https://doi.org/10.5664/jcsm.9750

JCSM | Journal of Clinical Sleep Medicine

SCIENTIFIC INVESTIGATIONS

Electronic health record–derived outcomes in obstructive sleep apnea managed with positive airway pressure tracking systems

Brian W. Locke, MD[1]; Sarah E. Neill, MD[2]; Heather E. Howe, MD[1]; Michael C. Crotty[3]; Jaewhan Kim, PhD[4]; Krishna M. Sundar, MD[1]

[1]Division of Pulmonary, Critical Care, and Sleep Medicine, Department of Internal Medicine, University of Utah, Salt Lake City, Utah; [2]Pulmonary, Critical Care, and Sleep Medicine, Owensboro Health Medical Group, Owensboro, Kentucky; [3]University of Utah Health, Enterprise Data Warehouse, Salt Lake City, Utah; [4]Department of Physical Therapy and Athletic Training, University of Utah, Salt Lake City, Utah

Study Objectives: To assess the effectiveness of continuous positive airway pressure (CPAP) management guided by CPAP machine downloads in newly diagnosed patients with obstructive sleep apnea (OSA) using electronic health record–derived health care utilization, biometric variables, and laboratory data.

Methods: Electronic health record data of patients seen at the University of Utah Sleep Program from 2012–2015 were reviewed to identify patients with new diagnosis of OSA in whom CPAP adherence and residual apnea-hypopnea index as measured by a positive airway pressure adherence tracking device data for ≥ 1 year were available. Biometric data, laboratory data, and system-wide charges were compared in the 1 year before and after CPAP therapy. Subgroups were divided by whether patients met tracking criteria, mean nightly usage, and OSA severity.

Results: 976 consecutive, newly diagnosed participants with OSA (median age 55 years, 56.6% male) met inclusion criteria. There was a mean decrease of systolic blood pressure (BP) of 1.2 mm Hg and diastolic BP of 1.0 mm Hg within a year of initiation of CPAP therapy. BP improvements in the subgroup meeting CPAP tracking targets were 1.36 mmHg (systolic) and 1.37 mmHg (diastolic). No significant change was noted in body mass index, glycated hemoglobin, or serum creatinine values within a year of starting CPAP therapy, and health care utilization increased (mean acute care visits 0.22 per year to 0.53 per year; mean charges of $3,997 per year to $8,986 per year).

Conclusions: An improvement in BP was noted within a year of CPAP therapy in newly diagnosed patients with OSA, with no difference in the magnitude of improvement between those meeting tracking system adherence targets.

Keywords: obstructive sleep apnea, continuous positive airway pressure, treatment outcome

Citation: Locke BW, Neill SE, Howe HE, Crotty MC, Kim J, Sundar KM. Electronic health record–derived outcomes in obstructive sleep apnea managed with positive airway pressure tracking systems. *J Clin Sleep Med*. 2022;18(3):885–894.

BRIEF SUMMARY

Current Knowledge/Study Rationale: Current treatment for obstructive sleep apnea involves optimizing continuous positive airway pressure (CPAP) therapy based upon adherence (duration of CPAP use) and efficacy (residual apnea-hypopnea index) data from tracking systems embedded in CPAP machines. However, the effectiveness of this management strategy during routine obstructive sleep apnea care has not been evaluated.

Study Impact: Integrating electronic health record data with CPAP remote-tracking downloads can be used to study the effectiveness of obstructive sleep apnea management algorithms on clinical outcomes. Although this study did not show a statistically significant difference in electronic health record–derived clinical outcomes between patients meeting treatment targets and those who did not, extensions of this methodology could answer a variety of important, related questions.

INTRODUCTION

Thirty-four percent of middle-aged men and 17% of middle-aged women in the United States have obstructive sleep apnea (OSA).[1] The prevalence of OSA continues to increase in tandem with the obesity epidemic.[1] Continuous positive airway pressure (CPAP) is recommended as the first-line treatment for OSA in patients that are symptomatic, have moderate to severe disease, or have certain comorbities.[2,3] It is estimated that 6.2 billion dollars are spent annually on nonsurgical OSA treatment in the United States, most of which is related to the costs of CPAP therapy.[4] The high prevalence, morbidity, and costs associated with OSA and its treatment justify ongoing interrogation of the real-world effectiveness of CPAP treatment, as highlighted in a recent Agency for Healthcare Research and Quality review.[5]

OSA is associated with a wide range of cardiac,[6] metabolic,[7] and neurocognitive[8] adverse outcomes, as well as increased health care utilization,[9] reduced health-related quality of life,[10] and death.[11] However, the effect of CPAP treatment in ameliorating these outcomes is less clear. Observational data suggest that CPAP treatment reduces cardiovascular risk and mortality,[12] but randomized trials do not.[13–16] Randomized controlled trials have shown improvement in neurocognitive parameters,[17] blood pressure control,[18] and health care utilization.[19] The "healthy adherer" effect or other residual confounding,[20] inadequate CPAP adherence thresholds;[21] limitations in trial size and duration;[22] exclusion of symptomatic patients;[23] and an

inability to separate short-term from cumulative effects[24] have all been proposed to explain why CPAP efficacy remains uncertain despite extensive study.[2,25]

Large, longitudinal databases enabled by electronic health records (EHRs) have the potential to verify that treatments are effective when applied across heterogeneous populations in practice.[26] Linkages between EHR and CPAP-vendor data can overcome financial and logistical barriers that have previously impeded cohort studies.[24]

A unique aspect of CPAP therapy is that CPAP machines track CPAP usage and efficacy by estimating the residual apnea-hypopnea index (AHI_{flow}[27]) of patients receiving treatment.[28] A 2013 American Thoracic Society (ATS) position statement reviewed data on adherence tracking systems (also sometimes referred to as "remote tracking" or "tele-monitoring"[28]) and found preliminary support for the accuracy of measured signals, but an absence of research evaluating the clinical impact of tracking system-guided care. They proposed an algorithm where suboptimal adherence (< 70% of nights with 4 hours or more usage) triggered a nursing visit, elevated AHI_{flow} (above 10–20 events/h) prompted evaluation of PAP pressure and mask fit, and large leak lead to a mask fit assessment.[27] Since that time, the reliability of AHI_{flow} has been questioned and may vary among different manufacturers.[29] Some evidence suggests that AHI_{flow} < 10 events/h accurately identifies patients without residual sleep apnea.[30] Yet other studies show frequent discordance with polysomnogram, particularly when identifying hypopneas and central events that may arise after treatment initiation.[31–33] This has led to a call for evaluating the role of CPAP downloads and the practice of titrating CPAP to reduce AHI_{flow} < 5 events/h (or 8 events/h in some studies[34]). The availability of autotitrating CPAP machines and reimbursement restrictions on titration polysomnograms led to the widespread practice of using CPAP adherence and AHI_{flow} tracking to guide chronic OSA management. However, this approach still has not been studied to show an effect on clinical outcomes.[34]

This study aimed to use EHR data of patients with newly diagnosed OSA who were managed using CPAP adherence and residual AHI_{flow} data to infer the effectiveness of this approach on improving biometric variables, routine laboratory data, and health care utilization. We hypothesized that the real-world data generated during CPAP tracking system-guided care would provide adequate data fidelity to confirm usage-dependent and severity-of-disease-dependent improvement in blood pressure following initiation of CPAP therapy. We predicted that these improvements from CPAP in variables above would be seen mainly in patients meeting treatment adherence targets as assessed by download data. Changes in body mass index (BMI), peripheral oxygen saturation (SpO_2), percentage of glycated hemoglobin (HbA1c), serum creatinine, and health care expenditure are also described.

