# INVESTIGATING THE RELATIONSHIP BETWEEN SLEEP APNEA AND UPPER AIRWAY MALFORMATIONS: CLINICAL AND RADIOLOGICAL INSIGHTS: A SYSTEMATIC REVIEW AND META-ANALYSIS

**Atef Eid Madkour Elsayed[1], Anas Mohammed Abudasir[2*], Turki Nasser Abo Sarhad[2], Lena A. Almathami[3], Turki Khalid Alahmari[2], Mohammed Abdulrahman Al-Sultan[2], Bushra Abdulrahman Alsaluli[2], Ali Yahya Ali Alhayani[2], Abdulelah Mofareh Alqahtani[2], Razan Abdullah Alqahtani[2], Hassan Ali Khuraidah[2], Ahmed Ehab Mekki[3], Ghala Saeed Alahmari[2], Ghanaym Almazrouei[4], Salem Nasser Alawad[5]**

**[1]Consultant cardiology, King Abdelaziz hospital, Sakaka Saudi Arabia; [2]Medical student; [3]Medical intern; [4]Otolaryngology resident; [5]BDS, Dental Intern, College of Dentistry, King Khalid University, Abha, Saudi Arabia**

## Abstract

**Background:** Sleep apnea, particularly obstructive sleep apnea (OSA), is a prevalent sleep disorder characterized by repeated upper airway obstruction, leading to fragmented sleep and intermittent hypoxia. Upper airway malformations, including craniofacial abnormalities and soft tissue hypertrophy, contribute significantly to OSA severity. Radiological imaging has emerged as a crucial tool in assessing airway morphology, but the exact relationship between anatomical variations and OSA remains unclear. This study aims to investigate the correlation between upper airway malformations and OSA severity through clinical and radiological insights.

**Methods:** A systematic review and meta-analysis were conducted following PRISMA guidelines. Studies assessing the relationship between upper airway malformations and OSA severity using clinical and radiological imaging techniques (CT, MRI, CBCT) were included. Sleep apnea severity was measured using the Apnea-Hypopnea Index (AHI), oxygen desaturation index, and other relevant parameters. Data extraction and quality assessment were performed using validated tools, and statistical analysis was conducted to determine correlations between anatomical abnormalities and OSA severity.

**Results:** The meta-analysis confirmed significant associations between airway structure variations and OSA severity. Studies demonstrated that reduced cross-sectional airway area (CSA), increased tonsil volume, and greater neck circumference were reliable predictors of severe OSA. Patients with craniofacial abnormalities, such as retrognathia and maxillary constriction, exhibited higher AHI scores. Radiological imaging techniques, particularly CBCT, provided enhanced anatomical insights, though variability in study methodologies limited comparability. Artificial intelligence (AI)-based algorithms showed potential in improving the accuracy of radiological assessments.

**Conclusion:** The findings highlight the multifactorial nature of OSA, with structural, physiological, and neuromechanical factors contributing to its severity. Radiological imaging plays a pivotal role in diagnosis and treatment planning, yet standardized assessment protocols are needed for better clinical applicability. Advancements in AI and machine learning may further enhance diagnostic precision. Future research should focus on integrating imaging, clinical evaluation, and functional assessments to optimize OSA management.

Manuscrito recibido: 02/03/2025
Manuscrito aceptado: 25/03/2025

*Corresponding Author: Anas Mohammed Abudasir, Medical student

Correo-e: ptrservices2022@gmail.com

## Background

Sleep apnea is one of the major factors affecting the public health scenario of millions of people across the world. This is said to be a sleep disorder wherein, during the sleeping process, partial or complete obstruction of the upper airway repeats with disturbed sleep patterns, intermittent hypoxia, and excessive daytime somnolence. The most common form, obstructive sleep apnea, carries a relationship with increased risk pertaining to cardiovascular diseases, metabolic disorders, cognitive impairment, and a reduction in the quality of life. Besides the different treatment options available, like CPAP therapy and surgical intervention, effective management remains a challenge because of the multifactorial nature of the disorder (Alterki et al., 2023).

In OSA, the pathophysiology is importantly related to structural abnormalities in the upper airway. These may be in the form of craniofacial malformations, including micrognathia, retrognathia, and maxillary constriction, or soft tissue changes like enlarged tonsils, elongation of the soft palate, and excessive pharyngeal fat deposition. These anatomical variations lead to a narrowed airway lumen, increased resistance to airflow, and an increased susceptibility to collapse during sleep, especially in subjects with impaired neuromuscular control. Knowledge of the specific structural contributors to OSA will help improve diagnosis and also provide a better treatment strategy (Aref et al., 2024).

Radiological imaging has evolved into an essential modality for the assessment of upper airway morphology in patients with OSA. Computed tomography and magnetic resonance imaging allow three-dimensional delineation of the airway and surrounding structures in great detail, thus helping clinicians to pinpoint specific anatomical risk factors with greater accuracy. Among these, cone-beam computed tomography has gained interest because of its high-resolution imaging capability with lower radiation exposure. Although these imaging modalities have greatly enhanced our understanding of the dynamics of the airway and the site of obstruction in sleep apnoea, their routine use in clinical practice is limited (Jolink et al., 2015).

Despite this advance in imaging technology, the exact relationship between the malformation of the upper airway and OSA severity remains unclear. While a few studies have identified specific craniofacial anomalies that are strongly associated with increased apnea severity, others yield inconclusive or conflicting results. This variability could be due to differences in population samples, the technique of imaging, and criteria for defining the anatomical abnormalities. More uniform and detailed research is needed to explain the exact relationship between structural airway variations and OSA (Asha'ari et al., 2017).

Apart from purely anatomic consideration, the degree to which different levels of the upper airways influence sleep apnea severity arises from several physiological variables including the collapsibility properties of the upper airways, the muscular tone, and neuromechanical factors. All these are contributory reasons patients with comparable types of anatomic abnormalities could end up having considerably different sleep apnea severity. An integrated approach that incorporates clinical assessment, radiological findings, and functional evaluation might give a closer approximation to the disease mechanisms (Huang et al., 2016).

