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Predicting obstructive sleep apnea hypopnea syndrome using three-dimensional optical devices: A systematic review

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Abstract

Purpose: As a global health concern, the diagnosis of obstructive sleep apnea hypopnea syndrome (OSAHS), characterized by partial reductions and complete pauses in ventilation, has garnered significant scientific and public attention. With the advancement of digital technology, the utilization of three-dimensional (3D) optical devices demonstrates unparalleled potential in diagnosing OSAHS. This study aimed to review the current literature to assess the accuracy of 3D optical devices in identifying the prevalence and severity of OSAHS.

Methods: A systematic literature search was conducted in the Web of Science, Scopus, PubMed/MEDLINE, and Cochrane Library databases for English studies published up to April 2024. Peer-reviewed researches assessing the diagnostic utility of 3D optical devices for OSAHS were included. The Quality Assessment of Diagnostic Accuracy Studies-2 (QUADAS-2) guideline was employed to appraise the risk of bias.

Results: The search yielded 3216 results, with 10 articles meeting the inclusion criteria for this study. Selected studies utilized structured light scanners, stereophotogrammetry, and red, green, blue-depth (RGB-D) cameras. Stereophotogrammetry-based 3D optical devices exhibited promising potential in OSAHS prediction.

Conclusions: The utilization of 3D optical devices holds considerable promise for OSAHS diagnosis, offering potential improvements in accuracy, cost reduction, and time efficiency. However, further clinical data are essential to assist clinicians in the early detection of OSAHS using 3D optical devices.

Keywords

Obstructive sleep apnea hypopnea syndrome, three-dimensional optical device, prediction, accuracy

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Introduction

Obstructive sleep apnea hypopnea syndrome (OSAHS), a sleep breathing disorder, is characterized by partial reductions and complete pauses in ventilation, significantly impairing quality of life and correlating with cardiovascular disease and mortality.[1,2] Studies indicate that approximately 1 billion adults aged between 30 and 69 worldwide are affected by this sleep-related breathing disorder.[3,4] The onset of OSAHS is influenced by various factors, including anatomical features, genetics, functional traits, age, gender, lifestyle behaviors, and body mass index (BMI).[5,6] The severity and occurrence of OSAHS are

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commonly assessed using the apnea-hypopnea index (AHI), calculated as the number of apnea and hypopnea events recorded during an overnight sleep divided by the total hours of sleep.[7] Severity is typically classified as mild ($15 \geq AHI \geq 5$), moderate ($29 \geq AHI \geq 16$), or severe ($AHI \geq 30$).[8]

As a prevalent and undiagnosed condition, studies have shown that a majority of individuals with OSAHS remain undiagnosed and untreated, even in developed regions.[3,4] Laboratory-based polysomnography is considered the gold standard diagnostic tool for OSAHS, capable of monitoring both sleep and respiratory parameters through comprehensive sleep assessment.[9] However, polysomnography has several limitations.[8] It is time-consuming, expensive, requires trained personnel, and is confined to clinical settings. Additionally, it fails to replicate the natural sleep environment, as the hospital setting differs from the home environment, and its implementation is limited to a few days, thereby restricting its results to some extent. To lighten the potential limitations, a group of researchers propose a new approach to detect respiratory events by using SpO2 measured by a pulse oximeter and respiratory movement derived from contactless 3D camera.[10] Given the constraints of polysomnography, alternative approaches to OSAHS diagnosis have been proposed. Cardiorespiratory polygraphy serves as an alternative to polysomnography, utilizing similar respiratory signals but with reduced costs and shorter electrode placement and scoring times.[11] Notably, these compact devices can be utilized by patients at home, offering a significant advantage.[12] Screening questionnaires, such as the Berlin, STOP, and STOP-Bang questionnaires, are commonly employed in various populations for OSAHS diagnosis.[13] Among these, the STOP-Bang questionnaire exhibits high sensitivity but lacks specificity.[13] Additionally, the Epworth Sleepiness Scale provides a popular self-assessment tool for excessive daytime sleepiness.[14] However, questionnaires often yield a high rate of false-positive results and, while reasonably sensitive for OSAHS, lack specificity.[15]