METHODS

Study design

We performed a retrospective comparison of cardiometabolic variables, laboratory data, and health care expenditures 1 year before and 1 year after a new diagnosis of OSA and initiation of treatment with CPAP. The study was done at University of Utah Sleep-Wake Center, an American Academy of Sleep Medicine-accredited sleep program within the University of Utah Healthcare System based in Salt Lake City, Utah. Reporting of data and analyses were done per the STROBE guidelines for the reporting of observational studies.[35] The study was approved by the University of Utah Institutional Review Board with a waiver of individual informed consent (IRB # 00078021).

As is done in routine sleep apnea care, the University of Utah sleep program relies upon CPAP download data for the management of OSA once CPAP therapy is initiated. The ATS Statement on CPAP Adherence Tracking Systems algorithm is followed for addressing treatment adherence, efficacy, and mask leak,[27] but with lower residual AHI thresholds for making CPAP adjustments or other changes. Data on positive airway pressure therapy is entered into a custom CPAP tracking "flowsheet" created in the EHR (Epic., Epic Systems Corporation, Verona, Wisconsin) for capturing download data from CPAP equipment of all patients seen since 2012 (**Figure 1**). CPAP adherence downloads are extracted from proprietary tracking systems (EncoreAnywhere for Philips-Respironics CPAP devices, Philips Inc.; AirView for ResMed CPAP devices, ResMed Inc.) and entered this flowsheet at each patient visit by sleep clinic staff.

Participants

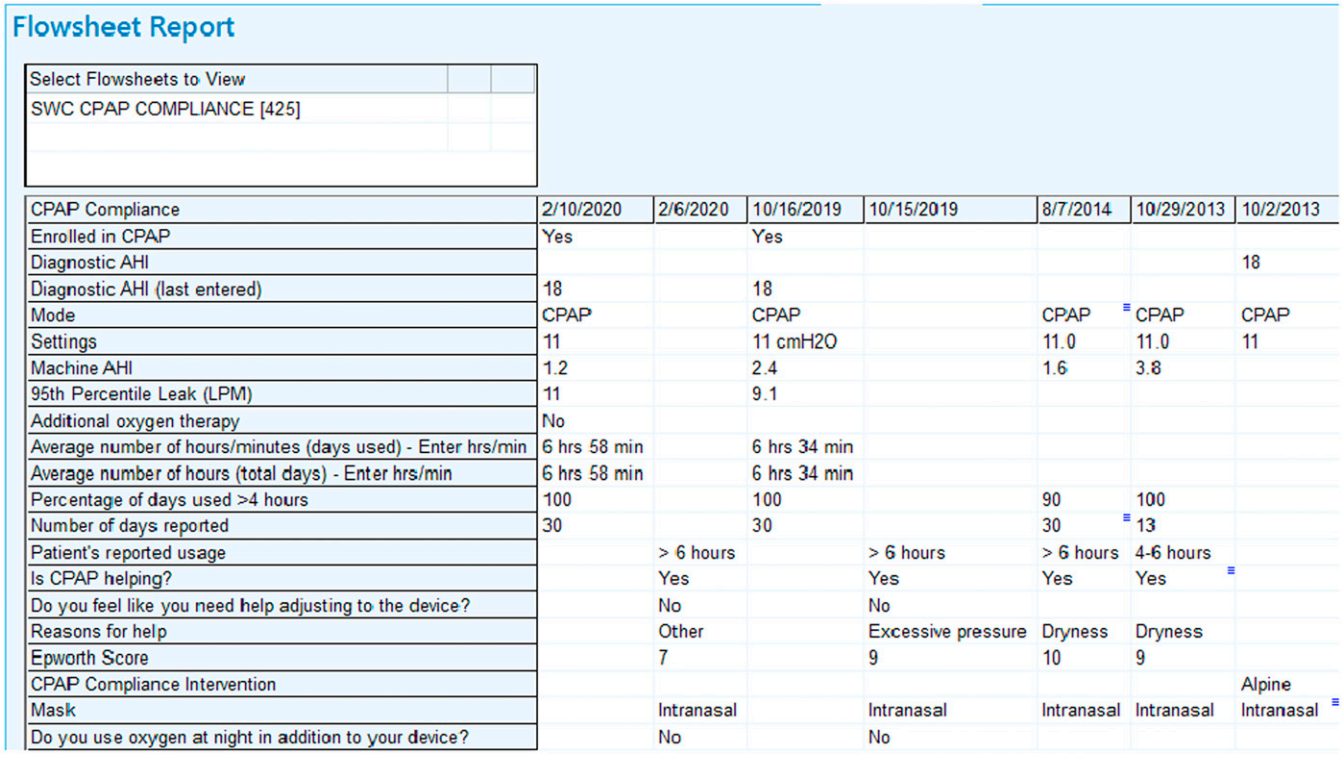
Using the CPAP tracking flowsheet in Epic, the University of Utah data warehouse team identified patients with OSA treated with CPAP between December 1, 2011, and August 31, 2015. To limit the study to only newly diagnosed adults with any usage of CPAP therapy 3–36 months after their CPAP prescription, the following criteria were used to include patients for analysis:

1. A sleep study billing code (polysomnography [current procedural terminology code 95810 or 95811] or home sleep apnea study [current procedural terminology code 95806])
2. Subsequent follow-up visit at the University of Utah Sleep-Wake Center
3. A durable medical equipment letter for a new prescription of CPAP within the University of Utah EHR, which was used as the time point for initiation of CPAP.
4. Age ≥ 18 years

Patients with prior OSA diagnosis at outside facilities and patients with previous usage of CPAP or other therapies for OSA were excluded. Patients were also excluded from the study if they did not have any adherence data or AHI_{flow} recorded by their machine in the 3–36 months after CPAP was dispensed. A flow diagram of the algorithm used to identify these patients is shown in **Figure 2**.

An AHI ≥ 5 events/h was utilized for the diagnosis of OSA.[36] For the majority of patients, ≥ 30% airflow reduction with 4% oxygen desaturation (Medicare criteria) was to define hypopneas. OSA was further categorized as mild, moderate, and severe based on AHI with patients with AHI of 5–14.9 events/h deemed mild, AHI of 15–29.9 events/h as moderate, and AHI of ≥ 30 events/h as severe OSA.[36] Patients with upper airway resistance syndrome who received CPAP therapy were excluded.

Figure 1—A sample of CPAP-adherence tracking flowsheet from electronic health record within University of Utah sleep clinics.