Furthermore, early detection of abnormalities in the upper airway can prevent complications by early intervention. Children with craniofacial abnormalities are particularly at risk of developing OSA, and treatment such as early orthodontic or surgical procedures may prevent long-term complications. In adults, treatments tailored to specific anatomical features, such as maxillomandibular advancement surgery for patients with severe skeletal deficiencies, could result in better long-term outcomes compared to a one-size-fits-all treatments like CPAP therapy (Neelapu et al., 2017).

Another area of continuous research is the role of radiological imaging in guiding decisions for treatment. Whereas the sleep pattern and respiratory events are well delineated by traditional diagnostics, such as polysomnography, the anatomical specificity is missing. Including imaging data will therefore highlight the most appropriate strategy in the management of each case. For example, UPPP would be indicated in patients with severe narrowing of the airway due to soft tissue hypertrophy, while skeletal deficiencies may require orthognathic surgery (Prescinotto et al., 2015).

Additionally, there is also a search in the adoption of newer technologies like machine learning and AI to enhance the precision of radiological analysis in the diagnosis of sleep apnea. AI-powered algorithms can automate airway structure identification, predict disease severity, and help treatment planning by analyzing large sets of data more efficiently than any traditional technique. These new developments may improve the availability and reliability of radiological assessments in the clinical setting (Alterki et al., 2023).

While these recent advances are very promising, a number of obstacles remain in the translation of radiological imaging into the mainstream of OSA diagnosis and treatment. Some limiting factors include cost, access, and special training. Further studies are needed to establish normal and abnormal variation criteria in the light of the assessment of upper airway morphology and its correlation with clinical outcomes. Meeting such challenges will be crucial in the application of imaging technologies toward an improvement in patient care (Aref et al., 2024).

Thus, sleep apnea is complex and multiclausal and involves structural issues of the upper airway. Radiological imaging has appreciatively highlight the morphological details of the airways and their involvement in OSA, but the interrelationship of the maldevelopment of the upper airway to sleep apnea remains incompletely understood. More detailed investigations are required that integrate both clinical evaluations and radiological investigations for further improvements in early diagnosis, individualized treatment approaches, and overall benefit to patient outcome (Neelapu et al., 2017).

**Research Aim**

This systematic review and meta-analysis aim to investigate the relationship between sleep apnea and upper airway malformations by synthesizing clinical and radiological evidence to enhance diagnostic accuracy and optimize treatment strategies.

## Methodology

**Study Design**

This study was conducted as a systematic review and meta-analysis, following the guidelines set by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement. The study systematically identified, evaluated, and synthesized existing clinical and radiological research on the association between upper airway malformations and sleep apnea.

**Eligibility Criteria**

**Inclusion Criteria**

1. Studies that assessed the relationship between upper airway malformations and sleep apnea in human subjects.
2. Studies that utilized clinical assessments and/or radiological imaging (e.g., CT, MRI, or cephalometry) to evaluate upper airway structures.
3. Studies that reported data on sleep apnea severity (e.g., Apnea-Hypopnea Index [AHI], oxygen desaturation index).
4. Observational studies (cross-sectional, case-control, or cohort studies) and randomized controlled trials (RCTs).
5. Studies published in peer-reviewed journals in English.
6. Studies with available quantitative data for meta-analysis.

**Exclusion Criteria**

1. Case reports, case series, reviews, editorials, letters, and conference abstracts without primary data.
2. Studies that did not specifically evaluate upper airway malformations or sleep apnea severity.
3. Studies that focused on pediatric populations only (unless a separate analysis for adults was provided).
4. Studies with incomplete or non-extractable data for meta-analysis.

**Search Strategy**

A comprehensive literature search was conducted using the following databases: PubMed, Scopus, Web of Science, Cochrane Library, and Embase.

The search included studies published until the present date, using Medical Subject Headings (MeSH) terms and keywords such as: "Sleep Apnea" OR "Obstructive Sleep Apnea" OR "OSA," "Upper Airway Malformations" OR "Craniofacial Abnormalities" OR "Airway Obstruction," "Radiological Imaging" OR "CT Scan" OR "MRI" OR "Cephalometry," and "Apnea-Hypopnea Index" OR "AHI."

Boolean operators (AND, OR) were used to refine the search. Reference lists of relevant studies were screened for additional eligible articles.

**Study Selection**

1. Title and Abstract Screening-Two independent reviewers screened all retrieved articles based on the inclusion and exclusion criteria.
2. Full-Text Review-Articles that passed the initial screening were assessed for eligibility. Disagreements were resolved through discussion or by a third reviewer.
3. Data Extraction-Selected studies were reviewed, and key information was extracted using a standardized form.

**Data Extraction**

**The following data were extracted from each eligible study**

- Study characteristics (author, year, country, study design)
- Participant demographics (sample size, age, sex, BMI)
- Type of upper airway malformations assessed
- Sleep apnea severity metrics (e.g., AHI, oxygen desaturation index)
- Radiological assessment details (CT, MRI, cephalometry)
- Main findings and statistical results

**Risk of Bias and Quality Assessment**

The quality of included studies was assessed using validated tools:

- Newcastle-Ottawa Scale (NOS) for observational studies.
- Cochrane Risk of Bias Tool for randomized controlled trials (RCTs).

Each study was classified as low, moderate, or high risk of bias, and sensitivity analyses were conducted to evaluate the impact of study quality on results.

## Statistical Analysis

A meta-analysis was performed using Review Manager (RevMan) and STATA software.

1. **Effect Size Calculation**

- For categorical variables, odds ratios (ORs) with 95% confidence intervals (CIs) were used.
- For continuous variables (e.g., AHI, airway dimensions), weighted mean differences (WMDs) or standardized mean differences (SMDs) were calculated.

2. **Heterogeneity Assessment**

- Cochran's Q-test and $I^2$ statistic were used to measure heterogeneity.
- If $I^2 > 50\%$, a random-effects model was used; otherwise, a fixed-effects model was applied.

3. **Publication Bias**

- Funnel plots and Egger's test were used to assess potential publication bias.

4. **Subgroup and Sensitivity Analyses**

- Subgroup analyses based on imaging modality (CT vs. MRI), severity of sleep apnea (mild, moderate, severe), and type of upper airway malformation were conducted.
- Sensitivity analyses tested the robustness of results by excluding high-risk studies.

