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Editorial

Editorial

Metabolic syndrome and obstructive sleep apnea: two sides of the same coin

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Obstructive sleep apnea (OSA) is known to be associated with cardio-metabolic disorders and obesity [1]. Metabolic syndrome (MetS), which is a constellation of different metabolic abnormalities, including central obesity, hypertension, insulin resistance, and dyslipidemia, contributes significantly to the development of atherosclerotic cardiovascular diseases and type II diabetes mellitus [2]. Converging evidence indicates a bidirectional relationship between OSA and obesity [3], the latter also a common pathophysiologic link between OSA and MetS. In patients with OSA recurrent episodes of intermittent hypoxemia and sleep fragmentation trigger a cascade of pathophysiological processes, including increased sympathetic activity, oxidative stress, and systemic inflammation, which contribute to MetS components such as hypertension, dyslipidemia, and insulin resistance [2]. Likewise, components of MetS, mainly through factors such as elevated body mass index (BMI), increased visceral fat and hypertension contribute to upper airway collapsibility in OSA.

In this issue of *SLEEP*, Pant et al. [4] report pooled estimates of the prevalence of MetS in a large dataset of adults with OSA. About 60% of the 34 013 adults with polysomnography-confirmed OSA analyzed in this meta-analysis had MetS, much higher than global prevalence of MetS in the general adult population— ~31% in women and ~ 25.7% in men [5]. Notably, the prevalence of MetS in this meta-analysis study population varied by geographic regions, study design, and the diagnostic criteria used for MetS. Studies with higher mean BMI showed higher prevalence of MetS. Additionally, a trend for higher prevalence of MetS was noted with increasing AHI thresholds used for OSA diagnosis in the study population.

From a methodological perspective, this meta-analysis demonstrates distinct advantages in terms of managing the dependency of effect sizes within studies using the three-level framework as compared to the traditional univariate meta-analyses. Evidence synthesis in a meta-analysis typically involves coding information about empirical findings reported in primary studies in the form of effect sizes (i.e. the dependent variable), and the coding of factors, such as study design, ethnicity, or diagnostic criteria used that could influence the magnitude of the empirical findings (i.e. independent variables). In a traditional univariate meta-analytic approach, one assumes that there is no dependency between effect sizes in the data set being analyzed. However, if there is dependency between effect sizes (i.e. effect sizes are correlated), there can be a significant overlap in information to which correlated effect sizes are referring to. This could possibly lead to overconfidence in the results of a meta-analysis [6–8]. A three-level meta-analysis involves first pooling the results of individual participants in their primary studies and reporting the aggregated effect size, followed by nesting these effect sizes within several clusters— many effect sizes could be nested in one study, or many studies nested in one subgroup, where each study contributes only one effect size. In the last step, the aggregated cluster effects are pooled which lead to the overall true effect size. Three-level approach allows examining differences in outcomes within studies as well as differences between studies. If there is evidence for heterogeneity in effect sizes, moderator analyses are conducted to test variables that may explain within-study or between-study heterogeneity. Moderator effects in this meta-analysis [4] were evaluated using omnibus F-tests and presented as tests of moderators (coefficients) with *p*-values— the latter being much smaller than the significant level of 0.05 for geographic regions, study designs, MetS definitions, and AHI thresholds for OSA but not for publication year of the studies, implying that the regression coefficient of the variable "publication year" did not significantly deviate from zero. Therefore, we can conclude that the overall effect was not moderated by the publication status of the included primary studies but moderated by the other afore-mentioned moderators. However, despite the moderator analyses for categorical moderators, results of the tests for residual heterogeneity (QE) showed that there was still significant unexplained variance left between all effect sizes in the dataset, implying that the examined categorical moderators explained only part of the variance in MetS prevalence estimates. As for the continuous moderators (age, BMI and percentage of males) examined using multivariable three-level meta-regression, only BMI, as one would expect,

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showed significant association with MetS prevalence, with 1-unit increase in BMI in the study population increasing the prevalence of MetS by ~7% to 8%.

As noted by Pant et al. [4] highest pooled prevalence of MetS was observed in Eastern Europe and Southern Asia. Randomized controlled trials as compared to other study designs (cross-sectional/case–control and cohort studies) had the highest prevalence of MetS. Pooled prevalence of MetS in this meta-analysis study population was also noted to be the highest (~63.8%) with the International Diabetes Federation criteria (with specific waist circumference cut-offs for different ethno-geographic regions). However, the Japanese Committee for the Diagnostic Criteria of Metabolic Syndrome criteria, which too mandates central obesity for diagnosis but with relatively stringent waist circumference cut-offs, showed the lowest prevalence of MetS (~39.8%). Be that as it may, it is important to note that a small portion of the meta-analysis study population was recruited from cardio-metabolic and/or respiratory specialty clinics, thereby increasing the odds of recruiting participants with OSA and MetS. Thus, while, the three-level meta-analytic approach, by nesting effect sizes within studies avoided the Simpson's paradox (a phenomenon in statistics in which a trend appearing in several groups of data disappears or reverses when the groups are combined) [9], there does remain the possibility of Berkson's paradox/selection bias (an inherent limitation of such a meta-analysis) [10], where an association could be discerned between two variables, when the study population is recruited from specialized clinics, as duly noted by Pant et al. [4].

While the study by Pant et al. [4] focused on the pooled prevalence estimates of MetS in OSA population, prevalence estimates as such, offer a limited understanding of the temporal relationship between OSA and MetS in terms of clarifying whether changes in OSA severity precede MetS onset, or vice versa. A more recent study by applying Mendelian randomization analysis to a large population dataset has indicated a bidirectional causal relationship between OSA and MetS and found that baseline OSA increased the odds of MetS by ~52% and baseline MetS increased the odds of OSA by 97% [11]. The data in the literature, however, is still conflicting on the bidirectional relationship between OSA and MetS. In a multiethnic sample of two large population-based samples, moderate-to-severe OSA was associated with 2-fold increased risk of incident MetS in 6-year follow-up, mainly through an increase in waist circumference mediated by nocturnal hypoxemia [11, 12]. However, baseline MetS was not found to be an independent predictor of incident OSA [11, 12]. Conversely, in another large-scale population-based study those with baseline MetS were 50% more likely to develop OSA than those without MetS over 9 years of follow-up [12].

Beyond such cross-sectional associations, a comprehensive mechanistic understanding of the OSA and MetS relationship could perhaps be provided by multi-omics research studies incorporating genomics, transcriptomics, and metabolomics which could not only help in identifying biomarkers for early identification and targeting but also aid in discovering the components of MetS that are most affected by OSA and likewise, phenotypes of OSA most influenced by MetS. This approach would stratify patients for more personalized treatments. Nonetheless, we believe that the findings by Pant et al. underscore the need for integrated treatment strategies targeting shared risk factors, such as obesity.

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References

1. Tasali E, Pamidi S, Covassin N, Somers VK. Obstructive sleep apnea and cardiometabolic disease: obesity, hypertension, and diabetes. *Circ Res*. 2025;**137**(5):764–787. https://doi.org/10.1161/CIRCRESAHA.125.325676
2. Reutrakul S, Mokhlesi B. Obstructive sleep apnea and diabetes: a state of the art review. *Chest*. 2017;**152**(5):1070–1086. https://doi.org/10.1016/j.chest.2017.05.009
3. Framnes SN, Arble DM. The bidirectional relationship between obstructive sleep apnea and metabolic disease. *Front Endocrinol (Lausanne)*. 2018;**9**:440. https://doi.org/10.3389/fendo.2018.00440
4. Pant S, Kyrou I, Dallaway A, *et al*. Global prevalence of metabolic syndrome in adults with obstructive sleep apnoea: a systematic review and meta-analysis. *Sleep*. 2026;**49**(9):zsag144. https://doi.org/10.1093/sleep/zsag144
5. Noubiap JJ, Nansseu JR, Nyaga UF, *et al*. Worldwide trends in metabolic syndrome from 2000 to 2023: a systematic review and modelling analysis. *Nat Commun*. 2025;**17**(1):573. https://doi.org/10.1038/s41467-025-67268-5
6. Cheung MW. Modeling dependent effect sizes with three-level meta-analyses: a structural equation modeling approach. *Psychol Methods*. 2014;**19**(2):211–229. https://doi.org/10.1037/a0032968
7. Van den Noortgate W, Lopez-Lopez JA, Marin-Martinez F, Sanchez-Meca J. Three-level meta-analysis of dependent effect sizes. *Behav Res Methods*. 2013;**45**(2):576–594. https://doi.org/10.3758/s13428-012-0261-6
8. Van den Noortgate W, Lopez-Lopez JA, Marin-Martinez F, Sanchez-Meca J. Meta-analysis of multiple outcomes: a multilevel approach. *Behav Res Methods*. 2015;**47**(4):1274–1294. https://doi.org/10.3758/s13428-014-0527-2
9. Cates CJ. Simpson's paradox and calculation of number needed to treat from meta-analysis. *BMC Med Res Methodol*. 2002;**2**(1):1. https://doi.org/10.1186/1471-2288-2-1
10. Berkson J. Limitations of the application of fourfold table analysis to hospital data. *Biometrics*. 1946;**2**(3):47–53. https://doi.org/10.2307/3002000
11. Hirotsu C, Haba-Rubio J, Togeiro SM, *et al*. Obstructive sleep apnoea as a risk factor for incident metabolic syndrome: a joined Episono and HypnoLaus prospective cohorts study. *Eur Respir J*. 2018;**52**(5):1801150. https://doi.org/10.1183/13993003.01150-2018
12. Kim DH, Kim B, Han K, Kim SW. The relationship between metabolic syndrome and obstructive sleep apnea syndrome: a nationwide population-based study. *Sci Rep*. 2021;**11**(1):8751. https://doi.org/10.1038/s41598-021-88233-4

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Review

Review

Global prevalence of metabolic syndrome in adults with obstructive sleep apnea: a systematic review and meta-analysis

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Abstract

Study objectives: Metabolic syndrome (MetS) is considered to exhibit increased prevalence among adults with obstructive sleep apnea (OSA), but the reported prevalence estimates among such patients vary. Thus, this systematic review and meta-analysis aimed to investigate the global prevalence of MetS in adults with confirmed OSA.
Materials and methods: Ovid Medline, Embase, CINAHL, and the Cochrane Library databases were searched for all primary studies published in English that used standard polysomnography for OSA diagnosis and reported MetS estimates. At least two reviewers independently screened for eligible studies, extracted data, and graded the risk of bias using the Risk of Bias Assessment Tool for Non-randomised Studies. Three-level random-effects model was applied for the meta-analysis, reporting pooled prevalence estimate with 95% confidence intervals (CIs). Pre-specified subgroup analyses and meta-regression were also performed. Heterogeneity was quantified using I^2 and chi-square statistics.
Results: A total of 102 studies were eligible for inclusion (34 013 adults with OSA from 28 countries). The combined MetS prevalence was 55.4% (95% CI: 51.0%, 59.8%). Considerable heterogeneity was noted among the included studies ($I^2 = 97.8\%$), whilst the risk of bias ranged from low to high. Subgroup analysis examining the effects of geographic region, study design, MetS definition, and apnea-hypopnea index threshold showed a significant variation in prevalence estimates across most subgroups ($p < 0.0001$). Meta-regression analysis indicated a positive association between mean body mass index ($\beta = 0.0772$, $t = 4.56$, $p < 0.0001$) and MetS prevalence.
Conclusions: MetS has a high prevalence among adults with polysomnography-confirmed OSA, underscoring the need for prompt MetS screening in these patients. Future longitudinal and genetic/mechanistic studies should investigate the factors accounting for this association.
PROSPERO registration number: CRD420251073055.

Key words: obstructive sleep apnea; metabolic syndrome; adults; systematic review; meta-analysis

Introduction

Obstructive Sleep Apnea (OSA) is an increasingly prevalent chronic sleep-related breathing disorder, typically characterized by repetitive, sudden episodes of partial or complete upper pharyngeal airway closure during the nocturnal sleep cycle, causing apnea, snoring, intermittent hypoxia, sleep fragmentation, and daytime hypersomnolence [1]. Although OSA affects the daily life of nearly a billion adults worldwide [2], an estimated 80-90% of adults with OSA remain undiagnosed [3], indicating that the condition is frequently overlooked and inadequately

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addressed. The increasing prevalence of obesity and obesity-related metabolic diseases (e.g. type 2 diabetes, hypertension and dyslipidaemia), as well as the increasing ageing of the adult population globally—all established risk factors for OSA [4–6]—have positioned OSA as a pressing global health concern requiring renewed attention.

Metabolic syndrome (MetS; initially termed Syndrome X) represents a clustering of certain interrelated cardio-metabolic diseases, including obesity (particularly central), type 2 diabetes, hypertension and dyslipidaemia [7–9]. Thus, MetS is typically diagnosed based on the presence of at least three of these cardio-metabolic diseases; however, multiple national and international definitions exist, including those by the World Health Organization (WHO) [10], the National Cholesterol Education Program Adult Treatment Panel III (NCEP ATP III) [9, 11], and the International Diabetes Federation (IDF) [12]- each differing in their specific diagnostic criteria, cut-off values, and whether central obesity is a mandatory component. These variations in definition reflect population-specific differences in obesity measures, waist circumference thresholds, and ethnic considerations. OSA and MetS are frequently associated, with the OSA-MetS co-existence being historically referred to as "Syndrome Z" [13] or "two circumferences in the same individual", [14] suggesting a shared cardio-metabolic substrate. This dyad aggravates the long-term morbidity and mortality of cardiovascular disease [15], and impairs health-related life quality [16, 17]. OSA and MetS are considered to share common biological pathways, overlapping risk factors, and feedback loops, reflecting a complex bidirectional interplay. Indeed, there are data on underlying pathophysiological mechanisms [18–20], the temporal sequence of disease occurrence [21], and the efficacy of interventions [22, 23] which suggest a causative role of OSA in the pathogenesis of MetS, although the predominant/causative direction of the underlying pathogenetic association remains debated.

The presence of MetS in patients with OSA further stratifies risk and modifies treatment needs and responses [16, 24, 25]. Interestingly, although OSA frequency increases with age and is more prevalent among older adults [2], younger adults may also exhibit severe forms of OSA with corresponding metabolic dysfunctions [26]. Overall, men are more prone to OSA, whilst the risk in females significantly increases after menopause [27]. In parallel, MetS and cardiovascular disease are increasing in women, with obesity strongly linked to insulin-resistance related cardio-metabolic risks [27]. Epidemiological studies show that postmenopausal women experience stronger associations between OSA and MetS components than premenopausal women [28, 29], implicating sex and/or menopause as non-modifiable drivers. Lam and colleagues [30] suggested that visceral obesity contributes significantly to the pathophysiology of OSA and to the metabolic derangements associated with the MetS. Conversely, Kumor and colleagues [31] suggested that despite an evident correlation between the apnea-hypopnea index (AHI) and the presence of MetS, no such relationship could be confirmed between transient hypoxia and MetS. Furthermore, the diverse definitions of MetS [32] lead to variations in disease-prevalence reporting, even within individual population subsets [33]. Notably, regardless of any given definition, prevalence estimates increase with age and differ by sex and ethnicity [33].