Flowsheet Report

Select Flowsheets to View
SWC CPAP COMPLIANCE [425]

CPAP Compliance	2/10/2020	2/6/2020	10/16/2019	10/15/2019	8/7/2014	10/29/2013	10/2/2013
Enrolled in CPAP	Yes		Yes				
Diagnostic AHI							18
Diagnostic AHI (last entered)	18		18				
Mode	CPAP		CPAP		CPAP	CPAP	CPAP
Settings	11		11 cmH2O		11.0	11.0	11
Machine AHI	1.2		2.4		1.6	3.8	
95th Percentile Leak (LPM)	11		9.1				
Additional oxygen therapy	No						
Average number of hours/minutes (days used) - Enter hrs/min	6 hrs 58 min		6 hrs 34 min				
Average number of hours (total days) - Enter hrs/min	6 hrs 58 min		6 hrs 34 min				
Percentage of days used >4 hours	100		100		90	100	
Number of days reported	30		30		30	13	
Patient's reported usage		> 6 hours		> 6 hours	> 6 hours	4-6 hours	
Is CPAP helping?		Yes		Yes	Yes	Yes	
Do you feel like you need help adjusting to the device?		No		No			
Reasons for help		Other		Excessive pressure	Dryness	Dryness	
Epworth Score		7		9	10	9	
CPAP Compliance Intervention							Alpine
Mask		Intranasal		Intranasal	Intranasal	Intranasal	Intranasal
Do you use oxygen at night in addition to your device?		No		No			

AHI = apnea-hypopnea index, CPAP = continuous positive airway pressure, LPMs = leak per minute, SWC = (University of Utah) Sleep-Wake Center.

Data collection

Vital signs, anthropometric measurements, and laboratory values from all nonemergency clinic visits with the University of Utah Healthcare System were extracted from the University of Utah Enterprise data warehouse for up to a year before and year after CPAP initiation. Emergency Department visit data were excluded because of concerns that patients' assessments would be affected by acute illness and therefore not reflect the effects of OSA or its treatment.[37] The date of CPAP durable medical equipment prescription was used as the start date of CPAP treatment. Posttreatment values obtained 1 year ± 3 months after the start date of CPAP were averaged to accommodate for variations in yearly follow-up timing. The mean nightly CPAP usage for all available adherence downloads (most often summarizing 90 days) was used as an estimate for CPAP adherence throughout the entire period from CPAP initiation to 15 months after.

Health care utilization measures (emergency department visits and hospitalizations across the University of Utah Healthcare System) were determined using clinical encounter information and current procedural terminology codes. Total health care charges included medical and pharmacy charges shown in 2015 dollars, with correction for inflation across years of study using the consumer price index for medical care.[38] Both health care utilization and charges were tabulated for the 12 months before and 12 months after the durable medical equipment letter receipt.

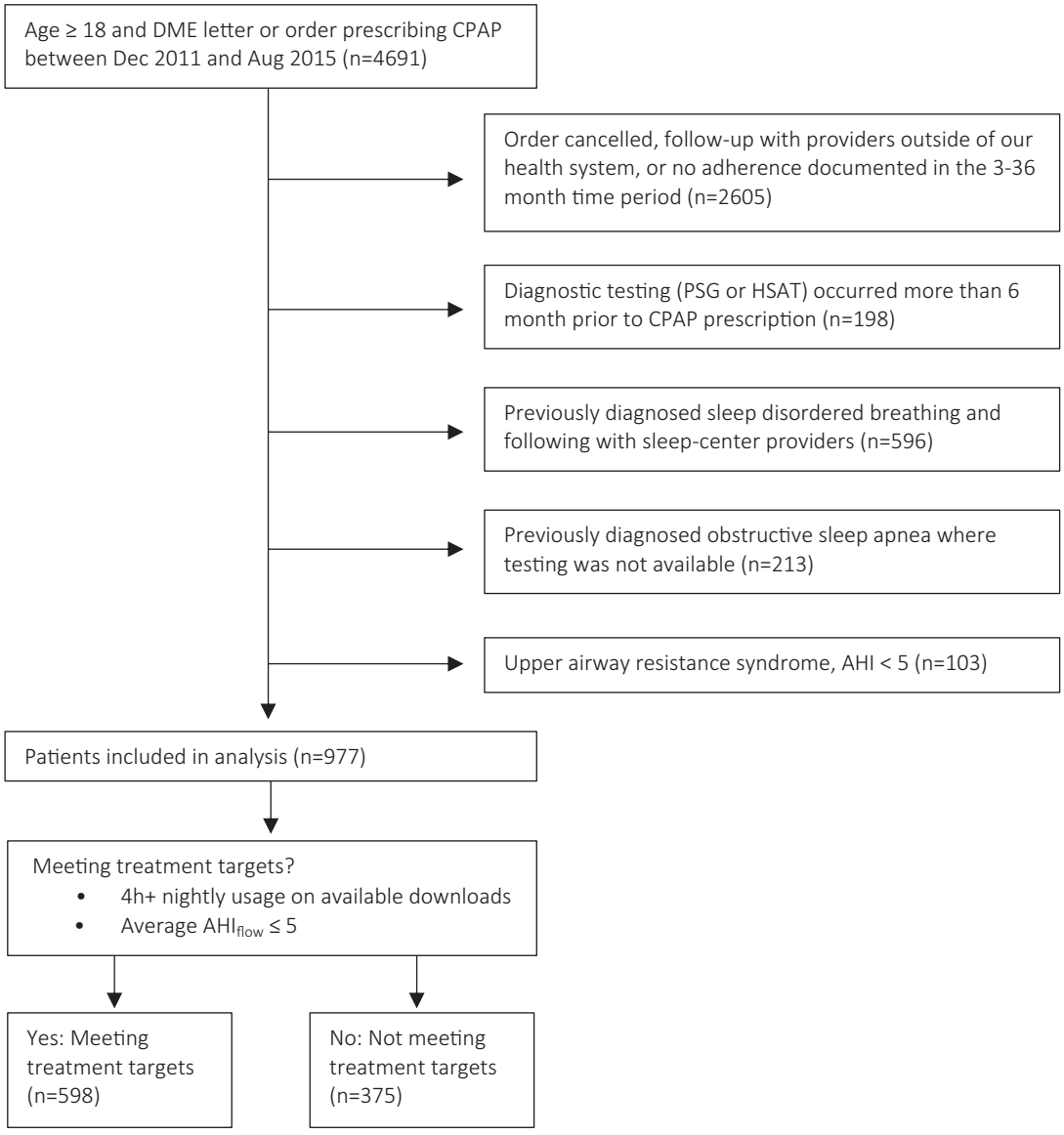
Statistical analysis

Median, interquartile range, and proportion were used to summarize the baseline data, which were generally nonnormally distributed. Comparisons were performed for each patient who had data available before and after the initiation of CPAP therapy. Mean and standard deviation were used to summarize pre-CPAP to post-CPAP comparisons, as the magnitude of changes followed a normal distribution.

Patients were categorized as meeting adequacy of treatment targets if they had 4 or more hours of nightly usage on available downloads (with no minimum requirement for the number of downloads) and an average machine-measured AHI_{flow} of less than 5 events/h while on treatment. We chose the average hours of CPAP usage given that hours of CPAP usage correlates with many outcomes ranging from mortality[12] to daytime levels of sleepiness.[7] Mask leak was also assessed at all clinic visits but was not systematically recorded and thus was not included in this analysis as an adequacy target. These criteria mirror the 2013 statement on remote adherence tracking,[27] but with a more stringent AHI_{flow} target of ≤ 5 events/h.