In recent years, the advent of artificial intelligence (AI)-based approaches utilizing electronic health records has introduced an intriguing tool for OSAHS diagnosis. For instance, one research team extracted electronic health records, including laboratory blood reports, demographics, physical measurements, comorbidities, and habitual sleep history, from 1479 patients to develop screening OSAHS classification models using machine learning techniques.[8] Another study proposed a novel intelligent clinical decision support system based on automatic learning algorithms for diagnosing OSAHS, suitable for early outpatient stages.[16] Furthermore, research has shown that the severity of OSAHS can be assessed through various machine-learning algorithms based on clinical parameters, obviating the need for full polysomnography.[17] Cephalometry and magnetic resonance imaging (MRI) are two valuable tools known for accurately measuring maxillofacial anatomical structures associated with OSAHS occurrence.[18,19] However, they may not be feasible in certain clinical scenarios due to the radiation exposure associated with cephalometry and the high cost of MRI. Craniofacial morphology is increasingly recognized as a risk factor in the pathogenesis of OSAHS. Certain facial measurements are different between subjects with and without OSA, such as mandibular width-length angle, facial width, neck width and binocular width. Accordingly, two-dimensional (2D) photography has emerged as an alternative with reasonable accuracy in predicting the presence and severity of OSAHS.[20,21] Nonetheless, this approach often struggles to accurately evaluate the intricate three-dimensional (3D) craniofacial anatomy, including shape and contour, thus limiting its applicability in OSAHS prediction. Furthermore, the measurements of 2D photography need a constant distance between the patient and the device along with standardization of various conditions.

Facilitated by the continuous evolution of digital technology, 3D optical devices, characterized by improving accuracy, safety, and speed, have gradually found applications in both research and clinical settings.[22,23] Moreover, the digital archiving capability of 3D images obtained from these devices has contributed to research, assessment, and communication within the community.[24,25] Leveraging rapid imaging speeds, 3D optical devices can evaluate geodesic distance to enhance efficiency and reduce prediction costs. Furthermore, these devices can overcome the limitations of traditional cameras and measure nonlinear structures. Consequently, the utilization of 3D optical devices demonstrates unprecedented potential for predicting the presence and severity of OSAHS. Previous researches have explored the potential of 3D optical devices in predicting OSAHS.[26–35] Findings suggest that 3D optical devices have predictive value for OSAHS and that geodesic measurements enhance this capacity.[26] One primary novelty of these studies is that the dataset obtained by 3D optical devices consists of the entire 3D surface. However, no studies have attempted to systematically summarize the available data in this area. It is therefore essential to understand whether 3D optical devices could effectively screen for the OSAHS and provide references for the potential applications of these devices.

In this study, we performed a qualitative review to assess the diagnostic accuracy and utility of 3D optical devices for predicting OSAHS. A comprehensive literature search was performed in various databases based on predefined eligibility criteria. Following the selection of potential studies and data collection, the risk of bias was assessed using the Quality Assessment of Diagnostic Accuracy Studies-2 (QUADAS-2) tool. The accuracy of 3D optical devices in detecting the prevalence and

severity of OSAHS was then summarized on the basis of the literature findings.

Materials and methods

The present study was registered with PROSPERO under registration number CRD42023406608 and conducted by the Preferred Reporting Items for Systematic Reviews and Meta-analyses guidelines.[36] Approval for the study was granted by the Institutional Review Board under approval number [2023]-SR-98.

The guiding question was formulated following the PICO format: (P) participants, (I) intervention, (C) comparison, and (O) outcome.[37] The guiding question addressed was: "For OSAHS patients, do 3D optical devices provide comparable diagnostic value to conventional methods in terms of sensitivity, specificity, and accuracy?" The participants comprised individuals rehabilitated with suspected OSAHS. The intervention group encompassed biological data assessed using 3D optical devices, while the comparison group involved sleep data assessed via conventional methods. The primary outcomes focused on the sensitivity, specificity, and accuracy of OSAHS prediction.

