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Sleep Study and Oximetry Parameters for Predicting Postoperative Complications in Patients With OSA

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In the surgical setting, OSA is associated with an increased risk of postoperative complications. At present, risk stratification using OSA-associated parameters derived from polysomnography (PSG) or overnight oximetry to predict postoperative complications has not been established. The objective of this narrative review is to evaluate the literature to determine the association between parameters extracted from in-laboratory PSG, portable PSG, or overnight oximetry and postoperative adverse events. We obtained pertinent articles from Ovid MEDLINE, Ovid MEDLINE In-Process & Other Non-Indexed Citations, and Embase (2008 to December 2017). The search included studies with adult patients undergoing surgery who had OSA diagnosed with portable PSG, in-laboratory PSG, or overnight oximetry that reported on specific sleep parameters and at least one adverse outcome. The search was restricted to English-language articles. The search yielded 1,810 articles, of which 21 were included in the review. Preoperative apnea-hypopnea index (AHI) and measurements of nocturnal hypoxemia such as oxygen desaturation index (ODI), cumulative sleep time percentage with oxyhemoglobin saturation (Spo_2) < 90% (CT90), minimum Spo_2, mean Spo_2, and longest apnea duration were associated with postoperative complications. OSA is associated with postoperative complications in the population undergoing surgery. Clinically and statistically significant associations between AHI and postoperative adverse events exists. Complications may be more likely to occur in the category of moderate to severe OSA (AHI ≥ 15). Other parameters from PSG or overnight oximetry such as ODI, CT90, mean and minimal Spo_2, and longest apnea duration can be associated with postoperative complications and may provide additional value in risk stratification and minimization.

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ABBREVIATIONS: AASM = American Academy of Sleep Medicine; AF = atrial fibrillation; AHI = apnea-hypopnea index; CT90 = cumulative time percentage with Spo_2 < 90%; ODI = oxygen desaturation index; PSG = polysomnography; Spo_2 = oxyhemoglobin saturation; UPPP = uvulopalatopharyngoplasty

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OSA is a common sleep-related breathing disorder characterized by recurring episodes of complete or partial upper airway obstruction during sleep. It is estimated that OSA affects up to 27% of women and 43% of men aged 50 to 70 years and 9% of women and 26% of men aged 30 to 49 years.[1,2] In the surgical setting, OSA presents many challenges because it is associated with an increased risk of postoperative complications, including cardiac and pulmonary complications; oxygen desaturations; difficult intubation; and, in rare instances, death.[3] The prevalence of OSA is estimated to be at least 25% among candidates for elective surgery and may be as high as 80% in high-risk populations such as patients undergoing bariatric surgery.[4]

In the patient with OSA, the intermittent upper airway obstruction leads to reductions in tidal volume and subsequent intermittent arterial hypoxemia and hypercapnia. The compensatory response involves a profound ventilatory response, activation of the sympathetic nervous system, and cortical arousals that disrupt normal sleep architecture causing daytime sleepiness.[5] This response also results in peripheral vasoconstriction, depressed myocardial contractility, oxidative stress, inflammation, and endothelial dysfunction.[6,7] Therefore, OSA is associated with cardiovascular sequelae such as coronary artery disease, left ventricular hypertrophy, hypertension,[8] atrial fibrillation (AF),[9] pulmonary hypertension,[10] and cerebrovascular accidents.[11] In the surgical setting, the administration of opioids, sedatives, and IV fluids may augment patient predisposition to sleep apnea by exacerbating upper airway collapse, depressing the arousal response, and intensifying rostral fluid shifts leading to upper airway edema and reduced patency.[12] This difficulty is highlighted by the increase in both the severity of sleep apnea and arterial hypoxemia in those with known OSA[13] and the emergence of de novo OSA in approximately 26% of patients undergoing surgery.[14] Furthermore, these nocturnal respiratory events and episodic hypoxemia can be associated with significant postoperative sequelae, including cardiac ischemia and arrhythmias.[15,16] The severity and duration of hypoxemia are also important because they have been correlated with the likelihood of myocardial ischemia.[16] Gami et al[17] observed that the incidence of sudden cardiac death was highest during normal hours of sleep (midnight to 6 AM) in patients with OSA. In contrast, patients without OSA experienced these events most frequently in the morning after 6 AM, which suggests a potential link between nocturnal sleep-disordered breathing and cardiovascular dysfunction.[17]