Despite growing interest in the association between OSA and MetS, the true prevalence of MetS among adults with OSA remains uncertain. Individual studies from India, China, Korea, and Portugal reported highly variable prevalence estimates ranging from 34% to 70% [34–37], influenced by factors such as the MetS definition, OSA severity, sex distribution, and body mass index (BMI). In the context of MetS and OSA, two meta-analyses were published almost a decade ago [38, 39]; however, both concentrated primarily on the risk associations between OSA and MetS rather than on establishing a pooled prevalence estimate. As a result, clinicians and researchers lack an up-to-date, evidence-based estimate of how prevalent MetS is in the global adult population, which can help to support early screening, prevention, and treatment strategies and pathways as part of an integrated sleep-cardio-metabolic care approach. Therefore, the present systematic review and meta-analysis aimed to provide an updated synthesis of evidence on the prevalence estimates of MetS among adults with polysomnography-confirmed OSA and explore potential drivers of heterogeneity in the existing evidence.

Table 1. Articles using search terms for Ovid Medline

#	Searches
1.	exp Sleep Apnea, Obstructive
2.	obstructive sleep apn?ea.ti
3.	(sleep∗ adj3 (apn?ea∗ or respirat∗ or breath∗)).mp.
4.	hypopn?ea∗.ti,ab,tw.
5.	(OSA or SHS or OSAHS or SAHS).tw.
6.	or/1-5
7.	exp Metabolic Syndrome
8.	("metabolic syndrome" or "Insulin resistance syndrome" or "syndrome x" or "dysmetabolic syndrome" or MetS).mp.
9.	or/7-8
10.	6 and 9

Materials and methods

The study protocol was prospectively registered on PROSPERO (CRD420251073055). Methodological decisions were guided by the Cochrane Handbook [40], and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed for reporting standards [41].

Inclusion criteria

Predefined eligibility criteria were applied based on the Population, Exposure, Comparator, Outcome, Study design (PECOS) framework [42] [i.e. Participants: Adults; Exposure: Obstructive Sleep Apnea; Comparator: Not applicable; Outcome: Prevalence or incidence of MetS; and Study characteristics: observational studies, and baseline (cross-sectional) data of cohort and experimental studies]; detailed in Supplementary Table S1.

Search strategy and study selection

A predefined electronic search was performed in Medline, Embase, CINAHL and Cochrane Library, from inception to 27th of November 2024, applying a combination of controlled vocabulary and free-text terms related to "obstructive sleep apnea" and "metabolic syndrome". The search strategy applied for Medline (via Ovid) is presented in Table 1, while the remaining strategies are detailed in Supplementary Tables S2–S4.

Initially, all retrieved records were imported into EndNote, and duplicates were removed. Two independent reviewers performed the title/abstract and full-text screening using Covidence [43]. At each stage, any uncertainty or disagreement between the two independent reviewers was resolved through consensus

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and, where required, a third reviewer provided independent arbitration.

To complement the standard search of the aforementioned databases, forward citation chasing was also performed in July 2025 to identify any additional eligible publications. For this citation chasing, eligible studies meeting the inclusion criteria were used to retrieve the lists of cited records using a citation chaser tool [44].

Data extraction

A standardized data extraction form was developed and reviewed by all authors. Summary datasets were prepared, including key study characteristics, and formatted according to the requirements for statistical analyses.

All eligible studies were assessed to identify potential study clusters and overlapping participants/populations. In instances where the same authors published two or more duplicate articles reporting data from an identical or substantially overlapping population with similar characteristics and outcomes, only the publication providing the most recent, comprehensive, and complete dataset was retained as the primary reference for inclusion in the quantitative synthesis. When relevant information was incomplete, unclear or inaccessible in the identified studies, the corresponding authors were contacted to obtain the missing data or clarification. Where the contacted authors did not respond to these requests, the corresponding studies were excluded from the analyses.

Assessing risk of bias

The risk of bias for each included eligible study was evaluated by two independent reviewers using the Risk of Bias Assessment Tool for Non-randomized Studies (RoBANS) [45]. This tool includes the following domains: participant selection, confounding variables, measurement of exposure, blinding of outcome assessments, incomplete outcome data, and selective outcome reporting. Each domain is rated for a low, high, or unclear risk of bias. Disagreements were resolved through consensus among the two reviewers.

Synthesis of results and statistical methods

Primary three-level random-effects model. Studies included in this meta-analysis differed in country of origin, study design, MetS diagnostic criteria, AHI threshold used to define OSA, and year of publication. These methodological and clinical differences were expected to introduce significant between-study heterogeneity, supporting the use of a random-effect modelling framework.

A total of 18 clusters, providing 48 prevalence estimates, and 61 studies, each contributing a single estimate, were identified. Clusters were defined based on shared hospital settings or underlying study populations (longitudinal cohorts) reported in the primary studies. Multiple estimates within clusters derived from one or more of the following: (i) analyses conducted by different research teams using the same population or hospital setting; (ii) application of different diagnostic criteria for MetS within a study population; (iii) repeated reporting by the same authors across different years or sub-group-specific estimates (*e.g.* gender) from the same sample. A three-level meta-analytic model [46, 47] was applied to account for this nested data structure while retaining all available estimates.

Within this framework, Level 1 variance represented sampling error across 109 prevalence estimates. Level 2 variance captured variability among the 48 estimates nested within the 18 multi-estimate clusters. Level 3 variance represented variability among independent sources, comprising 18 multiple-estimate clusters and 61 single-estimate studies, treated as clusters of size one. Model fit was evaluated by comparing the three-level model with a conventional two-level model using likelihood-ratio testing and information criteria (AIC and BIC).

Observed prevalence proportions were logit-transformed prior to analysis to normalize their distribution and stabilize variances across studies. Model estimates were back-transformed to prevalence percentages using the inverse-logit transformation for reporting and interpretation. Heterogeneity was quantified at each hierarchical level along with total variance, and variance components were visualized using tree plots generated with the *metafor* package [48]. I-squared statistics (I^2) were interpreted following Cochrane guidelines: 0-40% (not important), 30-60% (moderate), 50-90% (substantial), and 75-100% (considerable) [40]. To further describe between-study variability, 95% prediction intervals were estimated and displayed on a forest plot. Confidence intervals (CIs) reflect the precision of the pooled estimates, whereas prediction intervals indicate the range within which true prevalence is expected across comparable populations in the future.

Moderator analyses. Categorical moderators were examined using three-level random-effects subgroup analyses. Countries were grouped according to United Nations (UN) geographical regions based on the *Standard country or area codes for statistical use (M49)* [49]. The details for the different definitions and diagnostic criteria of MetS are presented in Supplementary Table S5.

Continuous moderators were examined using multivariable three-level meta-regression. Age and BMI were mean-centred before inclusion in the model, alongside the percentage of male participants.

For studies reporting mean ± Standard Error of the Mean, mean with CIs, or median with interquartile range, values were converted to mean ± standard deviation (SD) using established methods [50, 51]. When studies reported multiple participant groups with OSA (e.g. severity strata or comorbidity subgroups), group-specific means and SDs were aggregated using sample-size weighting.

Moderator effects were evaluated using omnibus F-tests to assess whether moderators explained variability in prevalence estimates. The QE statistic was used to determine whether significant heterogeneity remained after accounting for moderators.

Sensitivity analysis. Sensitivity analyses were conducted to assess the robustness of the pooled estimates and identify influential studies. Baujat plot was used to visualize each study's contribution to overall heterogeneity and influence on the pooled estimates [52]. Leave-one-out analysis was performed by systematically removing individual studies and recalculating the pooled estimate to determine whether any single study disproportionately affected the results [53].

Publication bias. Publication bias was explored descriptively using funnel plots. Formal statistical tests for funnel plot asymmetry (Egger's regression test) were not performed because the meta-analysis demonstrated extremely high overall heterogeneity. In the presence of marked heterogeneity, funnel plot asymmetry may reflect genuine between-study differences or small-study effects rather than selective publication, rendering asymmetry

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tests difficult to interpret and potentially misleading [54, 55]. Therefore, a funnel plot was presented for descriptive purposes only and should be interpreted with caution (Supplementary Figure S1).

Software. All analysis were conducted in R version 4.4.1 for Windows (R Core Team, Vienna, Austria; www.R-project.org). Three-level meta-analytic models were fitted using the *rma.mv* function from the *metafor* package [48]. The *meta* package [56] was used for visualisation, sensitivity analyses, influence diagnostics, and complementary prevalence estimation using the *metaprop* function with Hartung-Knapp CIs. Clustered analyses were based on inverse-variance weighting, while standard two-level analyses were conducted using the generalized linear mixed model approach. Pooled estimates and CIs were consistent across methods. Analytical syntax was adapted from previously published methodological studies [57, 58].

Results

Search results

The study selection process is presented in the PRISMA flow diagram of Figure 1. The performed searches retrieved 8072 records, of which 4229 were duplicates. After de-duplication, 3843 unique records were screened. At the title and abstract screening stage, 3578 studies were excluded, resulting in 265 records for full text review. Despite all possible efforts, two full-text records could not be retrieved [59, 60]. The remaining 263 full-text articles were assessed for eligibility, and 161 of these were excluded with reasons, resulting in 102 articles meeting the eligibility criteria and therefore included in this systematic review.

Characteristics of the included studies

Supplementary Table S6 presents the characteristics of all eligible studies included in the quantitative analysis. A total of 102 studies [20, 21, 30, 31, 34, 36, 61–156] ($k = 109$ effect sizes, with each effect size treated as a separate estimate) comprised 34 013 participants with polysomnography-confirmed OSA, of which 17 274 individuals had MetS. The sample sizes of patients with polysomnography-confirmed OSA in each study ranged from 21 to 3779, with included participants having a mean age ranging from 39.2 (± 7.8) [111] to 67.7 (± 9.0) [147] years, and BMI from 25.1(± 10.3) [116] to 47.4 (± 6.1) [133] kg/m^2.

The identified eligible articles were published between 2004 and 2025 and represented 12 United Nations geographic regions: Asia ($k = 58$, 53.2%), Europe ($k = 43$, 39.5%), the Americas (4.6%), Africa (1.8%) and Oceania (0.9%). Only 20 studies reported the participants' ethnicity and race, mostly Caucasian and Han Chinese. A total of 82 cross-sectional studies, 10 case–control studies [73, 74, 77, 80, 84, 119, 131, 132, 136, 137], and baseline data of four randomized controlled trials (RCT) [85, 86, 95, 133], three cohort [21, 36, 108] and three quasi-experimental studies [71, 101, 122] were included in the analysis. Two studies exclusively included female participants with OSA [97, 156], and 14 enrolled males only [64, 84, 85, 93, 98, 103, 115, 119, 121, 124, 127, 129, 144, 151]. Seven studies did not report the participants' sex [21, 81, 86, 109, 138, 143, 155], while the proportion of male subjects in the remaining studies ranged from 27.5% [133] to 93.6% [139].

To define MetS, most studies (55%) employed NCEP ATP III [9, 11] criteria, whilst the MetS harmonizing criteria [8] were the second most frequently applied criteria/definition (15.6% of the included studies); nine studies did not specify the applied MetS criteria [20, 92, 101, 102, 110, 117, 119, 150, 152]. This review comprised studies involving participants with polysomnography-confirmed OSA, predominantly conducted in hospital settings (89.2%), with the remainder from population-based (8.8%) or community (2.0%) cohorts. AHI thresholds varied across studies, with the majority (78%) applying AHI ≥5 events per hour (hr), followed by 12.8%, 7.4%, and 1.8% for ≥15, ≥10, and ≥ 30 events/hr, respectively.

Assessment of risk of bias across studies

Figure 2 presents the risk of bias summary for all included studies, as assessed across the six RoBANS domains. A traffic light plot with the risk of bias assessments for each individual eligible study is presented in Supplementary Figure S2.

Across the RoBANS domains, selection bias accounted for the largest proportion (65.7%, 67/102 studies included) of high-risk judgements. This judgement primarily reflected concerns about the representativeness of the included populations. Many studies recruited participants consecutively from a single centre, often from specialized clinics such as diabetes, metabolic, endocrine, or obesity management services. Other studies focused exclusively on clinical populations presenting with sleep-related symptoms undergoing polysomnography, or restricted inclusion to specific subgroups such as individuals with obesity, hypertension, diabetes, or to only males/females. In this domain, 24 (23.5%) studies were rated as low risk, whereas 11 (10.8%) were deemed unclear due to insufficient reporting of study design or recruitment procedures (e.g. whether sampling was random or consecutive).

With respect to confounding, 63 (61.8%) studies demonstrated adequate consideration of, or statistical adjustments for key variables and were therefore rated as low risk. Conversely, 34 (33.3%) studies showed substantial imbalance between comparison groups in factors such as age, sex, anthropometric indices, or biochemical measures. Although these differences were acknowledged and sometimes statistically significant, it was assessed that they were not appropriately addressed during the study design or analysis, resulting in a high-risk judgment. The remaining five studies (4.9%) [65, 86, 121, 148, 152] lacked sufficient information to determine the risk.

For exposure measurement, 97 (95.1%) studies were categorized as low risk, primarily because they used objective polysomnographic recordings. The five studies (4.9%) which had a high risk relied on symptom-based or questionnaire-derived classifications of control participants without physiological confirmation.

In the domain of detection bias, all 102 studies (100%) were considered low risk because the absence of blinding was unlikely to influence the pertinent metabolic outcome measurements, which are typically assessed by laboratory parameters.

Regarding incomplete outcome data, 90 studies (88.2%) were evaluated as low risk, and four (3.9%) [92, 118, 135, 153] as unclear. Eight studies (7.8%) [71, 102, 112, 127, 128, 136, 138, 141] were rated high risk due to substantial attrition (>20%) or missing key variables, such as polysomnography metrics, lipid measures, or waist circumference.