Subgroup analyses were performed by OSA severity (stratified by diagnostic AHI of mild 5–15 events/h, moderate 15–30 events/h, severe 30+ events/h) and nightly CPAP usage (stratified by 0–3 h/night mean, 3–6 h/night mean, and 6+ hours nightly) to investigate threshold effects. Significance testing of pre-post and between-group comparisons of blood pressure

Figure 2— A flow diagram demonstrating the rules for identifying patients with the inclusion and exclusion criteria.



AHI = apnea-hypopnea index, AHI_{flow} = estimate of on-treatment AHI generated by continuous positive airway pressure systems, DME = durable medical equipment, HSAT = home sleep apnea testing, PSG = polysomnogram.

changes was performed with paired and unpaired *t*-tests, respectively. Hypothesis testing was not performed for secondary analyses. Stata statistical package (version 14.2) and Python 3.0 were used to perform statistical calculations.

RESULTS

Nine hundred seventy-six eligible patients were identified as having newly diagnosed OSA with any usage of CPAP 3 months after prescription. Baseline characteristics of these patients are shown in **Table 1**. All patients had baseline vital signs and anthropomorphic data, but only 20.2% of patients had HbA1c (n = 197) and 41.2% had serum creatinine (n = 401) measurements from the year preceding the start of CPAP. Patients with severe OSA were more likely to have HbA1c information (23.5% severe; 17.6% mild). Of patients with values available prior to CPAP initiation, 9.2% had mean creatinine over 1.3 mg/dL and 28.9% had HbA1c over 6.5%. A slight male preponderance was seen, with most patients being middle-aged and obese (67.8% with BMI ≥ 30 kg/m^2). Mean diagnostic AHI was 33.2 events/h (interquartile range 12.0–45.3 events/h), with 291 patients having mild OSA, 293 with moderate OSA, and 392 with severe OSA. Patients with severe OSA were more likely to be male (67.1%) and more obese (median BMI 35.4 kg/m^2) than patients with mild OSA (45% male, mean BMI 31.3 kg/m^2). Other measured variables did not vary by OSA severity.

Table 1—Patient characteristics averaged over the year before time of diagnosis by OSA severity based on AHI.

	All OSA Patients (n = 976, 100%)	Mild OSA (n = 291, 30%)	Moderate OSA (n = 293, 30%)	Severe OSA (n = 392, 40%)
Age (years)	55.0 [44.0, 65.0], n = 976	55.0 [43.0, 54.0], n = 291	55.0 [45.0, 65.0], n = 293	56.0 [44.0, 65.0], n = 392
% Male	56.6	45.4	53.6	67.1
BMI (kg/m^2)	33.4 [28.8, 38.7], n = 960	31.3 [28.0, 36.9], n = 287	32.9 [28.4, 38.1], n = 287	35.4 [30.1, 41.0], n = 386
SBP (mmHg)	128.0 [120.0, 136.5], n = 972	127.1 [118.1, 135.0], n = 290	126.7 [119.4, 135.3], n = 292	128.0 [120.0, 136.5], n = 390
DBP (mmHg)	77.5 [71.6, 82.5], n = 972	77.0 [70.7, 82.2], n = 290	77.5 [71.8, 82.0], n = 292	78.3 [72.3, 83.7], n = 390
SpO_2 (%)	95.0 [93.8, 96.0], n = 965	95.3 [94.0, 96.7], n = 289	95.0 [94.0, 96.0], n = 289	94.8 [93.3, 95.9], n = 387

Data are presented as median [IQR] unless otherwise indicated. Mild OSA = AHI of 5–14.9 events/h, moderate OSA = AHI of 15–29.9 events/h, and severe OSA = AHI of ≥ 30 events/h. The number of patients (n) with a given value record in the electronic health record for the year prior to starting CPAP is listed in parentheses. For patients with multiple values in the year prior to starting CPAP, the mean value was used. AHI = apnea-hypopnea index, BMI = body mass index, CPAP = continuous positive airway pressure, DBP = diastolic blood pressure, IQR = interquartile range, OSA = obstructive sleep apnea, SBP = systolic blood pressure, SpO_2 = peripheral oxygen saturation.

Six hundred eighty patients had blood pressure (BP) measurements in both the year prior and at 1 year ± 3 months post-CPAP initiation. Each patient averaged 6.1 BP measurements before CPAP initiation and 3.5 BP measurements during CPAP therapy during the study period. Patients (n = 296) who did not have both pre-CPAP and post-CPAP blood pressure measurements were slightly younger (median age 54 vs 55 years). They did not differ in OSA severity or likelihood of meeting treatment targets (**Table S5** in the supplemental material). Pre- and post-measurements were available for BMI (n = 675) and SpO_2 (n = 625) in the majority, but only limited numbers of patients had both pre- and post-laboratory assessments (serum creatinine n = 109; HbA1c n = 47 of which 23 had at least 1 HbA1c above 6.5%). **Table S2** and **Table S3** in the supplemental material summarize the number of measurements available for each outcome.

The mean nightly CPAP usage was 5.40 hours as extrapolated from a mean of 1.91 adherence downloads per patient, each usually summarizing 90 days. Four hundred fifty-eight (46.9%) of patients used CPAP for more than 6 hours, 38.2% (n = 373) used between 3 and 6 hours, and 14.9% (n = 145) used fewer than 3 hours per night. Median residual AHI_{flow} was 2 (interquartile range 1–4.3) events/h. Four hundred five patients used autotitrating PAP, and 571 were on fixed pressure CPAP.

Five hundred ninety-eight of 976 (61.2%) patients met treatment goals as defined by more than 4 hours of nightly usage on available downloads and an $AHI_{flow} < 5$ events/min. The proportion of patients meeting treatment goals did not vary by severity of OSA (**Table S1** in the supplemental material).

After 1 year of treatment with CPAP, mean systolic BP (SBP) decreased from 128.4 ± 13.3 mm Hg to 127.2 ± 13.7 mm Hg (95% confidence interval [CI] of change −0.25 to −2.2 mm Hg, $P = .01$) and mean diastolic BP decreased from 76.8 to 75.8 mm Hg (95% CI −0.38 to −1.6 mm Hg, $P < .01$) (n = 680; **Table 2**).

Among patients meeting treatment adequacy targets, the mean change in SBP from the year prior to the year after CPAP initiation measurements was −1.35 mm Hg (95% CI −2.7 to −0.02 mm Hg, n = 405) compared with −1.04 mm Hg (CI −2.46 to 0.38 mm Hg, n = 275) among patients not meeting targets. Similar decreases in diastolic BP were seen, with mean change in those meeting goals of −1.37 mm Hg (CI −2.22 to −0.53 mm Hg) and not meeting goals of −0.49 mm Hg (CI −1.43 to 0.45 mm Hg). No statistically significant difference was found between the amount of BP reduction in patients meeting adherence targets compared to those who did not (difference in reduction between groups of SBP: −0.32 mm Hg, 95% CI −2.33 to 1.69 mm Hg, $P = .75$ and diastolic BP: −0.88 mm Hg, 95% CI −2.17 to 0.40 mm Hg, $P = .17$).