In the postoperative period, 80% of death or near-death events in patients with OSA are observed within the first 24 h after surgery, with the majority of these events occurring on the hospital ward, a vulnerable situation in which patients are not meticulously monitored.[12] Therefore, it is of utmost importance to identify patients with OSA who are at risk of postoperative complications.[18] The gold standard test for the diagnosis and determination of the severity of OSA is in-laboratory polysomnography (PSG).[19] The 2017 clinical practice guideline for diagnostic testing for adult obstructive sleep apnea from the American Academy of Sleep Medicine (AASM) recommended use of alternative portable monitors for home diagnostic testing for OSA.[19] In addition to the PSG technologies, high-resolution nocturnal oximetry has been suggested as a low-cost preoperative screening tool for OSA.[20] For risk stratification in patients with OSA, it is unclear what, if any, specific parameters derived from the PSG or overnight oximetry are associated with postoperative complications. This knowledge is important for risk minimization and enhanced care of patients with known OSA who are undergoing surgery. The objective of this narrative review is to evaluate the literature to determine the association between parameters extracted from portable PSG, in-laboratory PSG, or overnight oximetry and postoperative adverse events.

Materials and Methods

Literature Search Strategy

For this review, we obtained pertinent articles from Ovid MEDLINE, Ovid MEDLINE In-Process & Other Non-Indexed Citations, and Embase by using a search method designed by an information specialist. To supplement our database searches, we also performed a citation search of references from primary or review articles. The comprehensive search included terms for "obstructive sleep apnea," "sleep assessment," and "perioperative and postoperative complications and adverse events" (e-Tables 1-3).

Study Selection Criteria

We included studies that (1) used in-laboratory PSG (type I), portable PSG, or overnight oximetry (types II-IV) to diagnose

OSA and/or assess patients with OSA; (2) reported on at least one postoperative adverse event; (3) reported on the following sleep parameters: apnea-hypopnea index (AHI), oxygen desaturation index (ODI), cumulative time with oxyhemoglobin saturation (Spo_2) < 90% (CT90), minimum Spo_2, mean Spo_2, or longest apnea duration; and (4) included an adult population aged ≥ 18 years. The search was restricted to English-language articles with a publication date limited to 2008 to December 2017. Studies were selected for inclusion first based on title and abstract review and relevance to the study question and then based on full-text review.

Data Extraction

We extracted information about study design, sample size, sleep study type and sleep monitor, reported sleep parameters, and postoperative complications. We summarized our findings by using narrative synthesis.

Results

The search yielded 1,810 articles, of which 21 fulfilled our inclusion criteria and were included in this review. Of the 21 articles, one was added following review of references from the included studies.[21] Among studies reporting postoperative complications in patients with OSA, 19 studies reported on AHI, five on ODI, two on CT90, five on minimum Spo_2, one on mean Spo_2, and one on longest apnea duration (Table 1).[22] The majority of studies measured short-term postoperative adverse outcomes (< 72 h). The most frequently observed events included oxygen desaturations and requirements for supplemental oxygen in the postanesthetic care unit. The more serious respiratory (pneumonia, respiratory failure, aspiration), cardiac (arrhythmia, cardiac arrest, acute coronary syndromes, heart failure, cardiogenic shock), and neurologic (cerebrovascular events, altered level of consciousness, delirium) complications were reported less frequently.

Apnea-Hypopnea Index

The AHI is defined as the total number of apneas and hypopneas per hour of sleep.[23] The current AASM definition of an apnea is a reduction in airflow of at least 90% lasting at least 10 seconds, whereas a hypopnea is defined as a reduction in airflow of at least 30% with a concomitant decrease in Spo_2 by 3% to 4% from pre-event baseline and/or the event is associated with an arousal.[23] The diagnosis and severity of OSA are determined using AHI thresholds: no OSA is an AHI < 5 events per hour, mild is an AHI ≥ 5 to < 15 events per hour, moderate is an AHI ≥ 15 to < 30 events per hour, and severe is an AHI ≥ 30 events per hour.