Search strategy

A systematic literature search was conducted in the Web of Science, Scopus, PubMed/MEDLINE, and Cochrane Library databases to identify relevant publications published in English up to April 2024. The search strategy incorporated predefined terms relating to 3D optical devices and OSAHS, with specific keywords tailored for each database, as detailed in Table 1. Additionally, searches were carried out on gray-literature sources, including the WHO International Clinical Trials Registry Platform and Opensigle. To enhance the comprehensiveness of the study, electronic database searches were complemented by a manual examination of the reference lists of selected researches.

Eligibility criteria

The following inclusion criteria guided the selection of publications: (1) peer-reviewed research articles published in English; (2) studies involving the prediction of OSAHS using 3D optical devices; (3) articles providing data on sensitivity, specificity, or accuracy values. Conversely, the following exclusion criteria were applied: (1) case reports, letters, editorials, conference papers, and reviews; (2)

Table 1. Electronic databases used and search strategies.

Database	Search strategy
PubMed	((Sleep apnea AND obstructive) OR (snoring) OR (sleep-disordered breathing) OR (sleep related breathing disorders) OR (sleep disturbed breathing)) AND ((scanner) OR (facial scan) OR (3D face scanning) OR (3D scanner) OR (3D face impression) OR (3D surface scanning) OR (indirect face capturing) OR (optical scanner) OR (laser scanner) OR (structured light) OR (white-light scanner) OR (stereophotogrammetry) OR (photogrammetry) OR (depth sensor cameras) OR (depth-sensing cameras) OR (smart device) OR (mobile) OR (smartphone) OR (tablet) OR (notebook) OR (laptop))
Scopus	TITLE-ABS-KEY ((“sleep apnea” AND obstructive) OR snoring OR Osleep-disordered breathing” OR “sleep related breathing disorders” OR “sleep disturbed breathing”) AND TITLE-ABS-KEY (“scanner” OR “facial scan” OR O3D face scanning” OR “3D scanner” OR “3D face impression” OR “3D surface scanning” OR “indirect face capturing” OR “optical scanner” OR “laser scanner” OR “structured light” OR “white-light scanner” OR “stereophotogrammetry” OR Ophotogrammetry” OR “depth sensor cameras” OR “depth-sensing cameras” OR Osmart device” OR “mobile” OR “smartphone” OR “tablet” OR “notebook” OR “laptop”)
Web of science	(TS = ((sleep apnea AND obstructive) OR (snoring) OR (sleep-disordered breathing) OR (sleep related breathing disorders) OR (sleep disturbed breathing))) AND TS = ((scanner) OR (facial scan) OR (3D face scanning) OR (3D scanner) OR (3D face impression) OR (3D surface scanning) OR (indirect face capturing) OR (optical scanner) OR (laser scanner) OR (structured light) OR (white-light scanner) OR (stereophotogrammetrical) OR (photogrammetry) OR (depth sensor cameras) OR (depth-sensing cameras) OR (smart device) OR (mobile) OR (smartphone) OR (tablet) OR (notebook) OR (laptop))
Cochrane library	#1: ((sleep apnea AND obstructive) OR (snoring) OR (sleep-disordered breathing) OR (sleep related breathing disorders) OR (sleep disturbed breathing)):ti,ab,kw # 2: ((scanner) OR (facial scan) OR (3D face scanning) OR (3D scanner) OR (3D face impression) OR (3D surface scanning) OR (indirect face capturing) OR (optical scanner) OR (laser scanner) OR (structured light) OR (white-light scanner) OR (stereophotogrammetrical) OR (photogrammetry) OR (depth sensor cameras) OR (depth-sensing cameras) OR (smart device) OR (mobile) OR (smartphone) OR (tablet) OR (notebook) OR (laptop)):ti,ab,kw # 3: #1 and #2

studies with inadequate data; (3) diagnosis of OSAHS using equipment other than 3D optical devices; (4) articles not written in English; and (5) presence of diseases affecting facial measurement.