There was an increase in mean SpO_2 from 94.68 to 95.01% (95% CI of difference 0.18–0.48%). SpO_2 improved in patients who both met goals and those who did not (meeting goals: 0.33%, CI 0.14–0.53%, n = 375; not meeting goals 0.33%, CI 0.10–0.55%, n = 250). We did not find evidence of a change in mean BMI (n = 675) following initiation of CPAP therapy, either in the entire cohort or among subgroups meeting treatment adequacy targets. Analyses of serum creatinine (n = 109) and HbA1c (n = 47) were severely limited by missing data (**Table S2**, **Table S3**, and **Table S6** in the supplemental material).

Subgroup analyses by average nightly adherence (< 3 hours, 3–6 hours, 6+ hours nightly; **Table 3**) and OSA severity (mild, moderate, and severe; **Table 4**) all showed decreases in mean systolic and diastolic blood pressure that may be the result of chance and did not provide clear evidence of a threshold effect. The increase in mean SpO_2 was consistently demonstrated across disease severity and adherence subgroups.

Healthcare utilization, as measured by the number of emergency department visits and inpatient admissions (mean 0.22 per year to 0.53 per year, 95% CI of difference 0.21 to 0.41 more visits per year after initiation) and total health care charges (mean $3,997/year to $8,986/year, 95% CI of difference $2816/y to $7124/y greater after CPAP initiation) increased in the year after initiation of CPAP compared to the year prior. This increase was seen in patients both meeting treatment targets (0.21 to 0.50 visits per year and $4,083/year to $8,563/year) and not meeting treatment targets (0.24 to 0.57 visits per year and $3,861/year to $9,660/year). Still, there were

Table 2—Cardiometabolic outcomes and health care utilization before and after CPAP.

	All OSA Patients				Patients Meeting Treatment Targets				Patients Not Meeting Treatment Targets			
	n	Year Prior to CPAP	1 year (±3 Months) after Starting CPAP	Change Pre to Post Mean Difference (95% CI)	n	Year Prior to CPAP	1 year (±3 Months) after Starting CPAP	Change Pre to Post Mean Difference (95% CI)	n	Year Prior to CPAP	1 year (±3 Months) after Starting CPAP	Change Pre to Post Mean Difference (95% CI)
Clinical Median [IQR]												
SBP (mmHg)	680	127.5 [120.2, 136.1]	126.0 [118.0, 135.7]	**−1.23 (−2.22 to −0.25)**	405	128.6 [120.2, 136.8]	126 [118.3, 135.7]	**−1.36 (−2.7 to −0.02)**	275	127.1 [118.5, 135.4]	125.1 [116.6, 135.9]	−1.04 (−2.46 to 0.38)
DBP (mmHg)	680	77.1 [71.0, 82.3]	76.0 [70.0, 82.0]	**−1.01 (−1.64 to −0.38)**	405	77.0 [71.0, 82.3]	75.5 [70.0, 81.5]	**−1.37 (−2.2 to −0.53)**	275	77.3 [71.1, 81.7]	76.0 [70.0, 82.0]	−0.48 (−1.43 to 0.45)
SpO_2 (%)	625	95.0 [93.5, 96.0]	95.0 [94.0, 96.3]	**0.33 (0.18 to 0.48)**	375	95.0 [93.4, 96.0]	95.0 [93.9, 96.0]	**0.33 (0.14 to 0.53)**	250	95.0 [93.8, 96.0]	95.0 [94.0, 96.5]	**0.33 (0.1 to 0.55)**
BMI (kg/m^2)	675	33.8 [30.0, 38.7]	33.6 [29.1, 38.8]	−0.09 (−0.30 to 0.11)	406	34.4 [29.4, 39.9]	34.7 [29.9, 40.0]	0.02 (−0.25 to 0.3)	269	32.7 [28.1, 37.8]	32.4 [27.8, 37.3]	−0.27 [−0.58 to 0.04]
Economic												
Mean charges per patient ($/y)	973	$3,997	$8,986	**$4,989 ($2,816 to $7,124)**	598	$4,083	$8,563	**$4,480 [$1,523 to $7,436]**	375	$3,861	$9,659	**$5,798 [$2,738 to $8,859]**
Yearly ED visits and admissions	973	0.22	0.52	**0.3 (0.21 to 0.41)**	598	0.21	0.50	**0.29 [0.17 to 0.42]**	375	0.24	0.57	**0.37 [0.16 to 0.51]**

A comparison of several key health-record–derived endpoints before and after starting CPAP. When multiple values were available during the study period (either the year preceding CPAP, or 1 year [±3 months]), the mean was taken. Patients were categorized as meeting adequacy of treatment targets if they had 4 or more hours of nightly usage on available downloads (with no minimum requirement for number of downloads or time period summarized by those downloads) and an average machine-measured AHI (AHI_{flow}) of ≤ 5 events/h while on treatment. Confidence intervals not including 0 are bolded. AHI = apnea-hypopnea index, BMI = body mass index, CI = confidence interval, CPAP = continuous positive airway pressure, DBP = diastolic blood pressure, ED = emergency department, IQR = interquartile range, OSA = obstructive sleep apnea, SBP = systolic blood pressure, SpO_2 = peripheral oxygen saturation.

Table 3—Cardiometabolic parameters before and after initiation of CPAP, stratified by mean nightly usage.

	0–3 Hours			3–6 Hours			>6 Hours		
	n	Prior to CPAP	After CPAP	n	Prior to CPAP	After CPAP	n	Prior to CPAP	After CPAP
SBP, mmHg	112	125.5 [117.7, 113.9]	125.3 [115.1, 135.9]	257	127.4 [121.9, 137.8]	127.0 [118.3, 136.3]	311	128.5 [118.8, 135.7]	125.7 [118.0, 134.2]
DBP, mmHg	112	77.8 [73.1, 82.3]	78.3 [70.9, 83.4]	257	77.3 [71.0, 82.3]	76.3 [70.0, 82.0]	311	76.7 [70.8, 81.3]	75.0 [70.0–80.0]
SpO_2, %	99	95.0 [93.8, 96.0]	95.4 [93.4, 96.8]	236	95.0 [93.5, 96.0]	95.0 [94.0, 96.0]	290	94.8 [93.3, 96.0]	95.0 [94.0, 96.0]
BMI, kg/m^2	109	34.4 [29.1, 40.9]	34.2 [28.8, 40.0]	252	33.5 [28.7, 38.3]	33.2 [28.7, 38.3]	314	33.7 [29.1, 38.3]	34.0 [29.5, 39.4]

Data are presented as median [IQR] unless otherwise indicated. Comparison of average values from the 12 months prior to CPAP initiation and 1 year (±3 months) after CPAP initiation for each strata of mean CPAP adherence based on hours of CPAP usage. CPAP adherence was determined by extrapolating from all available CPAP machine downloads. BMI = body mass index, CPAP = continuous positive airway pressure, DBP = diastolic blood pressure, IQR = interquartile range, SBP = systolic blood pressure, SpO_2 = peripheral oxygen saturation.

no significant differences when comparing the health care utilization between these 2 groups. The increase in health care expenditure was consistent among all different durations of CPAP usage and whether patients met treatment adequacy targets.