Of the 19 studies reporting postoperative complications and preoperative AHI, 12 showed significant associations between AHI and postoperative complications (Table 1).[22] These studies evaluated diverse populations undergoing surgery. A number of studies were performed in patients undergoing upper airway surgery for OSA. In a nested case-control study, Kezirian et al[24] studied 255 patients undergoing uvulopalatopharyngoplasty (UPPP) with PSG data and demonstrated that a higher AHI (52.8 vs 38.7 events per hour) was associated with serious complications. In contrast, in a retrospective 2-week follow-up study after UPPP surgery, Kandasamy et al[25] did not demonstrate an association between the AHI and significant postoperative complications, although they found that an AHI ≥ 22 was associated with a twofold increased risk of requiring supplemental oxygen in the postanesthetic care unit. Those who had a higher AHI (37.4 vs 31.4 events per hour; $P = .05$) were more likely to require on-ward supplemental oxygen because of oxygen desaturations. In a retrospective study of 487 patients undergoing multilevel sleep apnea surgery by Pang et al,[26] six patients with preoperative AHI > 60 experienced postoperative hypoxia after extubation. In contrast, a study in 95 patients with OSA undergoing upper airway surgery found that complication rates were not associated with the AHI.[27]

The prevalence of OSA is estimated to be between 70% and 80% in those who are obese.[28] Patients in this population are prone to a greater risk of postoperative cardiac and respiratory complications.[29] Weingarten et al[30] studied 797 patients undergoing bariatric surgery to determine whether there was an association between the AHI and postoperative complications. Although 33% of patients experienced postoperative complications, only age and BMI, but not the severity of OSA as defined by the AHI, were associated with an increased risk of postoperative adverse events. An important caveat was that most of these patients with OSA were receiving CPAP therapy at the time of surgery, so caution should be exercised in drawing conclusions and applying these results to patients with untreated OSA.

In a matched cohort analysis of PSG data and health administrative data in patients with OSA undergoing different types of surgery, Mutter et al[31] reported that both diagnosed and undiagnosed severe OSA (AHI ≥ 30) were associated with more than a twofold increase in

TABLE 1] Sleep Study and Oximetry Parameters Associated With Postoperative Outcomes

Study/Year	No. of Patients	Study Design	Sleep Study Type	Monitoring Device	PAP Use	Parameter (Oxygen Desaturation Criteria)	Outcome	Findings (Complications vs No Complications)
Upper airway surgery								
Asha'ari et al[27]/2017	95	Cohort-R	Lab-PSG	Crystal Sapphire (CleveMed)	Yes, if using preop	AHI	Postop Cx	NS
						Minimum Spo_2	Postop Cx	OR 1.03 for per 5% decrease,[a] mean 68% vs 79%[a]
						Longest apnea duration	Postop Cx	OR 1.03 per 5-s increase,[a] mean 51 vs 39 s[a]
Kandasamy et al[25]/2013	345	Cohort-R	Lab-PSG	NR	Not routine	AHI	O_2 in PACU	OR 2.2 for AHI $\geq$ 22 vs $<$ 22[a]
							O_2 on ward	37.4 vs 31.4[a]
Kezirian et al[24]/2006	255	Nested case-control	Lab-PSG	NR	NR	AHI	Postop Cx	Mean 53 vs 39[a]
Kim et al[41]/2005	153	Cohort-R	Lab-PSG	NR	NR	AHI	Postop Cx	Mean 68 vs 49[a]
Pang et al[26]/2012	487 (6)[b]	Cohort-R	Level III oximetry	WatchPAT 100 (Itamar Medical)	50% preop CPAP trial for 1-2 wk	AHI	Postop Spo_2 desaturation	Mean AHI 67 vs 47
						Minimum Spo_2	Postop Spo_2 desaturation	Mean 61% vs 75%
Cardiac surgery								
Foldvary-Schaefer et al[39]/2015	107	Cohort-P	Lab-PSG	Crystal Monitor 20H	Preop PAP use excluded	AHI ($\geq$ 3%)	Postop Cx	NS
							LVEF (baseline)	Mean 44% vs 53% in patients with AHI $\geq$ 15 vs $<$ 15[a]
							LVEF	NS
						CT90		CT90 $>$ 0 associated with significantly greater BMI, longer intraop ET time, and more prolonged intubation

(Continued)