For selective outcome reporting, 99 studies (97%) were assessed as low risk. The studies by Iren et al. [102] and Singh et al. [141] were judged as having a high risk of bias in this domain because critical information of a substantial proportion of participants was missing, and the potential impact of their exclusion on outcome measurement could not be determined. Finally, the study by Vekic and colleagues [149] was judged to have an unclear risk of bias in this domain, because the total number of clinically stable participants who underwent sleep assessment was not

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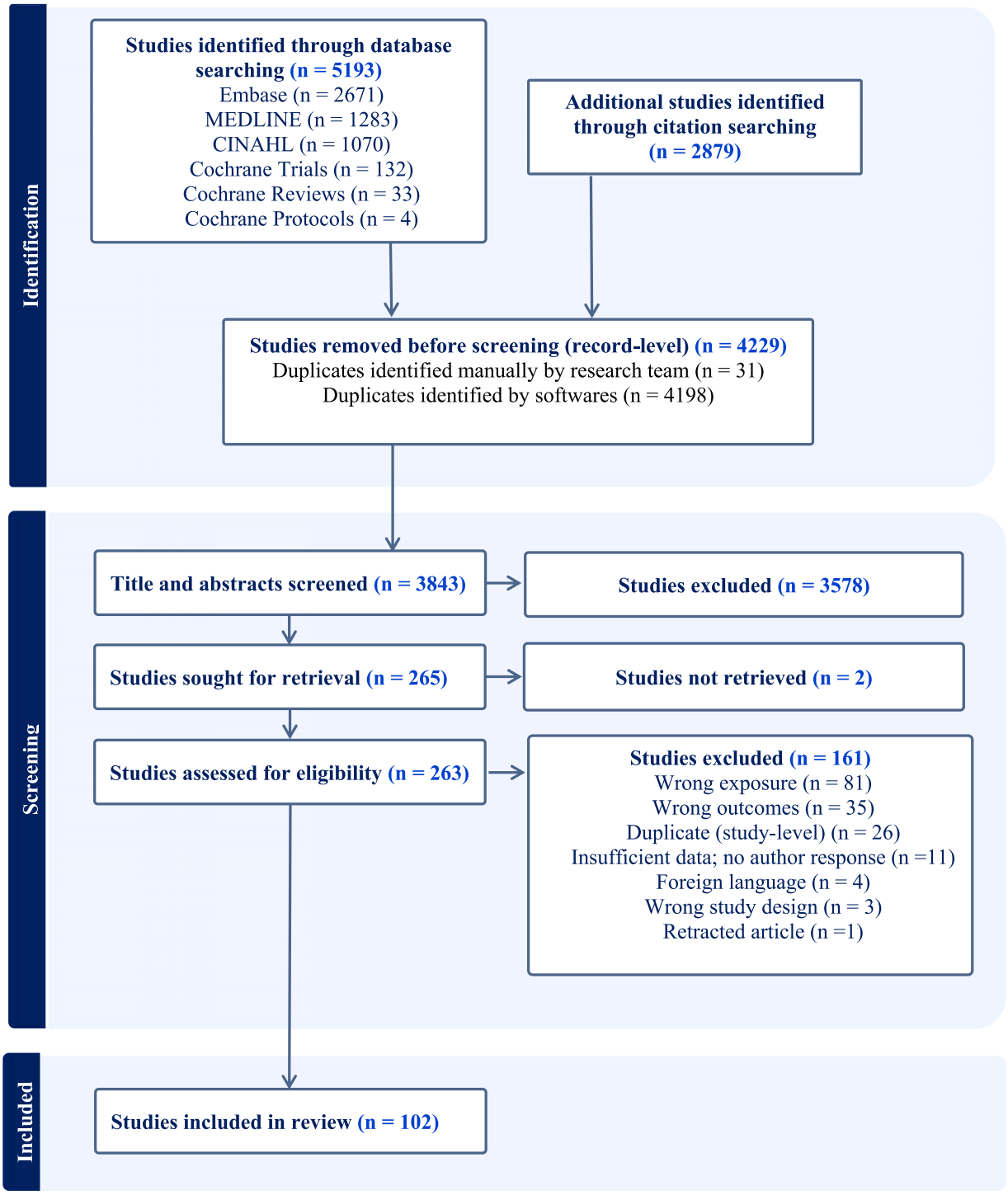

Figure 1. PRISMA flow diagram of the study selection process.

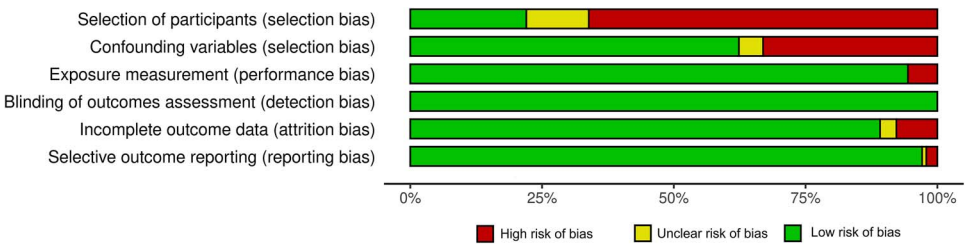

Figure 2. Risk of bias summary for the six domains of the applied RoBANS, presenting the reviewer judgements as percentages for each domain across all 102 included studies.

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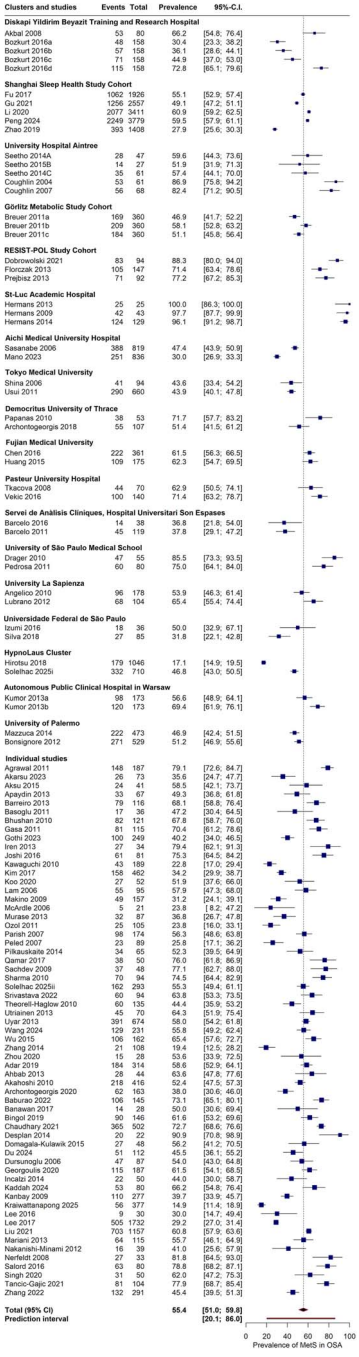

Figure 3. Pooled prevalence of MetS among adults with polysomnography-confirmed OSA. Studies grouped into clusters when multiple estimates originated from the same hospital setting or underlying cohort. "Individual studies" are primary studies that contribute a single prevalence estimate. Bozkurt 2016a–d, represent a single study reporting MetS prevalence using different diagnostic criteria; Breuer 2011a–c, represent multiple estimates derived from different MetS definitions within the same study; Seetho A–C, comprise publications by identical authors with overlapping populations reported across different years; and Solelhac 2025i–ii, represent two cohort datasets from different countries (Switzerland and India) analysed within a single study. "Events" indicate the number of patients with OSA diagnosed with MetS. "Total" denotes the number of patients with OSA included in each study. Horizontal lines represent 95% CI, and the diamond reflects the pooled prevalence estimate with its CI and prediction interval. Abbreviations: CI, confidence interval; MetS, metabolic syndrome; OSA, obstructive sleep apnea.

reported (only the number of participants diagnosed with OSA was provided).

Main effects

Model fit and global pooled prevalence. The overall pooled prevalence of MetS in the three-level meta-analytic model was estimated at 55.4% (95% CI: 51.0%, 59.8%) (Figure 3). Overall heterogeneity was considerable (total $I^2 = 97.76\%$). Within-cluster differences ($I^2_{\text{Level 2}}$) contributed 39.78% of total variance, whereas between-cluster differences ($I^2_{\text{Level 3}}$) constituted the largest proportion (57.98%). The distribution of variance across model levels is illustrated in Supplementary Figure S3 and Table 2.

The pooled estimate was accompanied by a wide 95% prediction interval (20.1%; 86.0%), indicating that prevalence in future studies conducted in comparable populations may vary substantially.

Model-fit assessment demonstrated that the full three-level model (AIC: 267.4, BIC: 275.4) provided a significantly better fit than the reduced model (AIC: 278.6, BIC: 284.0), as indicated by a significant likelihood-ratio test (LRT = 13.21, $p = 0.0003$).

Sensitivity analysis. Influence diagnostics indicated that the majority of studies had minimal impact on model estimates. One study [99] showed elevated influence consistent with summary statistics (Supplementary Figure S4). The Baujat plot revealed seven studies [21, 110, 112, 113, 116, 128, 154] that contributed disproportionately to heterogeneity (Supplementary Figure S5). The reanalysis after removing these eight studies (a new dataset with 101/109 estimates) produced a pooled prevalence of 56.4% (95% CI: 52.6%, 60.3%), consistent with the primary analysis. Heterogeneity remained considerable despite the exclusion of these studies ($I^2_{\text{Level 2}} = 43.77\%$, $I^2_{\text{Level 3}} = 51.89\%$, total $I^2 = 95.66\%$), indicating that the findings were robust to the influence of these studies.

Sub-group analysis. As presented in Table 2, moderator analyses using the three-level subgroup models demonstrated significant between-group differences in MetS prevalence across geographic region [$F(12, 97) = 3.69$, $p < 0.0001$], study designs [$F(5, 104) = 3.59$, $p < 0.01$], MetS definition/criteria [$F(10, 99) = 2.32$, $p < 0.05$], and AHI threshold [$F(4, 105) = 2.98$, $p < 0.05$]. Publication year did not significantly moderate MetS prevalence estimates [$F(4, 105) = 2.37$, $p > 0.05$].

The highest pooled prevalence was observed across studies conducted in Eastern Europe (70%; 95% CI: 56.4%, 80.9%), closely followed across Southern Asia (68.5%; 95% CI: 58.8%, 76.8%), Western Europe (68.3%; 95% CI: 52.2%, 81.0%), Northern Europe (63.3%, 95% CI: 48.0%, 76.3%), South America (61.7%, 95% CI: 39.5%, 80.0%), and Southern Europe (58.3%, 95% CI: 48.5%, 67.5%). Moderately high prevalence was noticed in Western Asia (47.9%, 95% CI: 38.3%, 57.7%) and Eastern Asia (44.2%, 95% CI: 36.9%, 51.7%). Higher prevalence estimates were present in the baseline data of RCTs (76.4%, 95% CI: 59.5%, 87.7%) and quasi-experimental studies (67.3%, 95% CI: 44.0%, 84.4%) compared to observational designs such as cross-sectional (54.9%, 95% CI: 50.2%, 59.6%) and case–control (53.8%, 95% CI: 41.4%, 65.8%) studies. The lowest MetS prevalence was noted in the baseline assessments of longitudinal cohort studies (33.6%, 95% CI: 18.3%, 53.4%). Regarding applied MetS criteria/definitions, higher pooled prevalence of MetS (63.8%, 95% CI: 53.2%, 73.1%) was noted when studies used the IDF definition, with slightly lower estimates for those

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Table 2. Subgroup analysis of prevalence of MetS among adults with polysomnography-confirmed OSA. "*Events*" represent the number of MetS cases, and "*Total*" denotes the number of adults with OSA included in each study. Overall, 102 eligible studies contributed 109 prevalence estimates (*k*). Abbreviations: AHI, apnea-hypopnea index; CI, confidence interval; IDF, International Diabetes Federation; JCCMS, Japanese Committee Of The Criteria For Metabolic Syndrome; MetS: metabolic syndrome; NCEP ATP III: National Cholesterol Education Program Adult Treatment Panel III (Third Report Of The Expert Panel On Detection, Evaluation, And Treatment Of High Blood Cholesterol In Adults); OSA: obstructive sleep apnea; RCT: randomized controlled trial; UN, United Nations; WHO, World Health Organization

Moderator variable	No. of estimates (k)	MetS events	Total OSA	Pooled logit prevalence (95% CI)	Prevalence % (95% CI)	Test of Moderators	Test for Residual Heterogeneity	I^2_{Level2}, %	I^2_{Level3}, %	*Total variance*, I^2, %
UN geographic regions						$F(12, 97) = 3.6922^{***}$	$QE(97) = 2202.8012^{***}$	47.34	49.75	97.09
Eastern Asia	28	10 607	21 374	-0.2339 (-0.5364; 0.0686)	44.2 (36.9; 51.7)					
Western Asia	17	1342	2665	-0.0839 (-0.4777; 0.3100)	47.9 (38.3; 57.7)					
Southern Europe	16	1376	2531	0.3355 (-0.0606; 0.7316)	58.3 (48.5; 67.5)					
Southern Asia	12	1260	1914	0.7765 (0.3553; 1.1977)	68.5 (58.8; 76.8)					
Western Europe	9	1284	3055	0.7694 (0.0877; 1.4511)	68.3 (52.2; 81.0)					
Eastern Europe	9	675	971	0.8495 (0.2568; 1.4421)	70.0 (56.4; 80.9)					
Northern Europe	9	352	567	0.5463 (-0.0781; 1.1706)	63.3 (48.0; 76.3)					
South America	4	152	256	0.4781 (-0.4273; 1.3836)	61.7 (39.5; 80.0)					
Northern Africa	2	67	108	0.3621 (-0.7127; 1.4369)	59.0 (32.9; 80.8)					
Northern America	1	98	174	0.2542 (-1.1683; 1.6767)	56.3 (23.7; 84.3)					
South-eastern Asia	1	56	377	-1.7461 (-3.1653; -0.3269)	14.9 (4.1; 41.9)					
Australia & New Zealand	1	5	21	-1.1632 (-2.8852; 0.5589)	23.8 (5.3; 63.6)					
Study designs						$F(5, 104) = 3.5872^{**}$	$QE(104) = 2594.4810^{***}$	35.48	62.17	97.65
Cross-sectional	86	15 211	29 585	0.1976 (0.0069; 0.3884)	54.9 (50.2; 59.6)					
Case–control	13	614	1178	0.1540 (-0.3465; 0.6544)	53.8 (41.4; 65.8)					
RCT	4	254	357	1.1756 (0.3863; 1.9650)	76.4 (59.5; 87.7)					
Cohort	3	1040	2665	-0.6795 (-1.4950; 0.1360)	33.6 (18.3; 53.4)					
Quasi-experimental	3	155	228	0.7216 (-0.2426, 1.6858)	67.3 (44.0; 84.4)					
MetS definitions						$F(10, 99) = 2.3173^{*}$	$QE(99) = 2486.1712^{***}$	37.26	60.36	97.62
NCEP ATP III	60	12 899	24 608	0.2812 (0.0602; 0.5022)	57.0 (51.5; 62.3)					
Harmonizing	16	1511	3343	0.3659 (-0.0255; 0.7572)	59.0 (49.4; 68.1)					
IDF	12	755	1277	0.5653 (0.1294; 1.0011)	63.8 (53.2; 73.1)					
National (JCCMS)	6	954	2354	-0.4152 (-1.1079; 0.2775)	39.8 (24.8; 56.9)					
WHO	2	138	304	-0.1485 (-1.0808; 0.7838)	46.3 (25.3; 68.6)					
National (Taiwan)	1	106	162	0.6381 (-0.9362; 2.2123)	65.4 (28.2; 90.1)					
National (China)	1	132	291	-0.1861 (-1.7435; 1.3713)	45.4 (14.9; 79.8)					
Metabolic Vascular System	1	209	360	0.6743 (-0.4858; 1.8343)	66.3 (38.1; 86.2)					
At least one definition	1	115	158	1.4081 (0.2597; 2.5565)	80.4 (56.5; 92.8)					
Not given	9	455	1156	-0.3549 (-0.8788; 0.1689)	41.2 (29.3; 54.2)					
AHI threshold for OSA diagnosis						$F(4, 105) = 2.9808^{*}$	$QE(105) = 2688.0646^{***}$	35.79	61.96	97.75
≥ 5 events/hr	85	14 990	29 670	0.1569 (-0.0395; 0.3533)	53.9 (49.0; 58.7)					
≥ 10 events/hr	8	841	1825	0.0584 (-0.5915; 0.7083)	51.5 (35.6; 67.0)					
≥ 15 events/hr	14	1271	2263	0.6435 (0.2264; 1.0607)	65.6 (55.6; 74.3)					
≥ 30 events/hr	2	172	255	0.6742 (-0.3407; 1.6891)	66.2 (41.6; 84.4)					
Publication year						$F(4, 105) = 2.3731$	$QE(105) = 2621.1539^{***}$	35.30	62.51	97.81
2004-2010	24	1782	3457	0.3985 (0.0768; 0.7202)	59.8 (51.9; 67.3)					
2011-2015	39	3487	6279	0.2246 (-0.0534; 0.5025)	55.6 (48.7; 62.3)					
2016-2020	28	5807	12 593	-0.0007 (-0.3134; 0.3119)	50.0 (42.2; 57.7)					
2021-2025	18	6198	11 684	0.2720 (-0.0872; 0.6313)	56.8 (47.8; 65.3)					