DISCUSSION

This study characterizes changes in certain EHR-derived outcomes within 1 year of CPAP therapy guided by adherence and AHI_{flow} tracking data. Most notably, improvements in blood pressure occurred after initiation of CPAP (mean decrease of systolic 1.23 mm Hg and diastolic 1.01 mm Hg), with no statistically significant difference in the magnitude of improvement between the group that met adherence targets and the group that did not. Improvement in daytime peripheral oxygenation (mean increase 0.3%) was also notable, but this may be caused by factors other than CPAP usage, given the improvements occurred identically in patients meeting treatment targets and those who did not. In contrast to prior studies demonstrating weight gain,[39] we did not find evidence for a change in weight after patients started CPAP. An unexpected increase in health care utilization, as measured by acute care visits and overall charges within the University of Utah Health system, was also found within the first year of CPAP initiation.

Our study is among the first to address the consequences of utilizing CPAP tracking downloads during routine care of patients with OSA. Despite the widespread adoption of adherence tracking guided algorithms due to presumed clinical effectiveness, there have not been studies that have validated the clinical utility of this approach to improve patient outcomes.

Our real-world dataset showed modest improvement in SBP and diastolic BP with the initiation of CPAP treatment, consistent with a lesser degree of antihypertensive effect compared with the efficacy estimates from prior randomized-controlled trials[40,41] and metanalyses.[18] Patients who both met adherence and physiology normalization targets had larger improvements in SBP (0.31 mm Hg) and diastolic BP (0.88 mm Hg) that were not statistically different from patients who did not meet those targets. This finding does not allow for inferences supporting the effectiveness of the ATS remote-tracking algorithm. However, this study utilized a convenience sample and is likely under-powered to test the between-group difference. Also, patients who continued to use CPAP but missed sleep clinic visits would potentially be misclassified as not meeting adherence

Table 4—Cardiometabolic outcomes before and after CPAP, with stratification by severity of OSA.

	Mild OSA			Moderate OSA			Severe OSA		
	n	Before CPAP	After CPAP	n	Before CPAP	After CPAP	n	Before CPAP	After CPAP
SBP, mmHg	205	127.5 [119.4, 135.5]	124.0 [117.0, 134.7]	203	126.0 [118.8, 134.2]	125.5 [116.8, 134.0]	272	129.0 [121.8, 138.1]	128.0 [119.0, 136.5]
DBP, mmHg	205	77.0 [70.4, 81.3]	76.0 [68.5, 81.7]	203	77.0 [71.1, 82.0]	75.9 [70.0, 81.8]	272	77.5 [71.4, 83.0]	76.0 [71.0, 82.0]
SpO_2, %	186	95.0 [93.8, 96.4]	95.5 [94.0, 96.8]	188	95.0 [93.8, 96.0]	95.0 [94.0, 96.0]	251	94.5 [93.0, 95.9]	95.0 [93.3, 96.0]
BMI, kg/m^2	207	31.3 [28.2, 37.2]	31.2 [28.0, 37.1]	197	33.0 [28.9, 38.3]	32.9 [29.1, 37.6]	271	36.0 [30.3, 41.5]	35.8 [30.0, 40.7]

Data are presented as median [IQR] unless otherwise indicated. Comparison of average values from the 12 months prior to CPAP initiation and 1 year (±3 months) after CPAP initiation for each stratum of severity of OSA. BMI = body mass index, DBP = diastolic blood pressure, OSA = obstructive sleep apnea, SBP = systolic blood pressure, SpO_2 = peripheral oxygen saturation.

targets, which would bias results toward the null. Lastly, moderate adherence that does not meet the ATS criteria may still result in some antihypertensive effect.

The increase in health care utilization is unexpected and occurred in both examined metrics: mean number of acute care visits (emergency department visits and inpatient hospitalizations) and mean total charges. These increases were consistent across most strata of adherence, as well as among patients meeting treatment targets and those who did not. Prior research in Medicare beneficiaries suggests that comorbidity-matched patients with untreated OSA have higher health care utilization than their treated counterparts,[8] health care utilization is high in the 2 months preceding diagnosis,[42] and partial adherence and full adherence had a divergent relationship to health care charges.[42] Similarly, a large health system in the southeastern United States also stratified patients by CPAP adherence and found a negative association between CPAP usage and acute care visits after diagnosis with OSA.[43] One explanation for this study's discordant findings may be that patients shifted care to our health system from patients who previously received care elsewhere (health-system patient flux discussed further in the supplemental material). Alternatively, unrelated increases in costs and utilization may occur if sleep evaluation referrals were done in anticipation of an elective procedure, such as bariatric or joint replacement surgery.

A key limitation of our retrospective, within-subjects observational design is an inability to extract potential confounders that could plausibly strongly influence measured outcomes, such as contemporaneous medication changes (particularly antihypertensive medications), bariatric surgery, or other disease management interventions. To address this, we performed separate analyses for patients meeting treatment targets and those who did not. Suppose effective CPAP treatment (measured by adherence) leads to normalized physiology (measured by AHI_{flow}) that mediates improvements in outcomes. In that case, improvements should not be seen in patients who do not meet these targets (a concept known as a falsification endpoint[44]). Except for SpO_2, the remaining analyses demonstrated 95% CIs, including the null among patients who did not meet treatment adequacy targets. While increases in SpO_2 following CPAP initiation have been seen in randomized trials,[45] the improvement in both groups in this study suggests it may be the result of confounders, such as the addition of supplemental oxygen, which we were not able to assess in our dataset.

While a contemporaneous control group not utilizing remote tracking for optimizing CPAP therapy would have strengthened this analysis, the widespread adoption of tracking into current systems of health care makes a direct comparison of these 2 management strategies difficult now. Another limitation of our methodology is a slight deviation from the ATS guidance statement on CPAP tracking[27] in targeting an AHI_{flow} of 5 events/h, not 10 events/h. Additionally, the ATS guidance statement recommends assessment and adjustment of treatment based on the severity of air leak, in addition to mean nightly adherence and residual AHI_{flow}. Air leak is assessed during every sleep clinic visit within the University of Utah sleep program. Increased air leak triggers a mask-fitting visit with an on-site sleep technologist. However, information on air leak was not reliably recorded, and we could not present descriptive data of the frequency of mask adjustments. Finally, due to the methodology we used for identifying patients (**Figure 2**), we do not have information on patients prescribed CPAP that either never attempted or ceased attempts at CPAP use prior to 3 months after prescription.

A principal concern arising from the usage of EHR-based data is the potential for informed presence bias, which results from patients with values recorded in the EHR being systematically different from those with no value recorded.[46] For example, in this cohort, only a minority of patients had an HbA1c drawn because that test is preferentially ordered on patients with a clinical suspicion for undiagnosed or uncontrolled diabetes. Those patients likely have higher HbA1c values than the rest of the sample population who did not warrant that test.[47] The potential for informed presence bias is greater on laboratory outcomes than on vital sign assessments, which are routinely obtained at each visit regardless of the presence of a specific clinical question. Data missingness was particularly problematic for laboratory-based outcomes, which should be considered when designing future investigations of the real-world effectiveness of sleep-disordered breathing treatments.