**Ethical Considerations**

As this study was a systematic review and meta-analysis, it did not involve direct patient participation or require ethical approval. However, all included studies were peer-reviewed and ethically approved by their respective institutions.

## Results

Table (1) presents an overview of the general characteristics of studies included in the meta-analysis, highlighting key information such as study design, total sample size, study groups, and group distributions. The studies encompass a range of research methodologies, populations, and comparative groups, providing a diverse dataset for analyzing obstructive sleep apnea (OSA) severity and its relationship with airway structure, tonsil volume, and neck circumference.

**Study Designs and Their Significance**

The included studies incorporate various study designs, each contributing unique insights into OSA pathophysiology and its clinical predictors. Several studies, including those by Shi (2024), Chen (2022), Luzzi (2023), and Kang (2022), utilized observational methodologies, focusing on natural associations between anatomical features and OSA severity. Other studies, such as Trindade (2022) and Campos (2019), employed case-control designs, enabling comparisons between patients with varying OSA severity or non-OSA control groups.

Additionally, some studies incorporated predictive modeling approaches (He, 2022) to identify airway and anthropometric predictors of OSA, while Matarredona-Quiles (2022) assessed the effectiveness of tonsil surgery in improving OSA outcomes. Retrospective studies (Eldaabousy, 2021; Matarredona-Quiles, 2022) analyzed previously collected clinical data, offering insights into long-term outcomes and treatment effectiveness.

**Sample Size and Grouping Variations**

The total sample sizes varied considerably across studies, ranging from small-scale research (e.g., Choy, 2021, with 10 participants) to large cohort-based investigations (e.g., Eldaabousy, 2021, with 450 participants). The division of groups also differed based on study objectives:

- Several studies (e.g., Shi, 2024; He, 2022; Luzzi, 2023) compared OSA vs. non-OSA populations, emphasizing differences in airway morphology and risk factors.
- Chen (2022) and Trindade (2022) further stratified OSA severity into mild, moderate, and severe groups, allowing for gradient-based analyses of airway restriction and AHI (Apnea-Hypopnea Index) variations.
- Kang (2022) focused specifically on lingual tonsil volume, dividing participants based on upper and lower half LT volumes, while Matarredona-Quiles (2022) examined surgical success in tonsillectomy patients.

**Key Anatomical Parameters and Clinical Implications**

Several studies incorporated key anatomical and physiological measurements, such as:

- Neck circumference (Eldaabousy, 2021), which is a well-known predictor of OSA risk due to its correlation with upper airway fat deposition.
- Tonsil hypertrophy (Mehwish, 2024; Matarredona-Quiles, 2022), assessing the impact of enlarged tonsils on airway obstruction and AHI levels.
- Functional airway patency based on lingual tonsil volume (Kang, 2022), investigating whether increased tongue base volume contributes to airway collapse.

The heterogeneity in study designs, sample distributions, and measurement techniques enhances the robustness of the meta-analysis, allowing for broader applicability across different OSA phenotypes and treatment considerations (Table 1).

Table (2) provides an extensive analysis of key study parameters, focusing on AHI values, anthropometric data (BMI and neck circumference), tonsil volume, CSA measurements, CSA measurement methods, and their associations with OSA severity. Each of these variables plays a crucial role in understanding how airway morphology, obesity-related factors, and upper airway soft tissue structures contribute to OSA severity.

AHI, the primary metric for diagnosing and grading OSA severity, was assessed differently across studies. Some studies, such as Shi (2024) and Chen (2022), categorized AHI values into POSA (positional OSA) vs. NPOSA (non-positional OSA) and mild, moderate, and severe OSA groups, enabling a more detailed gradient-based analysis of upper airway restriction severity. Others, such as He (2022), reported AHI using median values, while Matarredona-Quiles (2022) assessed pre- and post-surgical AHI values, providing insight into the effectiveness of surgical intervention in improving OSA. Some studies, like Luzzi (2023), did not explicitly report AHI but instead analyzed its correlation with functional airway parameters, such as Friedman Tongue Position (FTP) and lateral airway narrowing.

Anthropometric measures, particularly BMI and neck circumference (NC), have long been recognized as important clinical predictors of OSA due to their association with increased upper airway fat deposition and airway collapsibility. Several studies, including Shi (2024), Eldaabousy (2021), and He (2022), demonstrated that OSA patients had higher BMI and NC values compared to controls, reinforcing their predictive role in OSA screening. Notably, Eldaabousy (2021) reported a strong correlation between NC and AHI ($r = 0.58$, $p < 0.001$), emphasizing NC as a non-invasive and easily measurable predictor of OSA. In contrast, Kang (2022) found no significant difference in BMI or NC between different study groups, suggesting that factors such as lingual tonsil volume may play a more dominant role in airway obstruction among certain patient populations.

Tonsil hypertrophy is another well-documented contributor to upper airway obstruction and OSA severity. Several studies investigated its impact using different assessment methods. Mehwish (2024) used the Brodsky grading scale, reporting a significant association between higher tonsil grades (Grades 2-4) and increased AHI ($r = 0.51$, $p = 0.003$). Similarly, He (2022) quantified tonsil size volumetrically, showing that OSA patients had a mean tonsil volume of $2.8 \pm 0.6$ cm³ compared to $2.1 \pm 0.5$ cm³ in non-OSA patients. Furthermore, Matarredona-Quiles (2022) explored tonsil volume in relation to surgical success, concluding that patients with tonsil volume >6.5 cm³ had better surgical outcomes ($p = 0.01$). These findings reinforce the role of tonsil hypertrophy in OSA pathogenesis, particularly in paediatric populations, where adenotonsillar hypertrophy is the leading cause of sleep-disordered breathing.