$^{*}p$-value < 0.05. $^{**}p$-value < 0.01. $^{***}p$-value < 0.001

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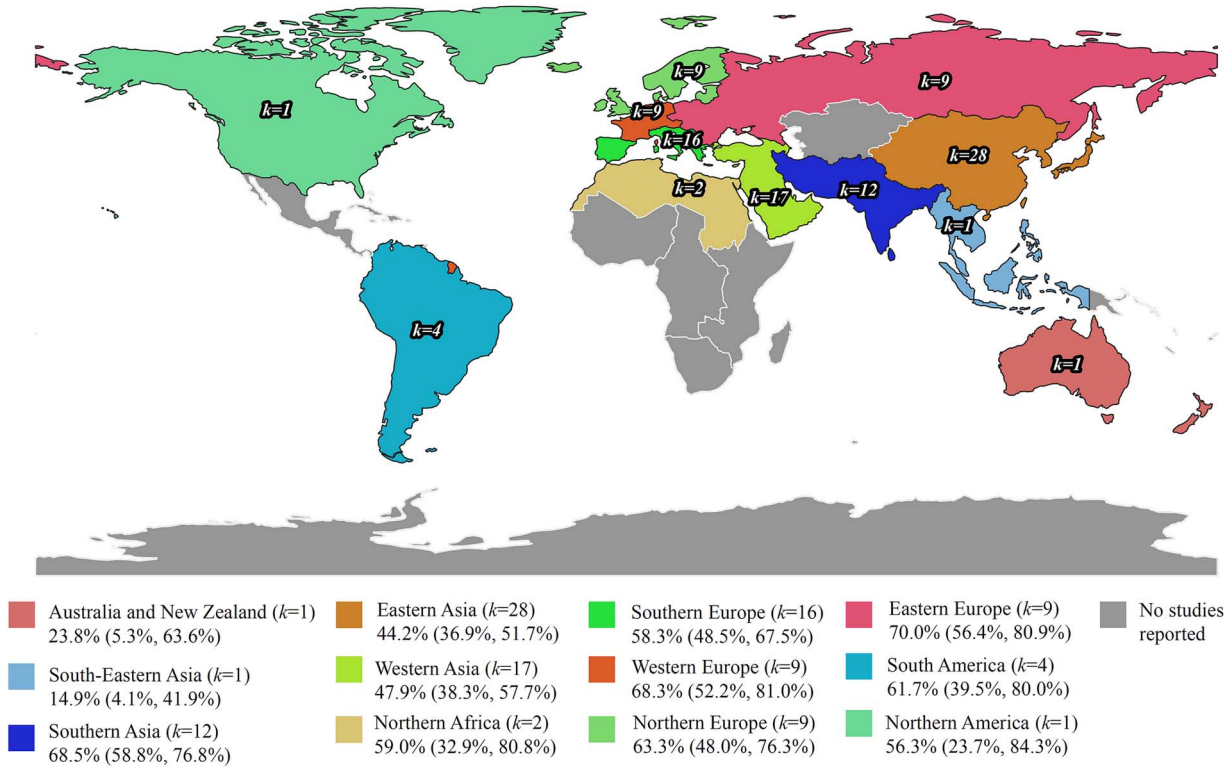

Figure 4. Global distribution of pooled prevalence of MetS among adults with polysomnography-confirmed OSA stratified by UN geographic regions. Regional prevalence estimates were obtained from three-level subgroup meta-analysis and visualized using the QGIS geographic information System [158]. Colour gradients represent pooled prevalence across regions with available data, while grey areas denote regions without data. For each region, the pooled MetS prevalence (%) with corresponding 95% CI is reported, whilst *k* indicates the number of prevalence estimates. Abbreviations: MetS, metabolic syndrome; OSA, obstructive sleep apnea, UN, United Nations.

that applied the harmonizing (59.0%, 95% CI: 49.4%, 68.1%) or the NCEP ATP III (57.0%, 95% CI: 51.5%, 62.3%) criteria/definition. Studies that applied the WHO definition [10] or the Japanese MetS criteria [157] had lower MetS prevalence estimate (46.3%, 95% CI: 25.3%, 68.6%) and (39.8%, 95% CI: 24.8%, 56.9%), respectively. The included studies used varying AHI cut-off values to define OSA, with thresholds of ≥5, ≥10, ≥15, and ≥ 30 events/hr. Studies were grouped according to the threshold used for OSA case definition rather than disease severity categories. Prevalence estimates increased with higher AHI thresholds. Studies applying a threshold of ≥5 events/hr reported a pooled MetS prevalence of 53.9% (95% CI: 49.0%, 58.7%), while higher thresholds yielded greater estimates, namely 65.6% (95% CI: 55.6%, 74.3%) for ≥15 events/hr and 66.2% (95% CI: 41.6%, 84.4%) for ≥30 events/hr. Studies using a threshold of ≥10 events/hr had a pooled MetS prevalence of 51.5% (95% CI: 35.6%, 67.0%). Finally, regarding publication year, MetS prevalence estimates ranged from 50.0% (95% CI: 42.2%, 57.7%) in studies published between 2016 and 2020 to 59.8% (95% CI: 51.9%, 67.3%) in those published between 2004 and 2010, with estimates of 55.6% (95% CI: 48.7%, 62.3%) and 56.8% (95% CI: 47.8%, 65.3%) for those published during 2011 and 2015, and 2021 and 2025, respectively (Table 2).

The initial high overall heterogeneity remained consistent across these subgroups. Residual heterogeneity remained significant within all subgroup models, suggesting that the examined moderators explained only part of the variability in MetS prevalence estimates. Regional prevalence estimates derived from subgroup analysis were visualized on a world map using QGIS [158], as presented in Figure 4.

Meta-regression. Meta-regression was performed on 93 studies with complete corresponding moderator data, adjusting for the key covariates. The results showed that, unlike mean age ($\beta = 0.0087$, SE = 0.0139, t = 0.63, $p = 0.53$, 95% CI: -0.02, 0.04) and percentage of male sex ($\beta = 0.0060$, SE = 0.0042, t = 1.43, $p = 0.15$, 95% CI: -0.002, 0.01), mean BMI was significantly associated with increased effect size ($\beta = 0.0772$, SE = 0.0169, t = 4.56, $p < 0.0001$, 95% CI: 0.04, 0.11). Indeed, a 5-unit increase in BMI was associated with 41% higher odds of MetS among adults with OSA (OR: 1.41, 95% CI: 1.21, 1.64), indicating that studies with higher mean BMI reported greater prevalence of MetS. The test for residual heterogeneity was statistically significant (Q_E (93) = 1704.7807, $p < 0.0001$), indicating the presence of additional unmeasured moderators. The overall test of these moderators was statistically significant [F (3, 93) = 6.98, $p < 0.001$], indicating that these variables collectively explained a significant proportion of between-study heterogeneity. The bubble plot for the meta-regression examining the effect of mean BMI on the prevalence of MetS in OSA is presented in Supplementary Figure S6.

Discussion

To the best of our knowledge, this is the first systematic review and meta-analysis investigating specifically the prevalence of MetS among adults with polysomnography-confirmed OSA, including a large number of studies (N = 102) and a pooled number of OSA cases (N = 34 013). It is noteworthy that, based on the applied eligibility criteria, data from studies with confirmed OSA diagnosis were included, relying on peer-reviewed publications/studies with "gold-standard" Level 1 sleep examinations, whilst all established MetS definitions were included. Accordingly, this meta-analysis showed a markedly high (55.4%) global prevalence of MetS among adults with polysomnography-confirmed OSA.

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This is the most up-to-date and robust estimate of MetS in such patients, generated by pooling data from observational and experimental studies conducted globally (28 countries across 12 UN geographic regions) and employing three-level random-effects models, while also accounting for potential confounding factors. As expected high heterogeneity was noted, explained, at least in part, by the inclusion of more studies [159]. Sensitivity analyses were also performed, which were in agreement with the primary findings.

The combined prevalence estimate of MetS (for the geographic regions with more than one eligible estimate/study; Table 2) from among adults with polysomnography-confirmed OSA showed geographic variability, ranging from 44.2% in Eastern Asia to 70% in Eastern Europe. A large meta-analysis of global data from the general adult population (28 million individuals) reported a global prevalence of MetS between 12.5% and 31.4% according to the definition considered, which also showed geographic variability with significantly higher prevalence in the Eastern Mediterranean Region and the Americas [160]. Notably, this high global prevalence of MetS in the general adult population is lower than the present MetS prevalence estimates among adults with OSA, suggesting that MetS prevalence is even higher in this patient population. The noted geographic variability can be attributed, at least in part, to the complex interplay of inherited body-composition phenotypes, ancestry-specific metabolic genetics, regionally evolving dietary patterns, variable physical activity levels, and differences in clinical diagnosis pathways. For example, genome-wide evidence shows that both overall adiposity phenotypes and body-fat distribution phenotypes are highly polygenic (e.g. numerous genetic loci associated with increased/decreased BMI and waist-to-hip ratio have been identified in predominantly European cohorts [161, 162]). Moreover, South Asian populations (e.g. populations in Indian and other South Asian countries) exhibit high visceral adiposity and insulin resistance at lower BMI, reflecting differences in the risk profile associated with body adiposity distribution/composition [163]. Additionally, the *FTO* variant (Fat Mass and Obesity-associated gene) is associated with increased waist circumference and interacts strongly with physical activity, amplifying susceptibility to central adiposity phenotypes in sedentary individuals [164]. Substantial regional differences also exist in lifestyle exposures which directly influence the cardio-metabolic risk, with existing data suggesting increased levels of insufficient physical activity in Europe and the Americas [165]. Furthermore, dietary factors similarly differ across regions/countries (e.g. South Asian populations increasingly adopt unhealthy diets with refined carbohydrates, sugar-rich beverages, and trans-fatty acids, whilst European populations also tend to follow such dietary habits) [166]. These lifestyle factors are not consistently/adequately reported in studies on the prevalence of MetS in adults with OSA and should be taken into account in the design of future studies in this field, particularly in relation to the noted variability across different regions/countries.

Most of the identified eligible studies originated from Europe and Asia, indicating a greater research focus on cardio-metabolic consequences of OSA in these regions. In contrast, studies from the Americas and Oceania were scarce, resulting in an uneven geographic distribution of the available evidence. This imbalance may influence the pooled estimate prevalence estimates, as regional differences in genetic background, lifestyle factors, obesity prevalence, and healthcare access could affect the coexistence of OSA and MetS. Future epidemiological studies from under-represented regions are needed to improve the global representativeness and external validity of the current evidence base.

Methodological factors may further influence the variability of the reported prevalence of MetS in adults with OSA. In the present dataset, many South Asian and European studies were conducted in cardio-metabolic, or specialist sleep/respiratory centres, increasing the likelihood of recruiting individuals with both OSA and MetS, and thereby potentially introducing a Berkson's type of selection bias [167]. Conversely, in most studies from East Asia, OSA is often diagnosed in Ear, Nose, and Throat or neurology settings among patients without obesity [93, 109, 111–113, 128], reducing the likelihood of concurrent MetS diagnosis/screening [168]. Moreover, despite the widespread use of the NCEP ATP III MetS criteria across the included studies, the noted regional differences in MetS prevalence is further shaped by the variable genetic and lifestyle background, rather than by MetS diagnostic inconsistencies alone.

The present findings show a higher average MetS prevalence in experimental and clinic-based observational studies, whereas it was lower in population-based cohorts. This may not be random, but rather consistent with methodological aspects, largely attributable to selection bias and the clinical context of study participants in the former study designs [85, 86, 95, 133]. This has also been noted in previous meta-analyses in other fields, such as for tuberculosis among people using drugs [169] or for cardiac abnormalities in COVID-19 [170], which have also reported differences between hospital-based compared with population-based cohort estimates; none, however, captured the full spectrum from RCT to broader cohort designs. The gradient in MetS prevalence among adults with OSA observed in the present analysis (i.e. experimental > quasi-experimental > cross-sectional/case–control > cohort studies) suggests that selection/recruitment bias linked to the study design may not merely be a source of heterogeneity, but also a potential determinant of the reported comorbidity burden. For example, the comparatively higher prevalence of MetS among baseline participants with OSA in RCTs may reflect a more severe comorbidity profile of those typically recruited into Continuous Positive Airway Pressure (CPAP) trials and studies based in specialist sleep clinics [85, 86, 95, 133]. This design-associated heterogeneity in the prevalence of comorbid MetS indicates that such factors should be considered when designing future studies in this field.