TABLE 1] *(Continued)*

Study/Year	No. of Patients	Study Design	Sleep Study Type	Monitoring Device	PAP Use	Parameter (Oxygen Desaturation Criteria)	Outcome	Findings (Complications vs No Complications)
Kaw et al[32]/ 2017	190	Cohort-R	Lab-PSG	Nihon Kohden	24% preop use	AHI (≥ 3%)		OR 1.06 per 5-unit increase in AHI[a] in unadjusted analysis (OR 1.04 in adjusted analysis; $P > .05$)
							AF	Effect modification with BMI > 32 kg/m^2
						ODI 3%	AF	NS
						ODI 4%	AF	NS
						Minimum Spo_2	Postop Cx	NS
						Minimum Spo_2	Postop Cx	71% vs 78%[a]
Kua et al[34]/ 2016	150	Cohort-P	Level III oximetry	WatchPAT 200 (Itamar Medical)	Preop PAP use excluded	AHI	AHI	OR 2.9 for AHI ≥ 15[a]
Roggenbach et al[33]/2014	92	Cohort-P	Level III oximetry	MiniScreen 4 (Heinen and Löwenstein)	Postop CPAP if needed	AHI (≥ 3%)	Delirium	OR 6.04 for AHI ≥ 19[a]
						Mean Spo_2	Delirium	NS
						Minimum Spo_2	Delirium	NS
						CT90	Delirium	NS
Unosawa et al[51]/2012	89	Cohort-P	Level IV oximetry	SAS-2100 (Nihon Kohden)	No	AHI (postop)	AF	NS
							PVC	19.2% vs 3.2% between AHI ≥ 15 vs < 15[a]
							Minimum Spo_2	Minimum Spo_2 78% vs 87% between postop AHI ≥ 15 vs < 15[a]
Vascular surgery								
Utriainen et al[35]/2014	82	Cohort-P	Lab-PSG	Embla/ Somnologica (Natus)	No	AHI (≥ 4%)	MACCE	HR 5.1 AHI ≥ 20 vs AHI < 20 for a median follow-up of 52 mo[a]

(Continued)

TABLE 1] *(Continued)*

Study/Year	No. of Patients	Study Design	Sleep Study Type	Monitoring Device	PAP Use	Parameter (Oxygen Desaturation Criteria)	Outcome	Findings (Complications vs No Complications)
Bariatric surgery								
Turan et al[40]/ 2015	218	Cohort-R	Lab-PSG	NR	63% using preop CPAP	CT90	Opioid consumption	Decrease in median postop opioid consumption by 16% per 5% increase in CT90[a]
						Minimum Spo_2	Opioid consumption	NS
						AHI	Opioid consumption	NS
Weingarten et al[30]/2011	797	Cohort-R	Lab-PSG	NR	82% using preop PAP; postop PAP applied if preop use	AHI (≥ 2 or 4)	Postop Cx	NS among AHI categories (mild 5 ≤ AHI < 15, moderate 15 ≤ AHI < 30, severe AHI ≥ 30)
Other populations undergoing surgery								
Chung et al[21]/ 2014	573	Cohort-P	Level IV oximetry	PULSOX-300i (Konica Minolta Sensing)	None, undiagnosed OSA	ODI 4	Postop Cx	OR 2.2 for ODI > 29[a]
						CT90	Postop Cx	OR 2.6 for CT90 > 7%[a]
						Mean Spo_2	Postop Cx	OR 2.8 for mean Spo_2 < 93%[a]
Devaraj et al[22]/2017	245	Cohort-P	Level III oximetry	ApneaLink Plus (ResMed)	None, undiagnosed OSA	AHI (≥ 3%)	Postop Cx	OR 3.6 for AHI ≥ 5 (within 7 d postop)[a]
								OR 3.5 for AHI ≥ 5 (within 30 d postop)[a]
							Postop desaturation	OR 6 for AHI ≥ 5
Hwang et al[37]/2008	172	Cohort-P	Level IV oximetry	NR	None, undiagnosed OSA	ODI 4	Postop Cx	OR 7.0 for ODI ≥ 5[a]
						CT90	Postop Cx	Mean 21% vs 10%[a]

(Continued)