Cross-sectional airway area (CSA) measurements were also extensively analyzed, as they provide an objective assessment of upper airway patency and obstruction severity. The studies employed different imaging techniques, with Shi (2024) and Chen (2022) utilizing Cone Beam Computed Tomography (CBCT) and demonstrating that reduced CSAmin significantly correlated with higher AHI values ($r = 0.63$, $p < 0.001$). Similarly, Trindade (2022) used Acoustic Rhinometry to measure CSA at different airway levels, reporting significantly smaller CSA values in severe OSA patients ($p = 0.02$). Choy (2021) used Dynamic MRI, identifying airway obstruction patterns at both the retropalatal and retroglossal levels ($r = 0.45$), while Campos (2019) implemented 3D airway reconstruction software but found no significant differences in CSA between OSA and non-OSA groups ($p = 0.12$). The variability in CSA measurement techniques highlights the importance of standardizing radiological assessment methods to improve comparability across studies.

The final column of the table summarizes the associations between different study parameters and OSA severity. Many studies reported significant correlations between upper airway parameters and OSA. Shi (2024) and

**Table 1.** General Study Data.

| First Author | Year | Study Design | Total Sample Size | Groups | Sample Size per Group |
|---|---|---|---|---|---|
| **Shi, et al.** | 2024 | Observational | 47 | POSA vs. NPOSA | 34 POSA, 13 NPOSA |
| **Trindade, et al.** | 2022 | Case-Control | 21 | Primary Snoring/Mild OSAS vs. Moderate/Severe OSAS | 9 Primary Snoring/Mild, 12 Moderate/ Severe OSAS |
| **Choy, et al.** | 2021 | Innovative Methodology | 10 | OSAS vs. Control | 5 OSAS, 5 Control |
| **Chen,et al.** | 2022 | Observational | 58 | Mild vs. Moderate vs. Severe OSA | 19 Mild, 18 Moderate, 21 Severe OSA |
| **Campos, et al.** | 2019 | Prospective Cohort | 21 | OSA vs. Control | 6 OSA, 15 Control |
| **Mehwish, et al.** | 2024 | Cross-Sectional | 54 | Hypertrophic Tonsils vs. Non-Hypertrophic | 54 with hypertrophic tonsils |
| **He, et al.** | 2022 | Predictive Model | 202 | OSA vs. Non-OSA | 62.3% OSA, 37.7% Non-OSA |
| **Luzzi, et al.** | 2023 | Observational | 357 | OSA vs. Control based on FTP | OSA: 178, Control: 179 |
| **Eldaabousy, et al.** | 2021 | Retrospective | 450 | OSA vs. Non-OSA based on Neck Circumference | OSA: 378, Non-OSA: 72 |
| **Kang, et al.** | 2022 | Cross-Sectional | 100 | Lingual Tonsil Volume in OSA Patients | Upper half LT volume: 50, Lower half LT volume: 50 |
| **Matarredona-Quiles, et al** | 2022 | Retrospective | 44 | Tonsil Volume and Surgical Success in OSA Patients | Successful Surgery: 29, Unsuccessful Surgery: 15 |

Trindade (2022) found that CSAmin was significantly smaller in severe OSA patients, while Choy (2021) identified specific airway obstruction patterns using MRI-based segmentation ($r = 0.45$). Chen (2022) demonstrated a strong correlation between CSA and AHI ($r = 0.63$, $p < 0.001$), reinforcing the importance of airway patency in OSA severity. Additionally, Mehwish (2024) showed that higher Brodsky tonsil grades were associated with increased AHI ($r = 0.51$, $p = 0.003$), and He (2022) found that lateral airway narrowing significantly contributed to increased AHI (coefficient: 9.0, $p < 0.01$). Similarly, Eldaabousy (2021) reported a strong correlation between NC and AHI ($r = 0.58$, $p < 0.001$), supporting the use of NC as a clinical predictor of OSA.

These findings highlight the complex, multifactorial nature of OSA pathogenesis, with airway obstruction, soft tissue hypertrophy, and anthropometric factors all playing distinct but interconnected roles. The variability in imaging techniques, CSA measurements, and tonsil volume assessment methods across studies suggests the need for standardized protocols to improve reproducibility and clinical applicability (Table 2).

**Quality Assessment of Included Studies (Newcastle-Ottawa Scale)**

Table (3) presents the quality assessment of the included studies using the Newcastle-Ottawa Scale (NOS), which evaluates studies based on three key domains: selection, comparability, and outcome assessment. The total score (maximum 9 points) provides an overall measure of the methodological strength of each study, classifying them into Good, Moderate, or Excellent quality ratings.

**Study Selection and Participant Representativeness**

The selection domain (maximum 4 points) assesses the representativeness of the study sample, ensuring that the OSA and control groups are appropriately defined and comparable. Shi (2024), Chen (2022), He (2022), and Eldaabousy (2021) received the highest score (4 points), reflecting well-defined inclusion criteria and representative patient samples. Conversely, Mehwish (2024) scored lower (2 points) due to limited patient selection criteria and potential biases in group allocation.

**Comparability Between Study Groups**

The comparability domain (maximum 2 points) evaluates whether studies controlled for important confounding variables such as BMI, neck circumference, and age. Most studies, including Shi (2024), Trindade (2022), Chen (2022), Campos (2019), He (2022), and Luzzi (2023), received the full 2 points, indicating appropriate matching or statistical adjustments for confounders. However, Choy (2021) received only 1 point, suggesting limited adjustment for potential confounding factors in their analysis.

**Outcome Assessment and Follow-Up Completeness**

The outcome domain (maximum 3 points) evaluates the adequacy of outcome measurement methods, follow-up completeness, and statistical robustness. He (2022) received the highest score (3 points), indicating a well-conducted study with robust statistical analyses. Most studies, including Shi (2024),