Strengths of the current study include the relatively high adherence (mean 5.4 hours of nightly usage) that may accurately reflect expected long-term usage from those who begin treatment.[48] By utilizing a simple search strategy to identify patients newly diagnosed with OSA with minimal exclusion criteria, we were able to generate real-world data reflecting current practice patterns and thus provide a very close approximation of the actual effect of CPAP treatment in usual care after the diagnosis of OSA.

CPAP therapy for OSA is uniquely positioned among chronic disease treatments to pioneer real-world data generation and usage for research given the high prevalence of OSA and the availability of remote monitoring technology with every CPAP prescription.[28] Given the low cost of this methodology, future studies could be powered to explore the effect of CPAP on subgroups or multiple other variables of interest, such as patient-reported outcome measures that are now being collected at many sleep centers.[49] Non-AHI markers of OSA phenotype such as nocturnal hypoxia, frequency of arousals, and the presence of sleepiness[50] would also be of particular interest for further investigation, as they may lead to heterogeneity of CPAP treatment effects.[21,28]

In summary, we utilize EHRs and financial data to evaluate the effectiveness of adherence tracking system-guided CPAP in routine use. We find a modest improvement in blood pressure, with no statistically significant difference in the magnitude of improvement between patients meeting treatment targets within a year of CPAP initiation. SpO_2 also improved after CPAP initiation, although with less convincing evidence that CPAP treatment mediates the effect. These findings should inform providers' estimates about the real-world effectiveness of CPAP, but prompt further investigation into whether the current treatment adequacy targets improve clinical end points. Lastly,

it should motivate future research to fulfill the promise of CPAP-remote tracking as a model for chronic disease care by utilizing clinical data sources to establish real-world effectiveness.

ABBREVIATIONS

AHI, apnea-hypopnea index
AHI_{flow}, residual apnea-hypopnea index as measured by a PAP adherence tracking device
ATS, American Thoracic Society
BMI, body mass index
BP, blood pressure
CI, confidence interval
CPAP, continuous positive airway pressure
EHR, electronic health record
HbA1c, percentage of glycated hemoglobin
OSA, obstructive sleep apnea
SBP, systolic blood pressure
SpO_2, peripheral oxygen saturation

REFERENCES

1. Peppard PE, Young T, Barnet JH, Palta M, Hagen EW, Hla KM. Increased prevalence of sleep-disordered breathing in adults. *Am J Epidemiol.* 2013;177(9):1006–1014.
2. Gottlieb DJ, Punjabi NM. Diagnosis and management of obstructive sleep apnea: A review. *JAMA.* 2020;323(14):1389–1400.
3. Patil SP, Ayappa IA, Caples SM, Kimoff RJ, Patel SR, Harrod CG. Treatment of adult obstructive sleep apnea with positive airway pressure: an American Academy of Sleep Medicine Clinical Practice Guideline. *J Clin Sleep Med.* 2019;15(2):335–343.
4. Watson NF. Health care savings: the economic value of diagnostic and therapeutic care for obstructive sleep apnea. *J Clin Sleep Med.* 2016;12(8):1075–1077.
5. Agency for Healthcare Research and Quality. Technology Assessment for Public Comment. https://www.ahrq.gov/research/findings/ta/draft-review-form.html. Accessed April 2021.
6. Gottlieb DJ, Yenokyan G, Newman AB, et al. Prospective study of obstructive sleep apnea and incident coronary heart disease and heart failure: the sleep heart health study. *Circulation.* 2010;122(4):352–360.
7. Reutrakul S, Mokhlesi B. Obstructive sleep apnea and diabetes: a state of the art review. *Chest.* 2017;152(5):1070–1086.
8. Weaver TE, Maislin G, Dinges DF, et al. Relationship between hours of CPAP use and achieving normal levels of sleepiness and daily functioning. *Sleep.* 2007;30(6):711–719.
9. Wickwire EM, Tom SE, Vadlamani A, et al. Older adult US Medicare beneficiaries with untreated obstructive sleep apnea are heavier users of health care than matched control patients. *J Clin Sleep Med.* 2020;16(1):81–89.
10. Baldwin CM, Griffith KA, Nieto FJ, O'Connor GT, Walsleben JA, Redline S. The association of sleep-disordered breathing and sleep symptoms with quality of life in the Sleep Heart Health Study. *Sleep.* 2001;24(1):96–105.
11. Young T, Finn L, Peppard PE, et al. Sleep disordered breathing and mortality: eighteen-year follow-up of the Wisconsin sleep cohort. *Sleep.* 2008;31(8):1071–1078.
12. Campos-Rodriguez F, Peña-Griñan N, Reyes-Nuñez N, et al. Mortality in obstructive sleep apnea-hypopnea patients treated with positive airway pressure. *Chest.* 2005;128(2):624–633.
13. McEvoy RD, Antic NA, Heeley E, et al; SAVE Investigators and Coordinators. CPAP for prevention of cardiovascular events in obstructive sleep apnea. *N Engl J Med.* 2016;375(10):919–931.
14. Peker Y, Glantz H, Eulenburg C, Wegscheider K, Herlitz J, Thunström E. Effect of Positive airway pressure on cardiovascular outcomes in coronary artery disease patients with nonsleepy obstructive sleep apnea. The RICCADSA Randomized Controlled Trial. *Am J Respir Crit Care Med.* 2016;194(5):613–620.
15. Sánchez-de-la-Torre M, Sánchez-de-la-Torre A, Bertran S, et al; Spanish Sleep Network. Effect of obstructive sleep apnoea and its treatment with continuous positive airway pressure on the prevalence of cardiovascular events in patients with acute coronary syndrome (ISAACC study): a randomised controlled trial. *Lancet Respir Med.* 2020;8(4):359–367.
16. Yu J, Zhou Z, McEvoy RD, et al. Association of positive airway pressure with cardiovascular events and death in adults with sleep apnea: a systematic review and meta-analysis. *JAMA.* 2017;318(2):156–166.
17. McDaid C, Durée KH, Griffin SC, et al. A systematic review of continuous positive airway pressure for obstructive sleep apnoea-hypopnoea syndrome. *Sleep Med Rev.* 2009;13(6):427–436.
18. Montesi SB, Edwards BA, Malhotra A, Bakker JP. The effect of continuous positive airway pressure treatment on blood pressure: a systematic review and meta-analysis of randomized controlled trials. *J Clin Sleep Med.* 2012;8(5):587–596.
19. McMillan A, Bratton DJ, Faria R, et al. A multicentre randomised controlled trial and economic evaluation of continuous positive airway pressure for the treatment of obstructive sleep apnoea syndrome in older people: PREDICT. *Health Technol Assess.* 2015;19(40):1–188.
20. Gottlieb DJ. Does obstructive sleep apnea treatment reduce cardiovascular risk? It is far too soon to say. *JAMA.* 2017;318(2):128–130.
21. Bakker JP, Weaver TE, Parthasarathy S, Aloia MS. Adherence to CPAP: what should we be aiming for, and how can we get there? *Chest.* 2019;155(6):1272–1287.
22. Mansukhani MP, Somers VK, Shafazand S. PAP and cardiovascular events in adults with sleep apnea: is PAP useful? *J Clin Sleep Med.* 2017;13(12):1487–1489.
23. Pack AI, Magalang UJ, Singh B, Kuna ST, Keenan BT, Maislin G. Randomized clinical trials of cardiovascular disease in obstructive sleep apnea: understanding and overcoming bias. *Sleep.* 2021;44(2):zsaa229.
24. Peppard PE, Hagen EW. The last 25 years of obstructive sleep apnea epidemiology-and the next 25? *Am J Respir Crit Care Med.* 2018;197(3):310–312.
25. Javaheri S, Martinez-Garcia MA, Campos-Rodriguez F. CPAP treatment and cardiovascular prevention: we need to change the design and implementation of our trials. *Chest.* 2019;156(3):431–437.
26. Casey JA, Schwartz BS, Stewart WF, Adler NE. Using electronic health records for population health research: a review of methods and applications. *Annu Rev Public Health.* 2016;37(1):61–81.
27. Schwab RJ, Badr SM, Epstein LJ, et al; ATS Subcommittee on CPAP Adherence Tracking Systems. An official American Thoracic Society statement: continuous positive airway pressure adherence tracking systems. The optimal monitoring strategies and outcome measures in adults. *Am J Respir Crit Care Med.* 2013;188(5):613–620.
28. Pépin JL, Bailly S, Tamisier R. Big data in sleep apnoea: opportunities and challenges. *Respirology.* 2020;25(5):486–494.
29. Caples SM, Anderson WM, Calero K, Howell M, Hashmi SD. Use of polysomnography and home sleep apnea tests for the longitudinal management of obstructive sleep apnea in adults: an American Academy of Sleep Medicine clinical guidance statement. *J Clin Sleep Med.* 2021;17(6):1287–1293.
30. Gagnadoux F, Pevernagie D, Jennum P, et al. Validation of the System One RemStar Auto A-Flex for obstructive sleep apnea treatment and detection of residual apnea-hypopnea index: a European randomized trial. *J Clin Sleep Med.* 2017;13(2):283–290.
31. Reiter J, Zleik B, Bazalakova M, Mehta P, Thomas RJ. Residual events during use of CPAP: prevalence, predictors, and detection accuracy. *J Clin Sleep Med.* 2016;12(8):1153–1158.
32. Huang HC, Hillman DR, McArdle N. Control of OSA during automatic positive airway pressure titration in a clinical case series: predictors and accuracy of device download data. *Sleep.* 2012;35(9):1277–83A.