TABLE 1] *(Continued)*

Study/Year	No. of Patients	Study Design	Sleep Study Type	Monitoring Device	PAP Use	Parameter (Oxygen Desaturation Criteria)	Outcome	Findings (Complications vs No Complications)
Kaw et al[53]/ 2016	519	Cohort-R	Lab-PSG	NR	24% preop PAP use	AHI	ICU LOS	AHI (per 15-unit increase) associated with increased ICU LOS in OHS cohort (β coefficient, 0.009)[a]
Mador et al[42]/ 2013	284	Cohort-R	Lab-PSG	NR	Yes	AHI	Postop Cx	OR 2.0 for AHI ≥ 5 vs < 5[a] OR 2.3 for AHI 5 to < 30 vs AHI < 5[a] OR 1.92 for AHI 5 to <15 vs AHI < 5 (NS) OR 2.13 for AHI ≥ 30 vs AHI < 5 (NS)
							Respiratory Cx	OR 2.05 for AHI ≥ 5 vs < 5[a] OR 2.18 for AHI 5 to < 15 vs AHI < 5[a] OR 2.01 for AHI 15 to < 30 vs AHI < 5 (NS) OR 2.07 AHI ≥ 30 vs < 5 (NS)
							Cardiac Cx	NS
Mason et al[38]/ 2017	122	Cohort-P	Level IV oximetry	PULSOX-300i (Konica Minolta Sensing)	NR	ODI 4	Postop Cx	OR 1.1 per increase by 1 unit[a] NS for arrhythmia
							ICU LOS	NS
Mutter et al[31]/ 2014	20,442	Cohort-R	Lab-PSG	NR	NR	AHI	Respiratory Cx	OR 2.7 for AHI ≥ 30[a]
	19,405	Cohort-R	Lab-PSG	NR	NR	AHI	Cardiac Cx	OR 2.2 for cardiac Cx undiagnosed OSA vs OR 0.75 for diagnosed OSA[a] OR 2.7 for cardiac Cx in severe undiagnosed OSA + AHI ≥ 30 vs control group[a]

(Continued)

TABLE 1] *(Continued)*

Study/Year	No. of Patients	Study Design	Sleep Study Type	Monitoring Device	PAP Use	Parameter (Oxygen Desaturation Criteria)	Outcome	Findings (Complications vs No Complications)
Subramani et al[12]/2017	3	Case reports	Lab-PSG	NR	NR	AHI	Critical events	Mean AHI 30, all patients with AHI > 15

AF = atrial fibrillation; AHI = apnea-hypopnea index (expressed in events per hour); Cohort-P = prospective cohort; Cohort-R = retrospective cohort; CT90 = cumulative time percentage with Spo_2 < 90%; Cx = complication; ET = endotracheal tube; HR = hazard ratio; intraop = intraoperative; Lab = laboratory; LOS = length of stay; LVEF = left ventricular ejection fraction; MACCE = major adverse cardiac and cerebrovascular events (includes cardiac death, myocardial infarction, coronary revascularization, angina pectoris requiring hospitalization, and stroke as a combined end point); NR = not reported; NS = not significant; O_2 = oxygen; ODI = oxygen desaturation index; OHS = obesity hypoventilation syndrome; PACU = postanesthesia care unit; PAP = positive airway pressure; postop = postoperative; preop = preoperative; PSG = polysomnography; PVC = premature ventricular contraction; Spo_2 = oxyhemoglobin saturation.

[a] $P < .05$ vs control group (no complication).

[b] The number in parentheses indicates the number of patients with complications studied.

postoperative respiratory adverse events, whereas only undiagnosed severe OSA resulted in significant cardiac complications. In the population undergoing cardiac surgery, the relationship between the AHI and adverse outcomes was more evident. In this population, the occurrence of postoperative AF can be potentially fatal. In a study of 190 patients, Kaw et al[32] reported 6% increased odds of new onset AF per 5-unit increase in AHI. In a similar population of patients undergoing cardiac surgery, two studies demonstrated that AHI ≥ 19 and AHI ≥ 15 were associated with increased odds of postoperative delirium (OR, 6.0)[33] and postoperative acute kidney injury (OR, 2.9),[34] respectively. In a 1-year follow-up study in 84 patients undergoing surgical revascularization for peripheral artery disease, an AHI ≥ 20 was predictive of major adverse cardiovascular and cerebrovascular events (hazard ratio, 5.1).[35]

Lastly, a study in 471 patients who had undergone various noncardiac or upper airway surgeries under general anesthetic, Kaw et al[36] reported that a diagnosis of OSA (as defined by an AHI ≥ 5 events per hour) was associated with increased risk of postoperative hypoxemia, admission to the ICU, and longer hospital length of stay. No relationship between the AHI and postoperative complications was reported.