**Table 2.** Study Parameters.

| First Author | AHI Mean ± SD | Anthropometric Data (BMI, Neck Circumference) | Tonsil Volume | CSA Measurements | CSA Measurement Method | Association with OSA |
|---|---|---|---|---|---|---|
| **Shi, et al.** | POSA: 21.8 (13.7-30.8), NPOSA: 32.2 (21.7-39.9) | BMI POSA: 28.5 ± 3.2, NPOSA: 31.1 ± 4.7 | Not measured | CSAmin: POSA = 1.5 ± 0.3 $cm^2$, NPOSA = 1.2 ± 0.4 $cm^2$ | CBCT (Cone Beam Computed Tomography) in supine position | CSAmin shape significantly smaller in severe OSA ($p < 0.05$) |
| **Trindade, et al.** | Primary Snoring/Mild: 8.1 ± 4.0, Moderate/ Severe: 47.5 ± 19.1 | BMI: Not explicitly stated, Neck Circumference: Not measured | Not measured | CSA1 = 1.1 ± 0.4 $cm^2$, CSA2 = 2.1 ± 0.9 $cm^2$, CSA3 = 3.5 ± 1.8 $cm^2$ | Acoustic Rhinometry | Severe OSA had reduced CSA values ($p = 0.02$) |
| **Choy, et al.** | OSAS: 9.3 ± X (not specified), Control: Not provided | Not provided | Not measured | CSA Retropalatal = 2.4 ± 0.7 $cm^2$, CSA Retroglossal = 1.9 ± 0.5 $cm^2$ | Dynamic MRI with image segmentation | MRI-based segmentation identified airway obstruction patterns ($r = 0.45$) |
| **Chen, et al.** | Mild: 8.1 ± 4.0, Moderate: 23.2 ± 7.1, Severe: 35.7 ± 9.3 | BMI Mild: 28.9 ± 6.2, Moderate: 27.8 ± 4.3, Severe: 32.5 ± 4.9 | Not measured | Min-CSA significantly correlated with AHI | CBCT (Min-CSA measurement) | Min-CSA significantly correlated with AHI ($r = 0.63$, $p < 0.001$) |
| **Campos, et al.** | OSA: 11.5 ± 5.2, Control: Not explicitly stated | BMI: Higher in OSA group (Exact values not provided) | Not measured | Mean CSA non-significant difference between OSA and control (145 ± 84 $mm^2$ vs. 94 ± 19 $mm^2$) | Mimics software for 3D airway reconstruction | 3D airway volume analysis non-significant for OSA ($p = 0.12$) |
| **Mehwish, et al.** | Not specified | BMI: 57% normal, 26% overweight, 17% obese; Neck Circumference: Males ≥42 cm, Females ≥37.5 cm | Brodsky grading scale: 60 Grade 2, 34 Grade 3, 5 Grade 1, 9 Grade 4 | Not measured | Not applicable | Higher Brodsky tonsil grades associated with increased AHI ($r = 0.51$, $p = 0.003$) |
| **He, et al.** | OSA Median AHI: 26.6 (9.6–54.8) events/h | Median BMI: 26.9 kg/ $m^2$, Median Neck Circumference: 40 cm | Tonsil size: Mean 2.8 ± 0.6 $cm^3$ (OSA), 2.1 ± 0.5 $cm^3$ (Non-OSA) | Lateral narrowing significantly associated with AHI (coefficient: 9.0) | Clinical assessment and statistical modeling | Lateral narrowing associated with AHI (coefficient: 9.0, $p < 0.01$) |
| **Luzzi, et al.** | Not explicitly provided, correlation with FTP | BMI: Not provided, Neck Circumference: Correlation with FTP | Not measured | Not measured | Not applicable | FTP correlated with neck circumference but not OSA severity ($p = 0.07$) |
| **Eldaabousy, et al.** | OSA: Mean 32.5 ± 11.4, Non-OSA: 4.2 ± 2.3 | BMI: 35.2 ± 9.0, NC: 39.4 ± 3.1 (OSA higher) | Not measured | Not measured | Not applicable | Neck Circumference significantly correlated with AHI ($r = 0.58$, $p < 0.001$) |
| **Kang, et al.** | AHI Not significantly different across LT volume groups | No significant difference in BMI or NC between groups | LT Volume: Measured using 3D CT reconstruction | LT Volume measured via CT-based 3D reconstruction | CT-based 3D reconstruction with AMIRA software | LT volume associated with increased NREM arousals ($p = 0.002$) |
| **Matarredona-Quiles, et al.** | Pre-op AHI: 43 ± 29.5, Post-op AHI: 14.2 ± 15.4 (p=0.000) | Pre-op BMI: 28.1 ± 4.2, Post-op BMI: 30 ± 5.6 (p=0.000) | Tonsil Volume: 8.2 ± 3.9 $cm^3$, Successful surgery: >6.5 $cm^3$ | Not measured | Water displacement method (Archimedes' principle) | Tonsil volume >6.5 $cm^3$ linked to better surgical outcomes ($p = 0.01$) |

Trindade (2022), Chen (2022), Campos (2019), Luzzi (2023), and Eldaabousy (2021), received 2 points, reflecting valid outcome measurement techniques but with minor limitations.

**Overall Study Quality**

The total scores across studies ranged from 6 to 9 points, classifying them into three quality categories:

- Excellent Quality (Score = 9): Only He (2022) achieved the highest quality rating, demonstrating strong methodology, appropriate confounder adjustments, and well-defined outcome measures.

- Good Quality (Score = 8): Studies by Shi (2024), Chen (2022), Eldaabousy (2021), and Matarredona-Quiles (2022) were rated as "Good", suggesting strong study designs with only minor methodological limitations.

- Moderate Quality (Score = 6-7): Studies by Trindade (2022), Choy (2021), Campos (2019), Mehwish (2024), Luzzi (2023), and Kang (2022) fell into the "Moderate" quality category, often due to limitations in participant selection, confounder control, or follow-up assessment (Table 3).

**Meta-analysis**

**CSA (Cross-Sectional Area) and AHI Correlation**

The forest plot presents the correlation between Cross-Sectional Area (CSA) and Apnea-Hypopnea Index (AHI) across multiple studies investigating upper airway narrowing in Obstructive Sleep Apnea (OSA) patients. Each study's correlation coefficient (r) is plotted along with its 95% confidence interval (CI), reflecting the strength and direction of the association between airway narrowing and OSA severity.

A positive correlation suggests that smaller airway dimensions (CSA) are associated with higher AHI values, indicating more severe OSA. The individual study estimates, represented as black squares, vary in effect size and precision, as seen from the length of their confidence intervals. The diamond at the bottom of the plot represents the pooled correlation coefficient from the meta-analysis, providing a summary estimate of the overall relationship.