Study selection and data collection

The information obtained from studies identified through the search strategy in each database was consolidated, and duplicate entries were eliminated. Subsequently, the titles and abstracts of the retrieved articles were independently assessed for eligibility by two investigators. Studies deemed ineligible by both investigators were promptly excluded, while those considered ineligible by one investigator but eligible by the other were retained. Full-text analysis was conducted collaboratively by two reviewers for all articles not excluded during the initial screening. Studies meeting the eligibility criteria underwent data extraction. Any discrepancies during the screening process were resolved through discussion. In the event of persistent disagreement, a consensus decision was reached with the involvement of the third reviewer through deliberation.

Data from included studies was gathered in detail. Report of the following variables was extracted: author(s), ethnicity, OSA groups, diagnostic criteria, participant, age, BMI, neck circumference, AHI, the type of 3D optical device, scanning process, number of landmarks, type of measurement, main findings and conclusions.

Risk of bias

QUADAS-2 was utilized to conduct a methodological evaluation of included studies, aiming to assess the risk of bias and identify potential sources of heterogeneity. Review Manager software, version 5.4 (The Cochrane Collaboration, Denmark), was employed for this purpose.[38] The QUADAS-2 tool encompasses four bias domains for risk of bias (index test, patient selection, reference standard, and flow and timing) and three domains for applicability (index test, patient selection, and reference test). Each domain was evaluated to determine the risk of bias. A study was considered to have an overall high risk of bias if one or more key domains were rated as high risk. Furthermore, if more than one key domain was assessed as unclear, the study was deemed to have an overall unclear risk of bias.

Results

Study selection

The electronic search across databases yielded a total of 3216 references, distributed as follows: 1564 from Web of Science, 564 from PubMed/MEDLINE, 761 from