33. Li QY, Berry RB, Goetting MG, et al. Detection of upper airway status and respiratory events by a current generation positive airway pressure device. *Sleep.* 2015;38(4):597–605.
34. Fields BG, Behari PP, McCloskey S, et al. remote ambulatory management of veterans with obstructive sleep apnea. *Sleep.* 2016;39(3):501–509.
35. von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP; STROBE Initiative. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. *Ann Intern Med.* 2007;147(8):573–577.
36. American Academy of Sleep Medicine. *International Classification of Sleep Disorders.* 3rd ed. Darien, IL: American Academy of Sleep Medicine; 2014.
37. Pitts SR, Adams RP. Emergency department hypertension and regression to the mean. *Ann Emerg Med.* 1998;31(2):214–218.
38. US Bureau of Labor Statistics. Consumer Price Index, measuring price change in the CPI: Medical care. https://www.bls.gov/cpi/factsheets/medical-care.htm. Accessed June 29, 2020.
39. Quan SF, Budhiraja R, Clarke DP, et al. Impact of treatment with continuous positive airway pressure (CPAP) on weight in obstructive sleep apnea. *J Clin Sleep Med.* 2013;9(10):989–993.
40. Pépin JL, Tamisier R, Barone-Rochette G, Launois SH, Lévy P, Baguet JP. Comparison of continuous positive airway pressure and valsartan in hypertensive patients with sleep apnea. *Am J Respir Crit Care Med.* 2010;182(7):954–960.
41. Martínez-García MA, Capote F, Campos-Rodríguez F, et al; Spanish Sleep Network. Effect of CPAP on blood pressure in patients with obstructive sleep apnea and resistant hypertension: the HIPARCO randomized clinical trial. *JAMA.* 2013;310(22):2407–2415.
42. Chhatre S, Chang YHA, Gooneratne NS, Kuna S, Strollo P, Jayadevappa R. Association between adherence to continuous positive airway pressure treatment and cost among medicare enrollees. *Sleep.* 2020;43(1):zsz188.
43. Kirsch DB, Yang H, Maslow AL, Stolzenbach M, McCall A. Association of positive airway pressure use with acute care utilization and costs. *J Clin Sleep Med.* 2019; 15(9):1243–1250.
44. Lipsitch M, Tchetgen Tchetgen E, Cohen T. Negative controls: a tool for detecting confounding and bias in observational studies. *Epidemiology.* 2010;21(3): 383–388.
45. Alchanatis M, Tourkohoriti G, Kakouros S, Kosmas E, Podaras S, Jordanoglou JB. Daytime pulmonary hypertension in patients with obstructive sleep apnea: the effect of continuous positive airway pressure on pulmonary hemodynamics. *Respiration.* 2001;68(6):566–572.
46. Phelan M, Bhavsar NA, Goldstein BA. Illustrating informed presence bias in electronic health records data: How patient interactions with a health system can impact inference. *EGEMS (Wash DC).* 2017;5(1):22.
47. Rea S, Bailey KR, Pathak J, Haug PJ. Bias in recording of body mass index data in the electronic health record. *AMIA Jt Summits Transl Sci Proc.* 2013;2013: 214–218.
48. Cistulli PA, Armitstead J, Pepin JL, et al. Short-term CPAP adherence in obstructive sleep apnea: a big data analysis using real world data. *Sleep Med.* 2019;59:114–116.
49. Redline S, Baker-Goodwin S, Bakker JP, et al; Sleep Apnea Patient-Centered Outcomes Network. Patient partnerships transforming sleep medicine research and clinical care: perspectives from the sleep apnea patient-centered outcomes network. *J Clin Sleep Med.* 2016;12(7):1053–1058.
50. Robinson GV, Smith DM, Langford BA, Davies RJ, Stradling JR. Continuous positive airway pressure does not reduce blood pressure in nonsleepy hypertensive OSA patients. *Eur Respir J.* 2006;27(6):1229–1235.

ACKNOWLEDGMENTS

Author contributions: BL, final manuscript and final analysis; HH, preliminary analysis, final draft revisions; SN, preliminary analysis, final draft revisions; MC, data acquisition, final draft revisions; JK, economic analysis, final draft revisions; KS, project conceptualization and oversight, final draft revisions.

SUBMISSION & CORRESPONDENCE INFORMATION

Submitted for publication June 7, 2021
Submitted in final revised form October 22, 2021
Accepted for publication October 22, 2021
Address correspondence to: Brian Locke, MD, 26 North 1900 East Wintrobe 701, Salt Lake City, UT 84132; Email: brian.locke@hsc.utah.edu

DISCLOSURE STATEMENT

All authors have seen and approved this manuscript. K.M. Sundar is co-founder of Hypnoscure LLC—a software application for population management of sleep apnea through University of Utah Technology Commercialization Office—and is on the advisory board for Merck Inc. All other authors report no conflicts of interest.