Notably, the MetS definition emerged as an important moderator of MetS prevalence among adults with OSA in the present analysis. Among the commonly used MetS definitions/criteria, the IDF criteria yielded higher MetS prevalence (63.8%), which appears to be consistent with including central obesity as a prerequisite for MetS diagnosis and applying ethnicity-specific waist-circumference thresholds. Indeed, both these factors can increase the case detection in populations with a high burden of visceral adiposity, such as those with OSA [171, 172]. In comparison, the harmonized and the NCEP ATPIII MetS definitions produced similar, slightly lower estimates (59.0% and 57.0%, respectively), reflecting their more flexible criteria regarding central obesity, which in these definitions is not a prerequisite for MetS diagnosis [8, 9, 11]. The lowest prevalence (39.8%) was observed when applying the Japanese criteria/definition, which, as expected, was used exclusively in studies conducted in Japan. The JCCMS criteria are applied to Japanese patients/populations with distinct adiposity profiles, and, thus, impose stringent waist-circumference thresholds and require central obesity as an essential condition. Subgroup analyses demonstrated statistically significant MetS prevalence estimates across all definitions (all $p < 0.0001$).

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The present analysis also revealed a dose–response trend between the AHI threshold used to diagnose OSA and the pooled MetS prevalence estimates. Indeed, the higher AHI cut-offs for OSA diagnosis, typically reflecting greater OSA severity, were associated with higher MetS prevalence. This trend aligns with established evidence linking OSA severity to visceral adiposity, sympathetic activation, oxidative stress, and insulin resistance [173], which collectively increase the metabolic burden in the more severe phenotype. The slightly higher MetS prevalence observed in the AHI ≥5 events/hr group (53.9%) compared with the one for the AHI ≥10 events/hr group (51.5%), although seemingly counterintuitive, it is likely to reflect, at least in part, differences in study populations or unmeasured confounding in the included studies. However, the overall trend remains, since when the applied AHI threshold for the diagnosis of OSA increases to ≥15 and ≥ 30 events/hr the comorbidity burden of MetS also increases markedly (MetS prevalence of 65.6% and 66.2%, respectively). The similar MetS prevalence estimates for the higher AHI thresholds suggest a potential plateau effect, which can be attributed, at least in part, to two factors. First, key underlying mechanisms linking OSA to MetS (e.g. intermittent hypoxia, sympathetic activation, and sleep fragmentation) are active at moderate severity, with limited additional impact for the diagnosis of MetS at higher AHI levels. Second, at least a minimum degree of obesity (particularly central), which is a key risk factor for both OSA and MetS diagnosis, is present across all OSA severities, possibly confounding any severity-related differences in MetS prevalence, particularly at the higher AHI thresholds. Overall, these findings reinforce the notion that such higher AHI thresholds, beyond their diagnostic role, serve as an indicator of underlying cardio-metabolic stress. They also complement longitudinal evidence demonstrating that more severe OSA is associated with a greater risk of incident metabolic abnormalities [21].

In contrast to other categorical moderators, the publication year of the included eligible studies did not significantly influence the pooled prevalence of MetS. Although minor variations in point estimates were observed across the different publication periods, the prevalence estimates were broadly similar, with substantial overlap in their CIs. This suggests that the burden of MetS among adults with confirmed OSA has remained relatively consistent over time.

In the present meta-regression, a 5-unit increase in mean BMI was associated with 41% greater odds of MetS. This indicates that adiposity is a significant modifiable risk factor linking OSA and MetS, and is consistent with the extensive relevant pathophysiological evidence [173, 174]. By contrast, neither the mean age ($p = 0.53$) nor the percentage of male participants ($p = 0.15$) significantly moderated the noted MetS estimate. This suggests that the metabolic vulnerability associated with confirmed OSA is broadly consistent across the included adult age range (39–68 years) and does not vary substantially according to sex distribution within the identifiable eligible study samples.

Although the included covariates demonstrated a significant joint effect ($p < 0.0001$), the performed meta-regression left substantial residual heterogeneity unexplained ($Q_E(93) = 1704.78$, $p < 0.0001$). This indicates that while BMI is a key determinant, between-study variation is largely driven by a combination of other methodological and clinical factors (e.g. the diagnostic criteria for MetS, geographic region, and study design).

Strength and limitations

Evidence perspective. This systematic review and meta-analysis synthesizes evidence from a large, pooled sample size reporting the prevalence of MetS in adults with confirmed OSA. Notably, the OSA diagnosis across all included studies was based on standard polysomnography, ensuring accurate case selection and minimising misclassification with other sleep-disordered breathing phenotypes. The inclusion of studies from diverse geographic regions further enhances the external validity and generalisability of the findings.

A further strength is the inclusion of all established MetS definitions, allowing this review to also explore how MetS prevalence estimates vary by diagnostic definition/criteria. Furthermore, subgroup analyses and meta-regression of covariates enabled a structured examination of potential confounders and effect modifiers in the relationship between OSA and MetS.

However, certain limitations must be acknowledged. Substantial residual heterogeneity persisted despite meta-regression and subgroup analyses, suggesting that important covariates were unmeasured or inconsistently reported across the included eligible primary studies. In particular, ethnicity-related data [175, 176], lifestyle behaviours such as smoking [177, 178] and physical activity [179], menopausal status [179, 180], and other cardio-metabolic determinants were not reported consistently by the identified eligible studies, thus limiting the ability to fully adjust for these known MetS risk factors. Moreover, the predominance of observational study designs limits causal inference, whilst variability in MetS diagnostic criteria may have introduced classification inconsistencies at the study level. Finally, some geographic regions, particularly low-and middle-income countries/regions, remain under-represented, which may influence regional prevalence estimates.

Review perspective. This review was designed and conducted by a multidisciplinary team with expertise in sleep medicine, endocrinology, and systematic review/meta-analysis methodology, supporting strong conceptual, clinical and methodological rigour. The applied methodology facilitated a transparent, reproducible, and systematic workflow across database searching (an extensive search strategy of the most relevant databases, supplemented by citation chasing), screening, data extraction, and analysis processes.

The risk of bias was assessed independently by two researchers using a well-validated six-domain tool, enabling a comprehensive appraisal of selection, measurement, and analytical biases across studies. This structural assessment not only strengthens the internal validity but also highlights specific methodological limitations in the existing literature, providing guidance for future high-quality research.

Methodologically, the adoption of three-level random-effects modelling, a reproducible statistical procedure in R, further strengthened the robustness of the present findings. Of note, where studies provided sufficient detail, outcomes and characteristics were organized into clusters, allowing appropriate inclusion of these data and improving interpretability. Furthermore, examining multiple potential moderators enabled a detailed exploration of sources of heterogeneity and provided clinically informative insights. A limitation which relates to the statistical software used was that, although the primary analyses were conducted using the *rma.mv* function in the *metafor* package [48], visualisation and diagnostic tools are not fully integrated within this package, necessitating the use of functions from the *meta* package [56].

Finally, although every effort was made to ensure comprehensive coverage, the possibility of missing studies not registered in the searched databases or non-English studies cannot be entirely excluded.

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Conclusion

The findings of the present systematic review and meta-analysis indicate that nearly six out of 10 adults with a polysomnography-confirmed diagnosis of OSA have MetS. This is both clinically consequential and substantially higher than the estimate of MetS in general adult populations, and, thus, highlights the importance of systematically and promptly screening for MetS in adults with OSA. This high MetS burden among these patients is not attributable to a single factor, but likely arises from an interplay of various factors, including adiposity, cardio-metabolic risk clustering, and demographic variation. While meta-regression highlights BMI as a significant predictor of MetS in patients with OSA, substantial unexplained heterogeneity suggests that additional biological and/or contextual factors play a significant role. These findings warrant more rigorous phenotyping and well-designed large-scale studies to improve OSA-MetS research. Future research should further investigate underlying biological mechanisms, integrating standardized cardio-metabolic assessments, longitudinal designs, and population-level datasets with detailed genetic and biomarker information. Indeed, by highlighting the markedly high prevalence of MetS among adults with OSA, this meta-analysis provides a strong foundation and compelling rationale for leveraging large-scale cohorts to explore causal mechanisms and refine risk stratification in this patient population.

Supplementary material

Supplementary material is available at *SLEEP* online.

Author contributions

SP (first author): Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing—Original Draft, Writing—Review & Editing, Visualization, Project administration. **IK**: Conceptualization, Methodology, Validation, Investigation, Resources, Data Curation, Writing—Review & Editing, Visualization, Supervision, Project administration. **Alexander Dallaway**: Conceptualization, Methodology, Software, Validation, Investigation, Resources, Writing—Review & Editing, Visualization. **CK**: Conceptualization, Methodology, Validation, Investigation, Writing—Review & Editing, Visualization. **LL**: Conceptualization, Methodology, Validation, Investigation, Writing—Review & Editing, Visualization. AA: Writing—Review & Editing. **Ashesh Dhungana**: Conceptualization, Writing—Review & Editing, Supervision. **HSR** (senior author): Conceptualization, Methodology, Investigation, Writing—Review & Editing, Supervision, Project administration. **OPK** (senior author): Conceptualization, Methodology, Validation, Investigation, Resources, Data Curation, Writing—Review & Editing, Visualization, Supervision, Project administration.

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Data availability

The data supporting the findings of this review are available from the corresponding authors upon reasonable request.

References

1. Epstein LJ, Kristo D, Strollo PJ Jr, *et al.* Clinical guideline for the evaluation, management and long-term care of obstructive sleep apnea in adults. *J Clin Sleep Med*. 2009;**5**(3):263–276.
2. Benjafield AV, Ayas NT, Eastwood PR, *et al.* Estimation of the global prevalence and burden of obstructive sleep apnoea: a literature-based analysis. *Lancet Respir Med*. 2019;**7**(8):687–698. https://doi.org/10.1016/s2213-2600(19)30198-5
3. Chen L, Pivetta B, Nagappa M, *et al.* Validation of the STOP-Bang questionnaire for screening of obstructive sleep apnea in the general population and commercial drivers: a systematic review and meta-analysis. *Sleep Breath*. 2021;**25**(4):1741–1751. https://doi.org/10.1007/s11325-021-02299-y
4. Kryger MH, Roth T, Dement WC. *Principles and Practice of Sleep Medicine*. 6th ed. Philadelphia, PA, WB Saunders: Elsevier; 2017.
5. Jordan AS, McSharry DG, Malhotra A. Adult obstructive sleep apnoea. *Lancet*. 2014;**383**(9918):736–747. https://doi.org/10.1016/s0140-6736(13)60734-5
6. Young T, Peppard PE, Gottlieb DJ. Epidemiology of obstructive sleep apnea: a population health perspective. *Am J Respir Crit Care Med*. 2002;**165**(9):1217–1239. https://doi.org/10.1164/rccm.2109080
7. Simmons RK, Alberti KGMM, Gale EAM, *et al.* The metabolic syndrome: useful concept or clinical tool? Report of a WHO expert consultation. *Diabetologia*. 2010;**53**(4):600–605. https://doi.org/10.1007/s00125-009-1620-4
8. Alberti KG, Eckel RH, Grundy SM, *et al.* Harmonizing the metabolic syndrome: a joint interim statement of the International Diabetes Federation Task Force on Epidemiology and Prevention; National Heart, Lung, and Blood Institute; American Heart Association; World Heart Federation; International Atherosclerosis Society; and International Association for the Study of Obesity. *Circulation*. 2009;**120**(16):1640–1645. https://doi.org/10.1161/circulationaha.109.192644
9. Expert Panel on Detection, Evaluation, and Treatment of High Blood Cholesterol in Adults. Executive summary of the third report of the National Cholesterol Education Program (NCEP) Expert Panel on Detection, Evaluation, and Treatment of High Blood Cholesterol in Adults (Adult Treatment Panel III). *JAMA*. 2001;**285**(19):2486–2497. https://doi.org/10.1001/jama.285.19.2486
10. Alberti KG, Zimmet PZ. Definition, diagnosis and classification of diabetes mellitus and its complications. Part 1: diagnosis and classification of diabetes mellitus provisional report of a WHO consultation. *Diabet Med*. 1998;**15**(7):539–553. https://doi.org/10.1002/(sici)1096-9136(199807)15:7<539::Aid-dia668>3.0.Co;2-s
11. Grundy SM, Cleeman JI, Daniels SR, *et al.* Diagnosis and management of the metabolic syndrome: an American Heart Association/National Heart, Lung, and Blood Institute scientific statement. *Circulation*. 2005;**112**(17):2735–2752. https://doi.org/10.1161/circulationaha.105.169404
12. International Diabetes Federation (IDF). *IDF Consensus Worldwide Definition of the Metabolic Syndrome*. Brussels: IDF; 2006. Available from: https://idf.org/about-diabetes/resources/idf-consensus-worldwide-definition-of-the-metabolic-syndrome/