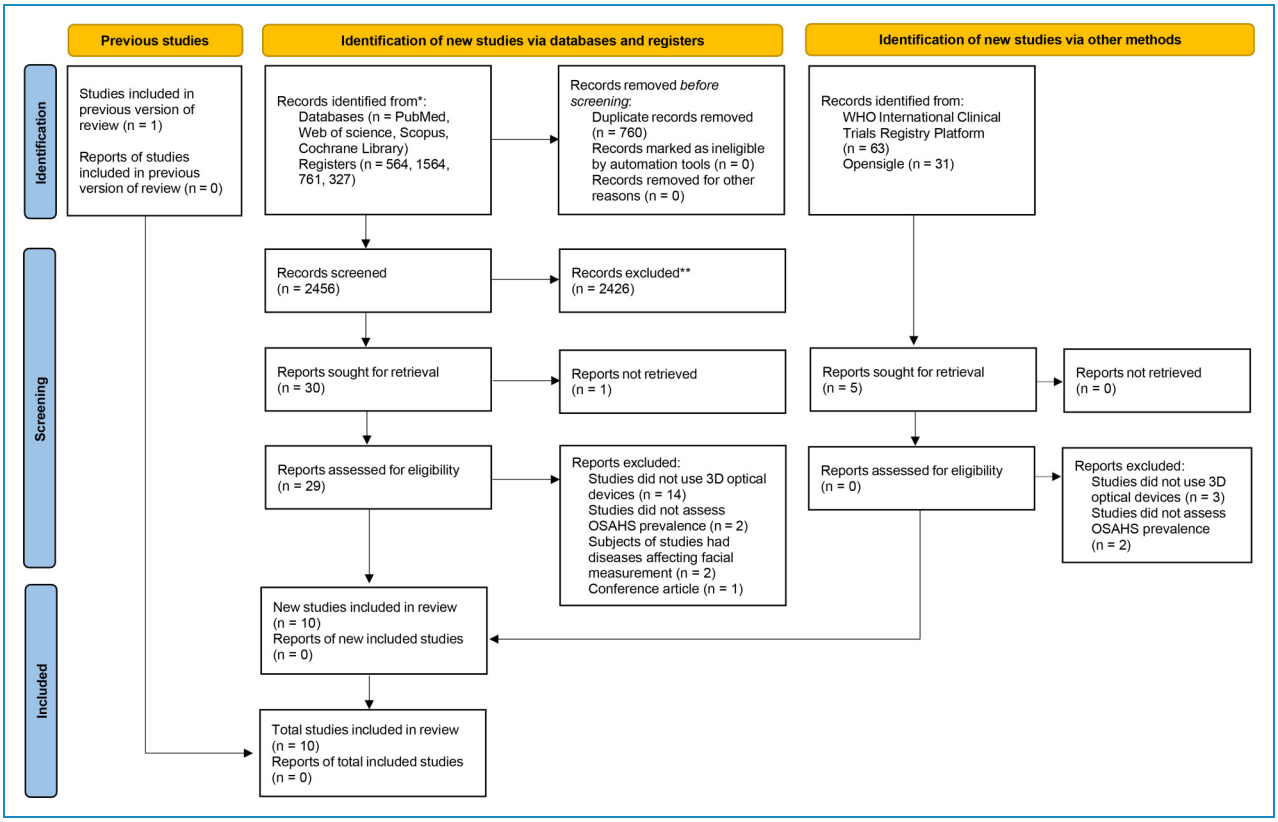

Figure 1. Flow chart of the literature search and results.

Scopus, and 327 from Cochrane Library. A manual search contributed one additional reference. None of the 94 references retrieved from gray literature were considered eligible. After removing duplicates, 2456 researches remained. The titles and abstracts were carefully evaluated by the authors based on the eligibility criteria. 2426 studies were excluded due to reasons including the inappropriate type of the studies, absence of 3D optical devices, lack of data related to the OSAHS assessment, language of articles, and existing diseases of subjects affecting facial measurement. 29 studies were remained after the analysis of titles and abstracts. Following full-text assessment, 19 studies were excluded, and 10 studies qualified for inclusion. Figure 1 provides a summary of the literature search process and outcomes.

Study characteristics

Detailed data from the 10 selected studies are presented in Table 2. These studies collectively involved 2641 participants from various racial backgrounds worldwide. 7 investigations evaluated the diagnostic accuracy of 3D optical devices in both non-OSAHS and OSAHS groups, while the remaining 3 studies exclusively focused on OSAHS patients. Most studies reported BMI, while the number of investigations that measured neck circumference and AHI were 6 and 7, respectively. Among the selected studies, 3D stereophotogrammetry emerged as the most commonly utilized scanning device, alongside the application of Artec 3D scanners and RGB-D cameras. However, due to discrepancies in devices and outcome characterization and assessment methods, conducting a meta-analysis was deemed unfeasible for this study.

Quality assessment and applicability concern

The risk of bias was evaluated using the QUADAS-2. For patient selection, 2 studies displayed an unclear risk of bias due to the lack of inclusion time and case continuity. All studies presented a low risk of bias in terms of the index test. Regarding the reference standard, one study displayed an unclear risk of bias since the questionnaire was used to determine the occurrence of OSAHS instead of polysomnography, the gold standard for the OSAHS diagnosis. Most of the included studies displayed an unclear risk of bias in flow and timing as the time interval between polysomnography and 3D optical devices was not mentioned. One research was regarded as a high risk of bias since only some patients have undergone polysomnography screening. For applicability, most studies showed a low level of concern, and only one study demonstrated a high level of concern in reference standard because polysomnography diagnosis was not fully adopted as the gold standard (Figure 2).

Discussion

Improving the early and timely diagnosis of OSAHS within the population holds the potential not only to alleviate the treatment burden on affected patients but also to yield significant cost savings. 3D optical devices, boasting high imaging accuracy, rapid scanning speeds, and radiation-free operation, demonstrate unprecedented promise in OSAHS diagnosis. Therefore, this review aimed to consolidate the existing knowledge on the use of 3D optical devices in predicting OSAHS. Despite a comprehensive search effort, only 10 articles informed the conclusions in the present study, most of which underscored the diagnostic potential of these devices. To our knowledge, this is the first study that focuses on the potential of 3D optical devices in diagnosing OSAHS.