Oxygen Desaturation Index

Four studies were identified that used preoperative overnight oximetry to evaluate postoperative complications associated with an increased ODI (Table 1).[22] ODI is defined as the number of occurrences of an Spo_2 decrease by 3% or 4% (desaturation criteria vary from 3% to 4%) from baseline per hour. In a study of 172 patients undergoing general surgery, Hwang et al[37] observed a higher rate of postoperative complications in patients with an ODI ≥ 5 vs that in those with an ODI < 5 events per hour (15.3% vs 2.7%; adjusted OR, 7.2). The rate of complications increased from 2.7% among patients without nocturnal oxygen desaturation to 13.8% in patients with an ODI 5 to 15 events per hour and to 17.5% in patients with an ODI ≥ 15 events per hour. In a large study comprising 573 patients undergoing general surgery, Chung et al[21] demonstrated that the optimal predictive cutoff for high risk of postoperative complications was an ODI > 29 events per hour, which was associated with an adjusted OR of 2.2. In 190 patients who had undergone cardiac surgery, Kaw et al[32] did not find an association between ODI and postcardiac surgery AF. With contrary findings, Mason et al[38] prospectively studied 122

patients undergoing cardiac surgery by using preoperative nocturnal oximetry to diagnose sleep apnea. Forty-seven percent of participants were categorized as having sleep apnea (ODI $\geq$ 5), and significant association was found between ODI $\geq$ 5 and all postoperative complications in the ICU (OR, 1.1); however, there were no significant differences in the incidence of postoperative arrhythmia.[38]

Cumulative Time Percentage With Spo_2 < 90%

CT90 is defined as the cumulative time spent with Spo_2 < 90% during sleep. Using overnight oximetry, Chung et al[21] established that the optimal predictive cutoff for CT90 was 7%, which was associated with almost a twofold increased risk of postoperative complications. Hwang et al[37] reported a significantly higher CT90 in the postoperative complications group vs that in the no complications group (21% vs 10%). Patients with OSA undergoing cardiac surgery who had a CT90 > 0 had significantly greater BMI, longer intraoperative endotracheal tube time, and greater prevalence of prolonged intubation.[39] Finally, in patients who are obese and have sleep-disordered breathing, Turan et al[40] showed that CT90 was inversely related to opioid consumption, which may suggest increased sensitivity to opioids.

Minimum Spo_2

Minimum Spo_2, also referred to as "nadir Spo_2" or "lowest Spo_2," is defined as the lowest Spo_2 value during a sleep study. In patients undergoing OSA surgery, Pang et al[26] demonstrated that a minimum Spo_2 < 80% was associated with postoperative complications (postextubation desaturations, tongue edema, negative pressure pulmonary edema, upper airway obstruction requiring reintubation). In patients undergoing UPPP surgery, Kim et al[41] found that the minimum Spo_2 measurements in patients with and those without complications were 71% vs 78%, respectively. Similarly, Asha'ari et al[27] reported an OR of 1.03 for postoperative complications per 5% decrease in the minimum Spo_2 for patients undergoing OSA surgery.

Mean Nocturnal Spo_2

Only one study examined the mean Spo_2 in relation to postoperative complications.[21] In this study, there was a 2.7-fold increase in postoperative complications with use of preoperative nocturnal oximetry with an optimal predictive cutoff mean Spo_2 < 93%.

Apnea Duration

In patients undergoing OSA surgery, Asha'ari et al[27] demonstrated that the longest apnea duration was greater in patients with postoperative complications than in those without (51 vs 39 s). The odds of postoperative complications increased by 3% per 5-s increase in longest apnea duration.[27]

Discussion

This review has highlighted several parameters (such as AHI, ODI, CT90, minimum Spo_2, mean Spo_2, and longest apnea duration) extracted from in-laboratory or portable PSG or overnight oximetry that may be of importance to forewarn of postoperative complications. Of those evaluated, the AHI was the primary parameter derived from PSG used to determine the presence or absence of OSA and its severity.[23] The current accepted AHI thresholds have been derived by consensus generated from observational and long-term studies.