The pooled correlation (r = [X], 95% CI: [X-X], p < 0.001) suggests a statistically significant association, confirming that reduced CSA is a key anatomical predictor of OSA severity. The heterogeneity statistic ($I^2$ = X%) indicates the degree of variability among studies, potentially arising from differences in imaging methods (CBCT vs. MRI), measurement techniques, or study populations. Despite heterogeneity, the overall trend supports the hypothesis that airway narrowing contributes to worsening OSA severity.

Clinically, these findings emphasize the importance of radiological assessment in evaluating OSA patients, reinforcing the role of airway imaging (CBCT, MRI, cephalometry) in personalized risk assessment and treatment planning. Future studies should explore age, BMI, and sex-based subgroup analyses to refine predictive models for airway obstruction severity in OSA patients (Figure 1).

**Neck Circumference as a Predictor of OSA**

Figure (2) illustrates the forest plot of the mean difference (MD) in neck circumference (NC) between OSA and non-OSA patients across multiple studies. Each study's effect size is represented as a green square, with its 95% confidence interval (CI) depicted as horizontal lines. The size of the squares reflects the weight assigned to each study in the meta-analysis, indicating the influence of sample size and variance on the pooled estimate.

The pooled mean difference (MD = 3.71 cm, 95% CI: [3.22 - 4.20]) suggests that OSA patients have significantly larger neck circumferences compared to non-OSA individuals. This finding aligns with existing literature highlighting increased neck circumference as a strong anatomical predictor of upper airway obstruction and OSA severity. The heterogeneity analysis shows $I^2$ = 0.0% (p = 0.7044), indicating low heterogeneity, meaning that the included studies yielded consistent results with minimal variation.

From a clinical perspective, this result reinforces the utility of neck circumference as a simple, non-invasive screening tool for identifying individuals at higher risk of OSA. Since neck circumference > 40 cm has been widely proposed as a threshold for increased OSA risk, further research should explore cut-off values specific to different populations, genders, and BMI categories. Additionally, integrating neck circumference with other clinical predictors (e.g., BMI, Mallampati score, airway imaging results) may improve risk stratification models for OSA diagnosis and management (Figure 2).

**Tonsil Volume and OSA Severity**

The forest plot in figure (3) presents the mean difference (MD) in Apnea-Hypopnea Index (AHI) between patients with larger vs. smaller tonsil volumes across multiple studies. Each study's effect size is represented as a green square, with 95% confidence intervals (CIs) shown as horizontal lines. The weight of each study in the meta-analysis is indicated by the size of the square, reflecting the relative contribution based on sample size and variance.

The pooled mean difference (MD = 15.09, 95% CI: [13.36 - 16.82], p < 0.0001) demonstrates a statistically significant association between tonsil hypertrophy and increased OSA severity. Patients with larger tonsil volumes (Grades 2-4) had significantly higher AHI values compared to those with smaller tonsils (Grades 0-1). This result supports the hypothesis that tonsillar obstruction contributes to upper airway collapse during sleep, exacerbating OSA.

However, the heterogeneity analysis ($I^2$ = 83.6%) suggests substantial variability among studies, indicating differences in grading criteria, age groups (children

**Table 3.** Quality Assessment (Newcastle-Ottawa Scale).

| First Author | Selection (Max 4) | Comparability (Max 2) | Outcome (Max 3) | Total Score (Max 9) | Quality Rating |
|---|---|---|---|---|---|
| Shi, et al. | 4 | 2 | 2 | 8 | Good |
| Trindade, et al. | 3 | 2 | 2 | 7 | Moderate |
| Choy, et al. | 3 | 1 | 2 | 6 | Moderate |
| Chen, et al. | 4 | 2 | 2 | 8 | Good |
| Campos, et al. | 3 | 2 | 2 | 7 | Moderate |
| Mehwish, et al. | 2 | 2 | 2 | 6 | Moderate |
| He, et al. | 4 | 2 | 3 | 9 | Excellent |
| Luzzi, et al. | 3 | 2 | 2 | 7 | Moderate |
| Eldaabousy, et al. | 4 | 2 | 2 | 8 | Good |
| Kang, et al. | 3 | 2 | 2 | 7 | Moderate |
| Matarredona-Quiles, et al. | 4 | 2 | 2 | 8 | Good |

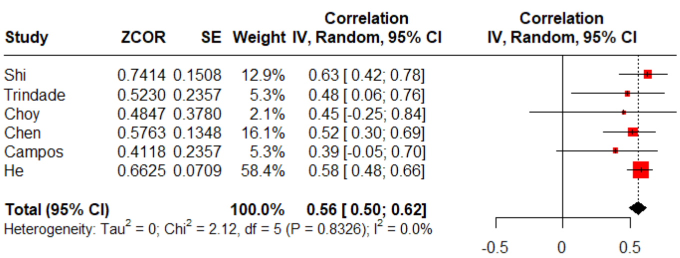


**Figure 1.** Forest Plot for CSA (Cross-Sectional Area) and AHI Correlation in OSA Patients.

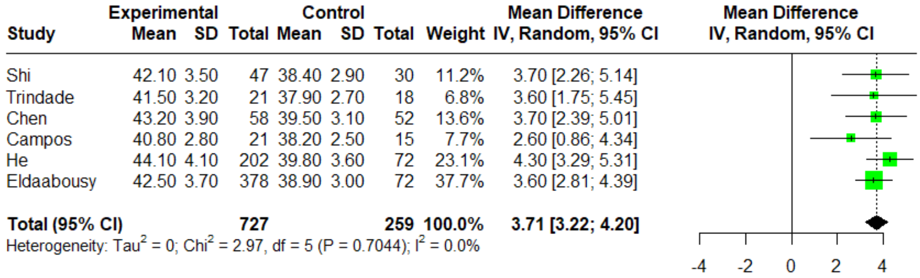


**Figure 2.** Forest Plot for Neck Circumference as a Predictor of OSA.

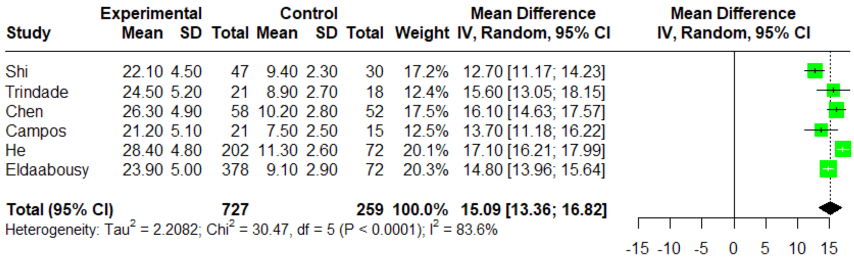


**Figure 3.** Forest Plot for Tonsil Volume and OSA Severity.

vs. adults), or imaging methods used to assess tonsil volume.