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13. Wilcox I, McNamara SG, Collins FL, Grunstein RR, Sullivan CE. "Syndrome Z": the interaction of sleep apnoea, vascular risk factors and heart disease. *Thorax*. 1998;**53**(Supplement 2):S25–S31. https://doi.org/10.1136/thx.53.2008.S25
14. Ortega KC, Mion D Jr. Metabolic syndrome and obstructive sleep apnoea: two circumferences in the same individual. *J Hum Hypertens*. 2009;**23**(12):836. https://doi.org/10.1038/jhh.2009.72
15. Tang R, Li C, Di D, *et al*. Evaluate the relationship between obstructive sleep apnea and metabolic syndrome in real-world data. *Nat Sci Sleep*. 2024;**16**:217–231. https://doi.org/10.2147/nss.S433514
16. Gaines J, Vgontzas AN, Fernandez-Mendoza J, Bixler EO. Obstructive sleep apnea and the metabolic syndrome: the road to clinically-meaningful phenotyping, improved prognosis, and personalized treatment. *Sleep Med Rev*. 2018;**42**:211–219. https://doi.org/10.1016/j.smrv.2018.08.009
17. Kim T. Quality of life in metabolic syndrome patients based on the risk of obstructive sleep apnea. *Behav Sci (Basel)*. 2024;**14**(2):127. https://doi.org/10.3390/bs14020127
18. Mesarwi OA, Sharma EV, Jun JC, Polotsky VY. Metabolic dysfunction in obstructive sleep apnea: a critical examination of underlying mechanisms. *Sleep Biol Rhythms*. 2015;**13**(1):2–17. https://doi.org/10.1111/sbr.12078
19. Li X, Liu X, Meng Q, *et al*. Circadian clock disruptions link oxidative stress and systemic inflammation to metabolic syndrome in obstructive sleep apnea patients. *Front Physiol*. 2022;**13**:932596. https://doi.org/10.3389/fphys.2022.932596
20. Akarsu FG, Algin DI, Erdinc OO. Evaluation of comorbid diseases in obstructive sleep apnea syndrome. *Rev Assoc Med Bras*. 2023;**69**(3):421–425. https://doi.org/10.1590/1806-9282.20221082
21. Hirotsu C, Haba-Rubio J, Togeiro SM, *et al*. Obstructive sleep apnoea as a risk factor for incident metabolic syndrome: a joined Episono and HypnoLaus prospective cohorts study. *Eur Respir J*. 2018;**52**(5):1801150. https://doi.org/10.1183/13993003.01150-2018
22. Kong DL, Qin Z, Wang W, Pan Y, Kang J, Pang J. Association between obstructive sleep apnea and metabolic syndrome: a meta-analysis. *Clin Invest Med*. 2016;**39**(5):E161–e172. https://doi.org/10.25011/cim.v39i5.27148
23. Cattazzo F, Pengo MF, Giontella A, *et al*. Effect of continuous positive airway pressure on glucose and lipid profiles in patients with obstructive sleep apnoea: a systematic review and meta-analysis of randomized controlled trials. *Arch Bronconeumol*. 2023;**59**(6):370–376. https://doi.org/10.1016/j.arbres.2023.03.012
24. Liu J, Xu J, Guan S, Wang W. Effects of different treatments on metabolic syndrome in patients with obstructive sleep apnea: a meta-analysis. *Front Med (Lausanne)*. 2024;**11**:1354489. https://doi.org/10.3389/fmed.2024.1354489
25. Li J, Zeng L, Feng T. The pathophysiological relationship and treatment progress of obstructive sleep Aanea syndrome, obesity, and metabolic syndrome. *Explor Res Hypothesis Med*. 2025;**10**(1):69–74. https://doi.org/10.14218/ERHM.2024.00048
26. Bhushan B, Ayub B, Loghmanee DA, Billings KR. Metabolic alterations in adolescents with obstructive sleep apnea. *Int J Pediatr Otorhinolaryngol*. 2015;**79**(12):2368–2373. https://doi.org/10.1016/j.ijporl.2015.10.046
27. Martins FO, Conde SV. Gender differences in the context of obstructive sleep apnea and metabolic diseases. *Front Physiol*. 2021;**12**:792633. https://doi.org/10.3389/fphys.2021.792633
28. Kim T, Kang J. Relationship between obstructive sleep apnea, insulin resistance, and metabolic syndrome: a nationwide population-based survey. *Endocr J*. 2023;**70**(1):107–119. https://doi.org/10.1507/endocrj.EJ22-0280
29. Feng T, Ou Q, Shan G, Hu Y, He H. Sleep-disordered breathing and metabolic syndrome across gender, age, and sleep subtypes in east Asians. *Front Endocrinol (Lausanne)*. 2025;**16**:1519638. https://doi.org/10.3389/fendo.2025.1519638
30. Lam JCM, Lam B, Cl L, *et al*. Obstructive sleep apnea and the metabolic syndrome in community-based Chinese adults in Hong Kong. *Respir Med*. 2006;**100**(6):980–987. https://doi.org/10.1016/j.rmed.2005.10.003
31. Kumor M, Bielicki P, Barnas M, Przybylowski T, Zielinski J, Chazan R. Prevalence of metabolic syndrome diagnosis in patients with obstructive sleep apnoea syndrome according to adopted definition. *Pneumonol Alergol Pol*. 2013;**81**(5):417–423. https://doi.org/10.5603/ARM.35515
32. Huang PL. A comprehensive definition for metabolic syndrome. *Dis Model Mech*. 2009;**2**(5-6):231–237. https://doi.org/10.1242/dmm.001180
33. Day C. Metabolic syndrome, or what you will: definitions and epidemiology. *Diab Vasc Dis Res*. 2007;**4**(1):32–38. https://doi.org/10.3132/dvdr.2007.003
34. Gothi D, Kumar R, Anand S, Patro M, Malhotra N, Vaidya S. A study on the prevalence of RLS in OSA and the consequences of co-occurrence. *Lung India*. 2023;**40**(4):321–326. https://doi.org/10.4103/lungindia.lungindia_28_23
35. Kim DH, Kim B, Han K, Kim SW. The relationship between metabolic syndrome and obstructive sleep apnea syndrome: a nationwide population-based study. *Sci Rep*. 2021;**11**(1):8751. https://doi.org/10.1038/s41598-021-88233-4
36. Liu L, Su X, Zhao Z, *et al*. Association of metabolic syndrome with long-term cardiovascular risks and all-cause mortality in elderly patients with obstructive sleep apnea. *Front Cardiovasc Med*. 2021;**8**:813280. https://doi.org/10.3389/fcvm.2021.813280
37. Mota PC, Drummond M, Winck JC, Santos AC, Almeida J, Marques JA. APAP impact on metabolic syndrome in obstructive sleep apnea patients. *Sleep Breath*. 2011;**15**(4):665–672. https://doi.org/10.1007/s11325-010-0417-5
38. Xu S, Wan Y, Xu M, *et al*. The association between obstructive sleep apnea and metabolic syndrome: a systematic review and meta-analysis. *BMC Pulm Med*. 2015;**15**(1):105. https://doi.org/10.1186/s12890-015-0102-3
39. Qian Y, Xu H, Wang Y, Yi H, Guan J, Yin S. Obstructive sleep apnea predicts risk of metabolic syndrome independently of obesity: a meta-analysis. *Arch Med Sci*. 2016;**5**(5):1077–1087. https://doi.org/10.5114/aoms.2016.61914
40. Higgins J, Thomas J, Chandler J, *et al*. *Cochrane Handbook for Systematic Reviews of Interventions version 6.5 (updated August 2024)*. Hoboken, NJ, USA: John Wiley & Sons. Updated August 2024. https://www.cochrane.org/authors/handbooks-and-manuals/handbook/current.
41. Page MJ, McKenzie JE, Bossuyt PM, *et al*. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*. 2021;**372**:n71. https://doi.org/10.1136/bmj.n71
42. Morgan RL, Whaley P, Thayer KA, Schünemann HJ. Identifying the PECO: a framework for formulating good questions to explore the association of environmental and other exposures with health outcomes. *Environ Int*. 2018;**121**(Pt 1):1027–1031. https://doi.org/10.1016/j.envint.2018.07.015
43. Covidence systematic review software. Veritas Health Innovation Ltd; Melbourne, Australia; 2025. Available from: https://support.covidence.org/
44. Haddaway NR, Grainger MJ, Gray CT. citationchaser: An R package and Shiny app for forward and backward

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citations chasing in academic searching. 2021. https://doi.org/10.5281/zenodo.4543513. Available from: https://github.com/nealhaddaway/citationchaser
45. Kim SY, Park JE, Lee YJ, *et al.* Testing a tool for assessing the risk of bias for nonrandomized studies showed moderate reliability and promising validity. *J Clin Epidemiol*. 2013;**66**(4):408–414. https://doi.org/10.1016/j.jclinepi.2012.09.016
46. Konstantopoulos S. Fixed effects and variance components estimation in three-level meta-analysis. *Res Synth Methods*. 2011;**2**(1):61–76. https://doi.org/10.1002/jrsm.35
47. Cheung MW. Modeling dependent effect sizes with three-level meta-analyses: a structural equation modeling approach. *Psychol Methods*. 2014;**19**(2):211–229. https://doi.org/10.1037/a0032968
48. Viechtbauer W. Conducting meta-analyses in R with the metafor package. *J Stat Softw*. 2010;**36**(3):1–48. https://doi.org/10.18637/jss.v036.i03
49. Department of Economic and Social Affairs, Statistics Division, United Nations. *Methodology: Standard country or area codes for statistical use (M49)*. New York, NY: United Nations. Accessed October 11, 2025. Available from: https://unstats.un.org/unsd/methodology/m49/
50. Wan X, Wang W, Liu J, Tong T. Estimating the sample mean and standard deviation from the sample size, median, range and/or interquartile range. *BMC Med Res Methodol*. 2014;**14**(1):135. https://doi.org/10.1186/1471-2288-14-135
51. Luo D, Wan X, Liu J, Tong T. Optimally estimating the sample mean from the sample size, median, mid-range, and/or mid-quartile range. *Stat Methods Med Res*. 2018;**27**(6):1785–1805. https://doi.org/10.1177/0962280216669183
52. Baujat B, Mahé C, Pignon J-P, Hill C. A graphical method for exploring heterogeneity in meta-analyses: application to a meta-analysis of 65 trials. *Stat Med*. 2002;**21**(18):2641–2652. https://doi.org/10.1002/sim.1221
53. Viechtbauer W, Cheung MW-L. Outlier and influence diagnostics for meta-analysis. *Res Synth Methods*. 2010;**1**(2):112–125. https://doi.org/10.1002/jrsm.11
54. Sterne JAC, Sutton AJ, Ioannidis JPA, *et al.* Recommendations for examining and interpreting funnel plot asymmetry in meta-analyses of randomised controlled trials. *BMJ*. 2011;**343**:d4002. https://doi.org/10.1136/bmj.d4002
55. Borenstein M, Hedges LV, Higgins JPT, Rothstein HR. *Introduction to Meta-Analysis*. Chichester, UK: John Wiley & Sons; 2009. https://doi.org/10.1002/9780470743386
56. Balduzzi S, Rücker G, Schwarzer G. How to perform a meta-analysis with R: a practical tutorial. *Evid Based Ment Health*. 2019;**22**(4):153–160. https://doi.org/10.1136/ebmental-2019-300117
57. Assink M, Wibbelink CJM. Fitting three-level meta-analytic models in R: a step-by-step tutorial. *Quant Method Psychol*. 2016;**12**(3):154–174. https://doi.org/10.20982/tqmp.12.3.p154
58. Wang N. Conducting meta-analyses of proportions in R. *J Behav Data Sci*. 2023;**3**:1–62. https://doi.org/10.35566/jbds/v3n2/wang
59. Prakasa K, Ahmed J, Hasan S, Yousef M, Shridharani S. Electrocardiographic changes in obstructive sleep apnea syndrome. *Mo Med*. 2005;**102**(6):555–559.
60. Zhang XL, Yin K-S, Wang H, Jia EZ, Yang Y. Changes of human parameters in patients with obstructive sleep apnea hypopnea and metabolic syndrome. 2005;**9**:92–95.
61. Adar A, Onalan O, Casim H, *et al.* A strong clue on chest radiography for metabolic syndrome in patients with obstructive sleep apnea: aortic arch calcification. *Duzce Medical Journal*. 2019;**21**(2):72–78. https://doi.org/10.18678/dtfd.534927
62. Agrawal S, Sharma SK, Sreenivas V, Lakshmy R. Prevalence of metabolic syndrome in a North Indian hospital-based population with obstructive sleep apnoea. *Indian J Med Res*. 2011;**134**(5):639–644. https://doi.org/10.4103/0971-5916.90988
63. Ahbab S, Ataoglu HE, Tuna M, *et al.* Neck circumference, metabolic syndrome and obstructive sleep apnea syndrome; evaluation of possible linkage. *Med Sci Monit*. 2013;**19**:111–117. https://doi.org/10.12659/MSM.883776
64. Akahoshi T, Uematsu A, Akashiba T, *et al.* Obstructive sleep apnoea is associated with risk factors comprising the metabolic syndrome. *Respirology*. 2010;**15**(7):1122–1126. https://doi.org/10.1111/j.1440-1843.2010.01818.x
65. Akbal E, Oktay Arslan B, Firat H, Mustafa Ö, Ardiç S, Murat K. Long oxygen desaturation time is a risk factor for metabolic syndrome. *Turk J Endocrinol Metab*. 2008;**12**:63–67.
66. Aksu O, Aydln B, Doguc DK, *et al.* The evaluation of Nesfatin-1 levels in patients with OSAS associated with metabolic syndrome. *J Endocrinol Invest*. 2015;**38**(4):463–469. https://doi.org/10.1007/s40618-014-0216-0
67. Angelico F, del Ben M, Augelletti T, *et al.* Obstructive sleep apnoea syndrome and the metabolic syndrome in an internal medicine setting. *Eur J Intern Med*. 2010;**21**(3):191–195. https://doi.org/10.1016/j.ejim.2010.03.006
68. Apaydin M, Ayik SO, Akhan G, Peker S, Uluc E. Carotid intima-media thickness increase in patients with habitual simple snoring and obstructive sleep apnea syndrome is associated with metabolic syndrome. *J Clin Ultrasound*. 2013;**41**(5):290–296. https://doi.org/10.1002/jcu.22040
69. Archontogeorgis K, Nena E, Papanas N, *et al.* Metabolic syndrome and vitamin D levels in patients with obstructive sleep apnea syndrome. *Metab Syndr Relat Disord*. 2018;**16**(4):190–196. https://doi.org/10.1089/met.2017.0181
70. Archontogeorgis K, Voulgaris A, Papanas N, *et al.* Metabolic syndrome in patients with coexistent obstructive sleep apnea syndrome and chronic obstructive pulmonary disease (overlap syndrome). *Metab Syndr Relat Disord*. 2020;**18**(6):296–301. https://doi.org/10.1089/met.2019.0126
71. Baburao A, Babu A, Pandey A, Narayanswamy H. Syndrome Z: its response to CPAP therapy. *Indian J Chest Dis Allied Sci*. 2022;**64**(2):68–72. https://doi.org/10.5005/jp-journals-11007-0012
72. Banawan LAH, Daabis R, Elsheikh WH, Tolba MM, Youssef AM. The prevalence of helicobacter pylori infection in patients with obstructive sleep apnea having metabolic syndrome and its relation to both disorders. *Egypt J Bronchol*. 2017;**11**(3):268–275. https://doi.org/10.4103/ejb.ejb_54_16
73. Barcelo A, Esquinas C, Robles J, *et al.* Gut epithelial barrier markers in patients with obstructive sleep apnea. *Sleep Med*. 2016;**26**:12EP–15EP. https://doi.org/10.1016/j.sleep.2016.01.019
74. Barcelo A, Pierola J, De La Pena M, *et al.* Free fatty acids and the metabolic syndrome in patients with obstructive sleep apnoea. *Eur Respir J*. 2011;**37**(6):1418–1423. https://doi.org/10.1183/09031936.00050410
75. Barreiro B, Garcia L, Lozano L, *et al.* Obstructive sleep apnea and metabolic syndrome in Spanish population. *Open Respir. Med. J*. 2013;**7**:71–76. https://doi.org/10.2174/1874306401307010071
76. Basoglu OK, Sarac F, Sarac S, Uluer H, Yilmaz C. Metabolic syndrome, insulin resistance, fibrinogen, homocysteine, leptin, and C-reactive protein in obese patients with obstructive sleep apnea syndrome. *Ann Thorac Med*. 2011;**6**(3):120–125. https://doi.org/10.4103/1817-1737.82440
77. Bhushan B, Misra A, Guleria R. Obstructive sleep apnea is independently associated with the metabolic syndrome in