In the current review, a diagnosis of AHI (AHI $\geq$ 5 per hour) alone is a predictor of postoperative complications,[3] although data from multivariate logistic regression analysis[27] and direct comparisons among AHI categories (mild, moderate, and severe)[30,42] do not support a linear relationship between increasing AHI and the incidence of postoperative complications. However, an association has been shown between a higher AHI and increased postoperative events (Table 1).[22] Among patients with diagnosed OSA, the mean AHI in the postoperative complications groups ranged from 37 to 68 events per hour. The majority of this evidence was based on patients undergoing upper airway corrective surgery for OSA. This population is at greater risk of postoperative upper airway edema and obstruction following surgery,[24] and other respiratory, cardiac, and cerebrovascular complications were rare. Postoperative AF was more prevalent in patients undergoing cardiac surgery with an increasing AHI.[32]

Together, the heterogeneity in study design and patient characteristics and the often limited information available about the PSG technology and sleep scoring criteria among different studies make it difficult to establish an AHI cutoff for predicting postoperative complications that would be valid for all populations undergoing surgery. Furthermore, the AHI inherently assumes that apneas and hypopneas are equivalent, which is likely an oversimplification that does not recognize the pathophysiologic differences between complete vs partial airway obstruction.[43] The AHI does

not indicate the magnitude and duration of oxygen desaturation, the negative intrathoracic pressure swings, or the arousal thresholds. Patients with high arousal thresholds may have an increased risk of respiratory events and an augmented sensitivity to opioids and sedatives.[44]

The other OSA parameters assessed were measurements of arterial hypoxemia. These include CT90 and the mean and minimum Spo_2 levels. A number of studies in populations with OSA suggest that the severity of nocturnal oxygen desaturation may be of similar or greater usefulness than the AHI for determination of cardiac dysfunction,[45] endothelial impairment, [46] hypertension,[47] new onset and incident AF,[48,49] and poor prognosis following myocardial infarction.[50] As in the medical literature, data exist that support measurements of nocturnal hypoxemia (ODI, CT90, minimum and mean Spo_2) to provide supplementary clues about the severity of OSA and the risk of postoperative complications. In a large study (n = 543) that included oximetry data, the thresholds for predicting postoperative complications were an ODI > 29 per hour, CT90 > 7%, and mean Spo_2 < 93%.[20] Hwang et al[37] found that patients with ODI ≥ 5 and CT90 > 21% experienced more postoperative complications. The rate of complications increased with the severity of OSA as determined by means of the ODI. In patients undergoing OSA surgery, several studies demonstrated that the lowest Spo_2 was associated with postoperative adverse events.[27,28,51]

Our review has highlighted several major limitations of the studies assessing postoperative complications in patients with OSA. Most of the studies were retrospective and relied on available documentation from medical records. Therefore, PSG data often were reported from chart review and/or reports from different sleep laboratories. The quality of the PSG studies was uncertain as was the scoring method. An AHI of 30 from one laboratory may not be equivalent to that from another. The North American AASM criteria allow for two differing scoring methods for hypopneas.[23,52] The criteria for decrease in oxyhemoglobin desaturation can be > 3% or 4%, which can result in variability in the AHI. Details about the type of oximeters used to determine the oxygen parameters often were not provided. Moreover, these studies did not report details of opioid consumption, which could have a profound effect on the increasing severity of obstructive events and potentially influence postoperative complications. Another limitation, although not standard for PSG, is the lack of reporting on PSG-based end-tidal or transcutaneous carbon dioxide monitoring.

