	.360	.206	---	.445
ER Referral by Provider							
	r	-0.058	-0.102	-0.022	-0.077	-0.049	1
	P-value	.369	.113	.731	.232	.445	---