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obese Asian Indians in northern India. *Metab Syndr Relat Disord*. 2010;**8**(5):431–435. https://doi.org/10.1089/met.2009.0125
78. Bingol Z, Karaayvaz EB, Telci A, Bilge AK, Okumus G, Kiyan E. Leptin and adiponectin levels in obstructive sleep apnea phenotypes. *Biomark Med*. 2019;**13**(10):865–874. https://doi.org/10.2217/bmm-2018-0293
79. Bonsignore MR, Esquinas C, Barcelo A, *et al*. Metabolic syndrome, insulin resistance and sleepiness in real-life obstructive sleep apnoea. *Eur Respir J*. 2012;**39**(5):1136–1143. https://doi.org/10.1183/09031936.00151110
80. Bozkurt NC, Beysel S, Karbek B, Unsal IO, Cakir E, Delibasi T. Visceral obesity mediates the association between metabolic syndrome and obstructive sleep apnea syndrome. *Metab Syndr Relat Disord*. 2016;**14**(4):217–221. https://doi.org/10.1089/met.2015.0086
81. Breuer HWM. Hypertension, metabolic syndrome, prediabetes, and diabetes associated with obstructive sleep apnea syndrome. The Gorlitz Metabolic Study. *Somnologie*. 2011;**15**(1):14–23. https://doi.org/10.1007/s11818-011-0503-3
82. Chaudhary P, Goyal A, Goel SK, *et al*. Women with OSA have higher chances of having metabolic syndrome than men: effect of gender on syndrome Z in cross sectional study. *Sleep Med*. 2021;**79**:83EP–87EP. https://doi.org/10.1016/j.sleep.2020.12.042
83. Chen GP, Qi JC, Wang BY, *et al*. Applicability of visceral adiposity index in predicting metabolic syndrome in adults with obstructive sleep apnea: a cross-sectional study. *BMC Pulm Med*. 2016;**16**(1):37. https://doi.org/10.1186/s12890-016-0198-0
84. Coughlin SR, Mawdsley L, Mugarza JA, Calverley PMA, Wilding JPH. Obstructive sleep apnoea is independently associated with an increased prevalence of metabolic syndrome. *Eur Heart J*. 2004;**25**(9):735–741. https://doi.org/10.1016/j.ehj.2004.02.021
85. Coughlin SR, Mawdsley L, Mugarza JA, Wilding JPH, Calverley PMA. Cardiovascular and metabolic effects of CPAP in obese males with OSA. *Eur Respir J*. 2007;**29**(4):720–727. https://doi.org/10.1183/09031936.00043306
86. Desplan M, Mercier J, Sabate M, Ninot G, Prefaut C, Dauvilliers Y. A comprehensive rehabilitation program improves disease severity in patients with obstructive sleep apnea syndrome: a pilot randomized controlled study. *Sleep Med*. 2014;**15**(8):906–912. https://doi.org/10.1016/j.sleep.2013.09.023
87. Dobrowolski P, Kołodziejczyk-Kruk S, Warchoł-Celińska E, *et al*. Primary aldosteronism is highly prevalent in patients with hypertension and moderate to severe obstructive sleep apnea. *J Clin Sleep Med*. 2021;**17**(4):629–637. https://doi.org/10.5664/jcsm.8960
88. Domagala-Kulawik J, Osinska I, Piechuta A, Bielicki P, Skirecki T. T, B, and NKT cells in systemic inflammation in obstructive sleep apnoea. *Mediators Inflamm*. 2015;**2015**(1):161579. https://doi.org/10.1155/2015/161579
89. Drager LF, Genta PR, Pedrosa RP, *et al*. Characteristics and predictors of obstructive sleep apnea in patients with systemic hypertension. *Am J Cardiol*. 2010;**105**(8):1135–1139. https://doi.org/10.1016/j.amjcard.2009.12.017
90. Du J, Chen B, Chen L, *et al*. High arousal threshold is associated with metabolic syndrome in patients with obstructive sleep apnea. *Respir Med*. 2024;**234**:107837. https://doi.org/10.1016/j.rmed.2024.107837
91. Dursunoglu N, Dursunoglu D, Ozkurt S, Kiter G, Evyapan F. Gender differences in global cardiovascular risk factors of obstructive sleep apnea patients. *Tuberk Toraks*. 2006;**54**(4):305–314.
92. Florczak E, Prejbisz A, Szwench-Pietrasz E, *et al*. Clinical characteristics of patients with resistant hypertension: the RESIST-POL study. *J Hum Hypertens*. 2013;**27**(11):678–685. https://doi.org/10.1038/jhh.2013.32
93. Fu Y, Xu H, Xia Y, *et al*. Excessive daytime sleepiness and metabolic syndrome in men with obstructive sleep apnea: a large cross-sectional study. *Oncotarget*. 2017;**8**(45):79693–79702. https://doi.org/10.18632/oncotarget.19113
94. Gasa M, Salord N, Fortuna AM, *et al*. Obstructive sleep apnoea and metabolic impairment in severe obesity. *Eur Respir J*. 2011;**38**(5):1089–1097. https://doi.org/10.1183/09031936.00198810
95. Georgoulis M, Yiannakouris N, Kechribari I, *et al*. Cardiometabolic benefits of a weight-loss Mediterranean diet/lifestyle intervention in patients with obstructive sleep apnea: the "MIMOSA" randomized clinical trial. *Nutrients*. 2020;**12**(6):1570. https://doi.org/10.3390/nu12061570
96. Gu M, Huang W, Li X, *et al*. Association of hypertriglyceridemic waist phenotype with obstructive sleep apnea: a cross-sectional study. *Nat Sci Sleep*. 2021;**13**:2165–2173. https://doi.org/10.2147/nss.s335288
97. Hermans MP, Ahn SA, Mahadeb YP, Rousseau MF. Sleep apnoea syndrome and 10-year cardiovascular risk in females with type 2 diabetes: relationship with insulin secretion and insulin resistance. *Diabetes Metab Res Rev*. 2013;**29**(3):227–234. https://doi.org/10.1002/dmrr.2387
98. Hermans MP, Ahn SA, Rousseau MF. Cardiometabolic phenotype and UKPDS risk in male type 2 diabetic patients with obstructive sleep apnoea. *Diabetes Metab Syndr*. 2009;**3**(1):50–54. https://doi.org/10.1016/j.dsx.2008.10.011
99. Hermans MP, Mahadeb YP, Katchunga P, Cikomola Cirhuza J, Ahn SA, Rousseau MF. Novel sexual dimorphisms of sleep apnea syndrome in diabetes. *Diabetes Metab Syndr*. 2014;**8**(1):36–44. https://doi.org/10.1016/j.dsx.2013.08.002
100. Huang J, Chen L-D, Lin Q, *et al*. The relationship between excessive daytime sleepiness and metabolic syndrome in severe obstructive sleep apnea syndrome. *Clin Respir J*. 2015;**10**(6):714–721. https://doi.org/10.1111/crj.12276
101. Incalzi RA, Pennazza G, Scarlata S, *et al*. Comorbidity modulates non invasive ventilation-induced changes in breath print of obstructive sleep apnea syndrome patients. *Sleep Breath*. 2014;**19**(2):623–630. https://doi.org/10.1007/s11325-014-1065-y
102. Iren C, Árpád S, Reka S, Adriana N. The metabolic syndrome and its correlations with the obstructive sleep apnea syndrome. *Indian J Appl Res*. 2011;**3**(8):50–52. https://doi.org/10.15373/2249555x/aug2013/179
103. Izumi S, Ribeiro FF, Carneiro G, Togeiro SM, Tufik S, Zanella MT. IGF-1 levels are inversely associated with metabolic syndrome in obstructive sleep apnea. *J Clin Sleep Med*. 2016;**12**(4):487–493. https://doi.org/10.5664/jcsm.5672
104. Joshi HS, Arjun P, Matthewa T. Relationship of obstructive sleep apnoea and metabolic syndrome: a study in a south Indian population. *Indian J Sleep Med*. 2016;**11**(1):20–29. https://doi.org/10.5958/0974-0155.2016.00005.x
105. Kaddah SZ, Korany MH, Ibrahim EK. Clinical features and predictors of metabolic syndrome among obstructive sleep apnea patients. *Egypt J Bronchol*. 2024;**18**(1):6. https://doi.org/10.1186/s43168-024-00259-0
106. Kanbay A, Ciftci TU, Kokturk O. Could obstructive sleep apnea syndrome be a component of metabolic syndrome? *Turk J Med Sci*. 2009;**39**(2):161–166. https://doi.org/10.3906/sag-0809-39
107. Kawaguchi Y, Fukumoto S, Inaba M, *et al*. Different impacts of neck circumference and visceral obesity on the severity

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of obstructive sleep apnea syndrome. *Obesity (Silver Spring)*. 2010;**19**(2):276–282. https://doi.org/10.1038/oby.2010.170
108. Kim J, Yoon DW, Lee SK, *et al.* Concurrent presence of inflammation and obstructive sleep apnea exacerbates the risk of metabolic syndrome: a KoGES 6-year follow-up study. *Medicine (Baltimore)*. 2017;**96**(7):e4488. https://doi.org/10.1097/MD.0000000000004488
109. Koo DL, Kim HR, Nam H. Moderate to severe obstructive sleep apnea during REM sleep as a predictor of metabolic syndrome in a Korean population. *Sleep Breath*. 2020;**24**(4):1751–1758. https://doi.org/10.1007/s11325-019-02005-z
110. Kraiwattanapong J, Rattanaarun K, Cunteerasup A, Papassornsiri T, Balankura T, Pavarajarn S. Clinical characteristics and treatment preferences of obstructive sleep apnea. *Sci Rep*. 2025;**15**(1):18976. https://doi.org/10.1038/s41598-025-03816-9
111. Lee GS, Lee LA, Wang CY, *et al.* The frequency and energy of snoring sounds are associated with common carotid artery intima-media thickness in obstructive sleep apnea patients. *Sci Rep*. 2016;**6**(1):30559. https://doi.org/10.1038/srep30559
112. Lee YJ, Jang HR, Huh W, *et al.* Independent contributions of obstructive sleep apnea and the metabolic syndrome to the risk of chronic kidney disease. *J Clin Sleep Med*. 2017;**13**(10):1145–1152. https://doi.org/10.5664/jcsm.6758
113. Li X, Fu Z, Xu H, *et al.* Influence of multiple apolipoprotein A-I and B genetic variations on insulin resistance and metabolic syndrome in obstructive sleep apnea. *Nutr Metab*. 2020;**17**(1):83. https://doi.org/10.1186/s12986-020-00501-8
114. Lubrano C, Saponara M, Barbaro G, *et al.* Relationships between body fat distribution, epicardial fat and obstructive sleep apnea in obese patients with and without metabolic syndrome. *PLoS One*. 2012;**7**(10):e47059. https://doi.org/10.1371/journal.pone.0047059
115. Makino S, Fujiwara M, Suzukawa K, *et al.* Visceral obesity is associated with the metabolic syndrome and elevated plasma retinol binding protein-4 level in obstructive sleep apnea syndrome. *Horm Metab Res*. 2009;**41**(3):221–226. https://doi.org/10.1055/s-0028-1100411
116. Mano M, Nomura A, Hori R, Sasanabe R. Association between rapid eye movement obstructive sleep apnea and metabolic syndrome in a Japanese population. *Intern Med*. 2023;**62**(13):1907–1913. https://doi.org/10.2169/internalmedicine.0336-22
117. Mariani S, Fiore D, Barbaro G, *et al.* Association of epicardial fat thickness with the severity of obstructive sleep apnea in obese patients. *Int J Cardiol*. 2013;**167**(5):2244–2249. https://doi.org/10.1016/j.ijcard.2012.06.011
118. Mazzuca E, Battaglia S, Marrone O, *et al.* Gender-specific anthropometric markers of adiposity, metabolic syndrome and visceral adiposity index (VAI) in patients with obstructive sleep apnea. *J Sleep Res*. 2014;**23**(1):13–21. https://doi.org/10.1111/jsr.12088
119. McArdle N, Hillman DR, Beilin L, Watts GF. Metabolic risk factors for vascular disease in obstructive sleep apnea: a matched controlled study. *Am J Respir Crit Care Med*. 2006;**175**(2):190–195. https://doi.org/10.1164/rccm.200602-270oc
120. Murase K, Mori K, Yoshimura C, *et al.* Association between plasma neutrophil gelatinase associated lipocalin level and obstructive sleep apnea or nocturnal intermittent hypoxia. *PLoS One*. 2013;**8**(1):e54184. https://doi.org/10.1371/journal.pone.0054184
121. Nakanishi-Minami T, Kishida K, Nakagawa Y, *et al.* Metabolic syndrome correlates intracoronary stenosis detected by multislice computed tomography in male subjects with sleep-disordered breathing. *Diabetol Metab Syndr*. 2012;**4**(1):6. https://doi.org/10.1186/1758-5996-4-6
122. Nerfeldt P, Nilsson BY, Mayor L, Uddén J, Rössner S, Friberg D. Weight reduction improves sleep, sleepiness and metabolic status in obese sleep apnoea patients. *Obes Res Clin Pract*. 2008;**2**(4):251–262. https://doi.org/10.1016/j.orcp.2008.08.001
123. Ozol D, Turkay C, Kasapoglu B, Karamanli H, Yildirim Z. Relationship between components of metabolic syndrome and polysomnographic findings in obstructive sleep apnea. *Metab Syndr Relat Disord*. 2011;**9**(1):13–18. https://doi.org/10.1089/met.2010.0033
124. Papanas N, Steiropoulos P, Nena E, *et al.* Predictors of obstructive sleep apnea in males with metabolic syndrome. *Vasc Health Risk Manag*. 2010;**6**(1):281–286. https://doi.org/10.2147/VHRM.S7948
125. Parish JM, Adam T, Facchiano L. Relationship of metabolic syndrome and obstructive sleep apnea. *J Clin Sleep Med*. 2007;**3**(5):467–472. https://doi.org/10.5664/jcsm.26910
126. Pedrosa RP, Drager LF, Gonzaga CC, *et al.* Obstructive sleep apnea: the most common secondary cause of hypertension associated with resistant hypertension. *Hypertension*. 2011;**58**(5):811–817. https://doi.org/10.1161/hypertensionaha.111.179788
127. Peled N, Kassirer M, Shitrit D, *et al.* The association of OSA with insulin resistance, inflammation and metabolic syndrome. *Respir Med*. 2007;**101**(8):1696–1701. https://doi.org/10.1016/j.rmed.2007.02.025
128. Peng Y, Shen H, Li C, *et al.* Genetic variations of low-density lipoprotein cholesterol on metabolic disorders in obstructive sleep apnea. *Nutr Metab*. 2024;**21**(1):31. https://doi.org/10.1186/s12986-024-00805-z
129. Pilkauskaite G, Miliauskas S, Vitkauskiene A, Sakalauskas R. Vascular adhesion molecules in men with obstructive sleep apnea: associations with obesity and metabolic syndrome. *Sleep Breath*. 2014;**18**(4):869–874. https://doi.org/10.1007/s11325-014-0958-0
130. Prejbisz A, Florczak E, Klisiewicz A, *et al.* Relationship between primary aldosteronism and obstructive sleep apnoea, metabolic abnormalities and cardiac structure in patients with resistant hypertension. *Endokrynol Pol*. 2013;**64**(5):363–367. https://doi.org/10.5603/EP.2013.0019
131. Qamar A, Baig MS, Saifullah N. Obstructive sleep apnea and metabolic syndrome; causal association or co-existence? *Med Forum*. 2017;**28**(4):188–192.
132. Sachdev SS, Suri JC, Jain AK, Khalid A, Isser HS, Mittal MK. Cardiovascular morbidity in subjects with obstructive sleep apnea and its correlation with the severity of disease. *Indian J Sleep Med*. 2009;**4**(2):49–60. https://doi.org/10.5005/ijsm-4-2-49
133. Salord N, Fortuna AM, Monasterio C, *et al.* A randomized controlled trial of continuous positive airway pressure on glucose tolerance in obese patients with obstructive sleep apnea. *Sleep*. 2016;**39**(1):35–41. https://doi.org/10.5665/sleep.5312
134. Sasanabe R, Banno K, Otake K, *et al.* Metabolic syndrome in Japanese patients with obstructive sleep apnea syndrome. *Hypertens Res*. 2006;**29**(5):315–322. https://doi.org/10.1291/hypres.29.315
135. Seetho IW, Parker RJ, Craig S, Duffy N, Hardy KJ, Wilding JPH. Obstructive sleep apnea is associated with increased arterial stiffness in severe obesity. *J Sleep Res*. 2014;**23**(6):700–708. https://doi.org/10.1111/jsr.12156
136. Seetho IW, Ramirez-Torres A, Albalat A, *et al.* Urinary proteomic profiling in severe obesity and obstructive sleep apnoea