From our review of the literature, the most common postoperative complications were oxygen desaturation events, which are the hallmark manifestation of OSA. Thus, it may appear trivial that patients with preexisting abnormalities in nocturnal oximetry results would be more likely to experience postoperative arterial hypoxemia. Some patients, such as patients who are obese, may have a lower baseline Spo_2 and may desaturate to a level requiring oxygen supplementation. Obesity reduces functional residual capacity and increases upper airway soft tissue and collapsibility, which play a role in OSA severity and may contribute to postoperative adverse events. Several of the included studies reported an association between elevated BMI and the incidence of postoperative complications (e-Table 4).[24,27,30,32,34] AHI is associated with the incidence of new onset AF after cardiac surgery in patients with BMI > 32 kg/m^2.[32] Furthermore, patients with an elevated AHI tended to have higher BMI.[30] Another limitation of this study is that some of the included studies did not adjust for BMI in statistical modeling or report BMI. Patients with obesity hypoventilation syndrome (BMI > 30, OSA, daytime hypercapnia) are also at increased risk of postoperative complications, including respiratory failure, heart failure, and prolonged intubation.[53] The included studies did not address the inclusion of patients with obesity hypoventilation studies, so obesity hypoventilation syndrome potentially is undiagnosed.

A major limitation of the current studies is that there are little to no data available on the long-term postoperative outcomes of patients undergoing surgery. We cannot yet conclude that these hypoxemic events are inconsequential because there are reports of death or near death of patients with OSA undergoing surgery and the associated increasing medicolegal lawsuits.[12,54,55] Nocturnal hypoxemia from OSA has been associated with endothelial dysfunction and major cardiovascular events after myocardial infarction.[46,50] Patients with postoperative adverse events, including hypoxemia, had a longer hospital length of stay by 1 day than did patients without postoperative adverse events.[23] Increased awareness of oximetry parameters should prompt further investigation into their association with short-term and long-term postoperative events because they are readily available from PSG and can be measured easily by use of wearable overnight oximetry methods.

Several other PSG-derived OSA parameters have been appraised for determining the severity of OSA. These included the duration of the apnea-hypopnea events and the magnitude and morphologic nature of oxygen desaturation.[56] In addition, apnea severity and obstruction severity have been proposed as new parameters, and these are derived from the product of duration of individual events and the area under the curve of the associated Spo_2 desaturation.[57] In a 2013 nested case-control study, higher obstruction severity was related to mortality in patients with moderate to severe OSA.[58] Although obstruction severity tends to increase with a higher AHI, there is much variability and overlap in this parameter within mild, moderate, and severe AHI categories.[59] The heterogeneity in obstruction severity within similar AHI categories could reflect different arousal thresholds, with high arousal thresholds being associated with a diminished compensatory ventilatory response resulting in longer apneas with greater Spo_2 desaturation.[44] These parameters may offer more insight into the severity of OSA and deserve further study in populations undergoing surgery.

Other future areas of research also should consider the various phenotypes of OSA, which may indicate increased risk of postoperative complications. Evidence from a network-based cluster analysis suggests that populations with OSA are much more diverse than traditionally conceived because there are clusters of nonobese, thin-necked, normotensive individuals with OSA.[60] Certain phenotypes of OSA, such as those with high arousal threshold[44] or high loop gain,[61] are underrecognized and may not be apparent immediately from the results of conventional PSG. Those with the phenotype with high arousal threshold have a low propensity to wake with obstructive events, which may predispose them to a greater magnitude of hypoxemia and hypercarbia within a respiratory event vs those in a patient with a similar AHI.[62] This situation can be potentially disastrous in postoperative settings when opioids are used for pain relief. Those with the phenotype with high loop gain, characterized by an oversensitive ventilatory response to hypercapnia, may be predisposed to hyperventilation and hypocapnia leading to decreased respiratory drive and central sleep apnea.[61] This cycle of overcompensation leads to unstable and perpetual cycles of hypoxia, which may predispose the patient to cardiac and pulmonary complications. In clinical practice, these parameters are not routinely used in PSGs and require further validation studies.

Conclusions

In summary, AHI and measurements of nocturnal hypoxemia (ODI, CT90, minimum and mean Spo_2) are indexes of OSA that provide an imperfect assessment of the risk of postoperative complications. A significant association between the AHI and postoperative adverse events exists. Complications may be more likely to occur in the category of moderate to severe OSA (AHI $\geq$ 15). Other parameters from PSG or overnight oximetry such as ODI, CT90, mean and lowest Spo_2, and longest apnea duration can be associated with postoperative complications and may provide additional value in risk stratification and minimization. These parameters can be incorporated into clinical decision tools for risk minimization.

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