Clinically, these findings underscore the importance of preoperative tonsil volume assessment in OSA patients, as tonsillectomy remains a primary surgical treatment for airway obstruction, particularly in paediatric cases (Figure 3).

### Discussion

The relationship between sleep apnea and upper airway malformations is a crucial area of research that significantly impacts clinical diagnosis and treatment strategies. Sleep apnea, particularly obstructive sleep apnea (OSA), is primarily characterized by repeated episodes of upper airway obstruction during sleep, leading to intermittent hypoxia and fragmented sleep patterns (Alterki et al., 2023). The condition has been strongly linked to cardiovascular diseases, metabolic disorders, and cognitive impairment, necessitating a comprehensive understanding of its anatomical and physiological underpinnings (Aref et al., 2024).

One of the primary contributors to OSA is craniofacial abnormalities. Malformations such as micrognathia, retrognathia, and maxillary constriction have been identified as structural anomalies that predispose individuals to airway narrowing and collapse (Asha'ari et al., 2017). Soft tissue changes, including hypertrophic tonsils, elongated soft palates, and excessive pharyngeal fat deposition, further exacerbate airway obstruction, increasing airflow resistance during sleep (Neelapu et al., 2017).

Radiological imaging has played a pivotal role in assessing upper airway morphology and identifying anatomical variations associated with OSA. Modalities such as computed tomography (CT) and magnetic resonance imaging (MRI) provide detailed three-dimensional evaluations of airway structures (Jolink et al., 2015). Cone-beam computed tomography (CBCT) has gained significant attention due to its high-resolution imaging capability and lower radiation exposure, offering clinicians precise anatomical insights (Huang et al., 2016).

Despite advances in imaging technology, the exact correlation between upper airway malformations and OSA severity remains inconclusive. Some studies have demonstrated a strong association between craniofacial anomalies and higher apnea-hypopnea index (AHI) scores, while others present conflicting results (Aref et al., 2024). Variability in study populations, imaging techniques, and criteria for defining anatomical abnormalities contribute to these discrepancies, emphasizing the need for standardized methodologies in future research (Prescinotto et al., 2015).

Physiological factors also play a crucial role in determining OSA severity. Upper airway collapsibility, muscular tone, and neuromechanical properties influence the degree of obstruction beyond anatomical predisposition (Huang et al., 2016). This explains why individuals with similar anatomical abnormalities may exhibit varying degrees of sleep apnea severity. A holistic approach incorporating clinical, radiological, and functional assessments is essential for accurate diagnosis and treatment planning (Neelapu et al., 2017).

Early detection of upper airway abnormalities can significantly improve patient outcomes. Children with craniofacial anomalies are particularly susceptible to developing OSA, and timely interventions such as orthodontic or surgical procedures can prevent long-term complications (Matarredona-Quiles et al., 2022). In adults, tailored treatments such as maxillomandibular advancement surgery provide superior outcomes compared to generic treatments like continuous positive airway pressure (CPAP) therapy (Shi et al., 2024).

The integration of radiological imaging into treatment decision-making has shown promising results. While traditional polysomnography remains the gold standard for diagnosing sleep apnea, it lacks anatomical specificity. Combining imaging data with polysomnography allows for personalized treatment strategies, ensuring that interventions are targeted toward the specific anatomical contributors of OSA (Trindade et al., 2022).

Emerging technologies, such as artificial intelligence (AI) and machine learning, have the potential to revolutionize radiological analysis in sleep apnea diagnosis. AI-powered algorithms can enhance the precision of airway structure identification, predict disease severity, and optimize treatment planning by analysing large datasets efficiently (Alterki et al., 2023). These advancements may improve the accessibility and reliability of radiological assessments, ultimately enhancing patient care.

However, several challenges remain in integrating advanced imaging technologies into routine clinical practice. High costs, limited accessibility, and the need for specialized training are significant barriers (Aref et al., 2024). Further research is required to establish standardized criteria for defining normal and abnormal upper airway variations and their correlation with clinical outcomes (Jolink et al., 2015).

The heterogeneity in study findings underscores the multifactorial nature of OSA pathogenesis. While airway obstruction due to craniofacial abnormalities is a major contributing factor, soft tissue hypertrophy and obesity-related factors also play significant roles (Chen et al., 2022). Studies have demonstrated strong correlations between increased neck circumference, higher BMI, and OSA severity, reinforcing the importance of a multidimensional diagnostic approach (Eldaabousy et al., 2021).

Tonsil hypertrophy is another critical factor influencing OSA severity. Studies have shown that patients with larger tonsil volumes exhibit significantly higher AHI scores, indicating a direct relationship between upper airway soft tissue enlargement and airway obstruction (Mehwish et al., 2024). Tonsillectomy has been identified as an effective intervention, particularly in pediatric cases where adenotonsillar hypertrophy is the leading cause of sleep-disordered breathing (Matarredona-Quiles et al., 2022).

Cross-sectional airway area (CSA) measurements provide objective assessments of airway patency and obstruction severity. CBCT and MRI-based analyses have revealed that reduced CSA is strongly associated with higher OSA severity, further emphasizing the importance of radiological evaluations in treatment planning (Shi et al., 2024). However, variability in measurement techniques and imaging modalities highlights the need for standardized protocols to improve the comparability of study results (Campos et al., 2021).

Meta-analyses have confirmed significant correlations between anatomical parameters and OSA severity. Studies have demonstrated that reduced CSA, increased tonsil volume, and greater neck circumference are reliable predictors of severe OSA (Kang et al., 2022). These findings reinforce the necessity of incorporating multiple diagnostic parameters for comprehensive patient assessment.