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with CPAP treatment. *Sleep Sc.* 2015;**8**(2):58–67. https://doi.org/10.1016/j.slsci.2015.06.004
137. Seetho IW, Siwy J, Albalat A, *et al.* Urinary proteomics in obstructive sleep apnoea and obesity. *Eur J Clin Invest*. 2014;**44**(11):1104–1115. https://doi.org/10.1111/eci.12346
138. Sharma SK, Reddy EV, Sharma A, *et al.* Prevalence and risk factors of syndrome Z in urban Indians. *Sleep Med*. 2010;**11**(6):562–568. https://doi.org/10.1016/j.sleep.2010.02.008
139. Shina K, Tomiyama H, Takata Y, *et al.* Concurrent presence of metabolic syndrome in obstructive sleep apnea syndrome exacerbates the cardiovascular risk: a sleep clinic cohort study. *Hypertens Res*. 2006;**29**(6):433–441. https://doi.org/10.1291/hypres.29.433
140. Silva LOE, Guimaraes TM, Luz GP, *et al.* Metabolic profile in patients with mild obstructive sleep apnea. *Metab Syndr Relat Disord*. 2018;**16**(1):6–12. https://doi.org/10.1089/met.2017.0075
141. Singh SK, Tentu AK, Singh S, *et al.* Association of metabolic syndrome in obstructive sleep apnea patients: an experience from zonal tertiary care hospital in eastern India. *Indian J Respir Care*. 2020;**9**(1):71–76. https://doi.org/10.4103/ijrc.ijrc_36_19
142. Solelhac G, Wachinou AP, Goyal A, *et al.* Prevalence and clinical significance of comorbid insomnia and sleep apnea (COMISA) in three population-based cohorts from Benin, Switzerland and India. *Sleep Med*. 2025;**131**:106526. https://doi.org/10.1016/j.sleep.2025.106526
143. Srivastava GN, Jain A, Suresh A, *et al.* Anthropometric indices and obstructive sleep apnea severity in syndrome Z. *Indian J Sleep Med*. 2022;**17**(1):10–14. https://doi.org/10.5005/jp-journals-10069-0093
144. Tancic-Gajic M, Vukcevic M, Ivovic M, *et al.* Obstructive sleep apnea is associated with low testosterone levels in severely obese men. *Front Endocrinol*. 2021;**12**:622496. https://doi.org/10.3389/fendo.2021.622496
145. Tkacova R, Dorkova Z, Molcanyiova A, Radikova Z, Klimes I, Tkac I. Cardiovascular risk and insulin resistance in patients with obstructive sleep apnea. *Med Sci Monit*. 2008;**14**(9):CR438–CR444.
146. Usui Y, Takata Y, Inoue Y, *et al.* Coexistence of obstructive sleep apnoea and metabolic syndrome is independently associated with left ventricular hypertrophy and diastolic dysfunction. *Sleep Breath*. 2011;**16**(3):677–684. https://doi.org/10.1007/s11325-011-0557-2
147. Utriainen KT, Airaksinen JK, Polo O, *et al.* Unrecognised obstructive sleep apnoea is common in severe peripheral arterial disease. *Eur Respir J*. 2013;**41**(3):616–620. https://doi.org/10.1183/09031936.00227611
148. Uyar M, Davutoglu V, Aydin N, Filiz A. Comparison of metabolic syndrome with growing epidemic syndrome Z in terms of risk factors and gender differences. *Sleep Breath*. 2013;**17**(2):647–651. https://doi.org/10.1007/s11325-012-0737-8
149. Vekic J, Joppa P, Habalova V, *et al.* Relationship between the apolipoprotein E genotype and LDL particle size in patients with obstructive sleep apnea. *Angiology*. 2016;**67**(10):937–944. https://doi.org/10.1177/0003319716636512
150. Wang D, Chen Y, Ding Y, *et al.* Application value of cardiometabolic index for the screening of obstructive sleep apnea with or without metabolic syndrome. *Nat Sci Sleep*. 2024;**16**:177–191. https://doi.org/10.2147/NSS.S449862
151. Wu WT, Tsai SS, Shih TS, *et al.* The association between obstructive sleep apnea and metabolic markers and lipid profiles. *PLoS One*. 2015;**10**(6):e0130279. https://doi.org/10.1371/journal.pone.0130279
152. Zhang Q, Zhao M, Huang H, Ding N, Zhang X, Wang H. Correlation of obstructive sleep apnea hypopnea syndrome with metabolic syndrome in snorers. *J Biomed Res*. 2014;**28**(3):222–227. https://doi.org/10.7555/JBR.28.20120120
153. Zhang XL, Zhang L, Li YM, *et al.* Multidimensional assessment and cluster analysis for OSA phenotyping. *J Clin Sleep Med*. 2022;**18**(7):1779–1788. https://doi.org/10.5664/jcsm.9976
154. Zhao X, Li X, Xu H, *et al.* Relationships between cardiometabolic disorders and obstructive sleep apnea: implications for cardiovascular disease risk. *J Clin Hypertens*. 2019;**21**(2):280–290. https://doi.org/10.1111/jch.13473
155. Zhou W, Li CL, Cao J, Feng J. Metabolic syndrome prevalence in patients with obstructive sleep apnea syndrome and chronic obstructive pulmonary disease: relationship with systemic inflammation. *Clin Respir J*. 2020;**14**(12):1159–1165. https://doi.org/10.1111/crj.13253
156. Theorell-Haglöw J, Berne C, Janson C, Lindberg E. The role of obstructive sleep apnea in metabolic syndrome: a population-based study in women. *Sleep Med*. 2011;**12**(4):329–334. https://doi.org/10.1016/j.sleep.2010.06.014
157. Metabolic Syndrome Diagnostic Criteria Review Committee. Definition and the diagnostic standard for metabolic syndrome: Committee to Evaluate Diagnostic Standards for Metabolic Syndrome. *Nippon Naika Gakkai Zasshi*. 2005;**94**(4):794–809. https://doi.org/10.2169/naika.94.794
158. QGIS Development Team. QGIS geographic information system. Beaverton, OR: Open Source Geospatial Foundation (OSGeo); 2025. Available from: https://qgis.org/download/
159. Migliavaca CB, Stein C, Colpani V, *et al.* Meta-analysis of prevalence: I^2 statistic and how to deal with heterogeneity. *Res Synth Methods*. 2022;**13**(3):363–367. https://doi.org/10.1002/jrsm.1547
160. Noubiap JJ, Nansseu JR, Lontchi-Yimagou E, *et al.* Geographic distribution of metabolic syndrome and its components in the general adult population: a meta-analysis of global data from 28 million individuals. *Diabetes Res Clin Pract*. 2022;**188**:109924. https://doi.org/10.1016/j.diabres.2022.109924
161. Shungin D, Winkler TW, Croteau-Chonka DC, *et al.* New genetic loci link adipose and insulin biology to body fat distribution. *Nature*. 2015;**518**(7538):187–196. https://doi.org/10.1038/nature14132
162. Loos RJF, Yeo GSH. The genetics of obesity: from discovery to biology. *Nat Rev Genet*. 2022;**23**(2):120–133. https://doi.org/10.1038/s41576-021-00414-z
163. Pomeroy E, Mushrif-Tripathy V, Cole TJ, Wells JCK, Stock JT. Ancient origins of low lean mass among south Asians and implications for modern type 2 diabetes susceptibility. *Sci Rep*. 2019;**9**(1):10515. https://doi.org/10.1038/s41598-019-46960-9
164. Moore SC, Gunter MJ, Daniel CR, *et al.* Common genetic variants and central adiposity among Asian-Indians. *Obesity (Silver Spring)*. 2012;**20**(9):1902–1908. https://doi.org/10.1038/oby.2011.238
165. Guthold R, Stevens GA, Riley LM, Bull FC. Worldwide trends in insufficient physical activity from 2001 to 2016: a pooled analysis of 358 population-based surveys with 1·9 million participants. *Lancet Glob Health*. 2018;**6**(10):e1077–e1086. https://doi.org/10.1016/s2214-109x(18)30357-7
166. Imamura F, Micha R, Khatibzadeh S, *et al.* Dietary quality among men and women in 187 countries in 1990 and 2010: a systematic assessment. *Lancet Glob Health*. 2015;**3**(3):e132–e142. https://doi.org/10.1016/s2214-109x(14)70381-x
167. Rothman KJ, Greenland S, Lash TL. *Modern Epidemiology*. 3rd Edition. 3rd ed. Philadelphia, PA: Lippincoott Williams & Wilkins; 2008.

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168. Salas C, Dreyse J, Contreras A, *et al*. Differences in patients derived from otolaryngology and other specialties with sleep apnea. *J Otolaryngol Head Neck Surg*. 2019;**48**(1):53. https://doi.org/10.1186/s40463-019-0373-4
169. Ngowi WS, Mandizadza OO, Wang M, Shao WT, Ji C. Prevalence of tuberculosis among people who use drugs 2000-2024: a systematic review and meta-analysis. *Front Public Health*. 2025;**13**:1635053. https://doi.org/10.3389/fpubh.2025.1635053
170. Dy LF, Lintao RCV, Cordero CP, Cabaluna ITG, Dans LF. Prevalence and prognostic associations of cardiac abnormalities among hospitalized patients with COVID-19: a systematic review and meta-analysis. *Sci Rep*. 2021;**11**(1):8449. https://doi.org/10.1038/s41598-021-87961-x
171. DECODA Study Group. Prevalence of the metabolic syndrome in populations of Asian origin. Comparison of the IDF definition with the NCEP definition. *Diabetes Res Clin Pract*. 2007;**76**(1):57–67. https://doi.org/10.1016/j.diabres.2006.07.020
172. Huang Y, Chen Z, Wang X, *et al*. Comparison of the three most commonly used metabolic syndrome definitions in the Chinese population: a prospective study. *Metabolites*. 2022;**13**(1):12. https://doi.org/10.3390/metabo13010012
173. Drager LF, Togeiro SM, Polotsky VY, Lorenzi-Filho G. Obstructive sleep apnea: a cardiometabolic risk in obesity and the metabolic syndrome. *J Am Coll Cardiol*. 2013;**62**(7):569–576. https://doi.org/10.1016/j.jacc.2013.05.045
174. Peppard PE, Young T, Palta M, Dempsey J, Skatrud J. Longitudinal study of moderate weight change and sleep-disordered breathing. *JAMA*. 2000;**284**(23):3015–3021. https://doi.org/10.1001/jama.284.23.3015
175. Hirode G, Wong RJ. Trends in the prevalence of metabolic syndrome in the United States, 2011-2016. *JAMA*. 2020;**323**(24):2526–2528. https://doi.org/10.1001/jama.2020.4501
176. Lu Y, Li X, Liu Y, *et al*. Trends in prevalence, treatment, and relationship of metabolic syndrome and individual components by race/ethnicity, 1999-2018. *JACC Adv* 2025;**4**(6 Pt 1):101785. https://doi.org/10.1016/j.jacadv.2025.101785
177. Zhong H, Ni X, Chen R, Hou X. Smoking contribution to the global burden of metabolic disorder: a cluster analysis. *Med Clin*. 2024;**163**(1):14–20. https://doi.org/10.1016/j.medcli.2024.02.001
178. Kim SW, Kim HJ, Min K, *et al*. The relationship between smoking cigarettes and metabolic syndrome: a cross-sectional study with non-single residents of Seoul under 40 years old. *PLoS One*. 2021;**16**(8):e0256257. https://doi.org/10.1371/journal.pone.0256257
179. Galván B, Enriquez Del Castillo LA, Flores LA, *et al*. Effectiveness of physical exercise on indicators of metabolic syndrome in adults: a systematic review with meta-analysis of clinical trials. *J Funct Morphol Kinesiol*. 2025;**10**(3):244. https://doi.org/10.3390/jfmk10030244
180. Farahmand M, Ramezani Tehrani F, Bahri Khomami M, Noroozzadeh M, Azizi F. Surgical menopause versus natural menopause and cardio-metabolic disturbances: a 12-year population-based cohort study. *J Endocrinol Invest*. 2015;**38**(7):761–767. https://doi.org/10.1007/s40618-015-0253-3

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