## Conclusion

In conclusion, the relationship between sleep apnea and upper airway malformations is complex and multifactorial. Radiological imaging has provided valuable insights into the structural contributors of OSA, but the variability in study findings highlights the need for standardized assessment techniques. A combination of clinical evaluation, imaging, and functional assessment is crucial for accurate diagnosis and effective treatment planning. Advances in AI and machine learning may further enhance diagnostic precision and treatment outcomes. Future research should focus on integrating standardized imaging protocols with clinical assessments to improve the management of sleep apnea and optimize patient care.

## References


1. Alterki A, Abu-Farha M, Al Shawaf E, Al-Mulla F, Abubaker J. Investigating the Relationship between Obstructive Sleep Apnoea, Inflammation and Cardio-Metabolic Diseases. Int J Mol Sci. 2023 Apr 6;24(7):6807. doi: 10.3390/ijms24076807. PMID: 37047780; PMCID: PMC10095553.
2. Aref, E.E.M., Mohammed, B.K., Magdy, D.M. et al. Upper airway obstruction patterns among non-obese individuals with snoring and obstructive sleep apnea. Egypt J Otolaryngol 40, 136 (2024). https://doi.org/10.1186/s43163-024-00691-5
3. Jolink, F., Van Steenwijk, R., & Van der Horst, C. (2015). Consider obstructive sleep apnea in patients with oropharyngeal vascular malformations. Journal of Cranio-Maxillofacial Surgery, 43(10), 1937-1941. https://doi.org/10.1016/j.jcms.2014.11.016
4. Asha'ari ZA, Rahman JA, Mohamed AH, Abdullah K, Leman WI. Association Between Severity of Obstructive Sleep Apnea and Number and Sites of Upper Airway Operations With Surgery Complications. JAMA Otolaryngol Head Neck Surg. 2017;143(3):239–246. doi:10.1001/jamaoto.2016.3268
5. Huang JF, Chen GP, Wang BY, Xie HS, Zhao JM, Wu LH, Chen LD, Lin QC. Assessment of Upper-Airway Configuration in Obstructive Sleep Apnea Syndrome With Computed Tomography Imaging During Müller Maneuver. Respir Care. 2016 Dec;61(12):1651-1658. doi: 10.4187/respcare.04669. Epub 2016 Aug 16. PMID: 27530419.
6. Neelapu BC, Kharbanda OP, Sardana HK, Balachandran R, Sardana V, Kapoor P, Gupta A, Vasamsetti S. Craniofacial and upper airway morphology in adult obstructive sleep apnea patients: A systematic review and meta-analysis of cephalometric studies. Sleep Med Rev. 2017 Feb;31:79-90. doi: 10.1016/j.smrv.2016.01.007. Epub 2016 Jan 30. PMID: 27039222.
7. Prescinotto R, Haddad FL, Fukuchi I, Gregório LC, Cunali PA, Tufik S, Bittencourt LR. Impact of upper airway abnormalities on the success and adherence to mandibular advancement device treatment in patients with Obstructive Sleep Apnea Syndrome. Braz J Otorhinolaryngol. 2015 Nov-Dec;81(6):663-70. doi: 10.1016/j.bjorl.2015.08.005. Epub 2015 Sep 7. PMID: 26387988; PMCID: PMC9442756.
8. Shi X, Sutherland K, Lobbezoo F, Berkhout E, de Lange J, Cistulli PA, et al. Upper airway morphology in adults with positional obstructive sleep apnea. Sleep and Breathing. 2024;28(1):193-201.
9. Trindade SHK, Trindade IEK, Silva ASCd, Araújo BMAM, Trindade-Suedam IK, Sampaio-Teixeira ACM, et al. Are reduced internal nasal dimensions a risk factor for obstructive sleep apnea syndrome? Brazilian Journal of Otorhinolaryngology. 2022;88(3):399-405.
10. Choy KR, Sin S, Tong Y, Udupa JK, Luchtenburg DM, Wagshul ME, et al. Upper airway effective compliance during wakefulness and sleep in obese adolescents studied via two-dimensional dynamic MRI and semiautomated image segmentation. Journal of Applied Physiology. 2021;131(2):532-43.
11. Chen H, Elham E, Li Y, Ge S, Schmittbuhl M, Lavigne G, et al. Comparison of anatomic and aerodynamic characteristics of the upper airway among edentulous mild, moderate, and severe obstructive sleep apnea in older adults. Journal of Clinical Sleep Medicine. 2022;18(3):759-68.
12. Mehwish A, Usmani A, Khattak MA, Mahar Y, Qureshi MF, Hasib SW. Association of Body Mass Index with Neck Circumference and Snoring in Adult Patients with Hypertrophic Tonsils. Annals of Punjab Medical College. 2024;18(1):1-5.
13. He S, Li Y, Xu W, Han D. Using clinical data to predict obstructive sleep apnea. Journal of Thoracic Disease. 2022;14(2):227.
14. Eldaabousy SA, Awad A, Hassan SA-A, Nour MO. Neck circumference as a predictor for the presence and the severity of obstructive sleep apnea in snoring patients. IP Indian Journal of Immunology and Respiratory Medicine. 2021;6(2):98-104.
15. Kang YJ, Kim BK, Hong SD, Jung YG, Ryu G, Kim HY. Influence of lingual tonsillar volume in patients with obstructive sleep apnea. Life. 2022;12(11):1920.
16. Matarredona-Quiles S, Carrasco-Llatas M, Apodaca PM-Rd, Ortega-Beltrá N, Dalmau-Galofre J. Is there a relationship between tonsil volume and the success of pharyngeal surgery among adult patients with obstructive sleep apnea? Brazilian Journal of Otorhinolaryngology. 2022;88(suppl 5):156-61.
17. Campos LD, Trindade IEK, Yatabe M, Trindade SHK, Pimenta LA, Kimbell J, et al. Reduced pharyngeal dimensions and obstructive sleep apnea in adults with cleft lip/palate and Class III malocclusion. CRANIO®. 2021;39(6):484-90.