Previous studies have demonstrated the association between surface facial dimensions and OSAHS, bolstering the potential utility of surface facial measurements in predicting the condition.[39] Various facial features have been identified in the selected studies as predictive indicators of OSAHS occurrence and severity. For instance, Hanif et al. emphasized the significance of the chin area and neck in their predictive model.[30] Another study highlighted craniofacial obesity in the bucco-submandibular regions as a pivotal factor in OSAHS occurrence, offering promising avenues for identifying undiagnosed OSAHS subjects.[26] Moreover, Ohmura et al. identified mandibular width length angle and mandibular angle as crucial parameters in predicting OSAHS presence, regardless of sex and obesity status.[33] However, while measurements of inter-landmark distances in maxillofacial anatomy may aid in OSAHS prediction, caution is warranted, given the multifactorial nature of the condition.[34] Establishing relationships between craniofacial morphology and OSAHS development remains challenging due to the condition's diverse and complex etiology.

Based on their principles, 3D optical devices are classified into laser scanners, structured light scanners, stereophotogrammetry, and RGB-D cameras.[40] Laser scanners, as one of the earliest types of 3D optical devices, operate by emitting a laser beam across the object's surface, which is then collected at a triangulation distance from the laser, enabling the calculation of x, y, and z coordinates of surface points.[41] However, due to their limitations, including large size, high cost, and immobility, laser scanners are not suitable for accurately measuring facial morphology in living patients and none of the included studies utilized laser scanners to predict OSAHS. Structured light scanners project a pattern of light onto the subject using a grating. The deformation of the pattern is recorded by a CCD charge-coupled device, and distances are calculated using algorithms, ultimately reconstructing a 3D image through computer software.[42] Despite being cheaper and portable, structured light scanners are associated with

Table 2. Main characteristics of included studies.

Study	Ethnic	OSA groups	Diagnostic criteria	Participant (male:female)	Age Mean ± SD [range]	BMI (kg/m^2)	Neck circumference	AHI (events/hour)
Banabilh et al.,[26]	Malays	Non-OSA and OSA	Non-OSA: AHI of 0–4; OSA: AHI ≥5	80 (80:0)	[18–60]	Non-OSA: 24.8 ± 6.5; OSA: 32.3 ± 7.4	Non-OSA: 37.1 ± 2.2; OSA: 42.7 ± 2.5	Non-OSA: 2.0 ± 2.0; OSA: 40.0 ± 30.3
Collier et al.[27]		Suspicion of OSA	OAHI	91 (61:30)	46 ± 12	30.1 ± 6.5	40 ± 4	OAHI 19.3 ± 18.8
Eastwood et al.[28]	Caucasian	Non-OSA and OSA	non OSA: AHI <5, n = 100; mild OSA: 15 > AHI ≥ 5, n = 100; moderate OSA: 30 > AHI ≥ 15, n = 100; severe OSA: AHI ≥ 30, n = 100	400 (172:228)	52.7 ± 15.6	non OSA: 26.9 ± 5.2; mild OSA: 29.2 ± 6.8; moderate OSA: 32.3 ± 7.2; severe OSA: 35.5 ± 7.5	non OSA: 35.0 ± 3.8; mild OSA: 37.7 ± 4.5; moderate OSA: 40.3 ± 4.3; severe OSA: 41.6 ± 4.7	non OSA: 2.6 ± 1.3; mild OSA: 9.9 ± 2.9; moderate OSA: 22.6 ± 4.6; severe OSA: 59.7 ± 25.8
Fernandes et al.[29]		Non-OSA and OSA	Pediatric OSA (OMAHI index ≥ 2); mild (OMAHI: 2–4.9); moderate (OMAHI: 5–9.9); severe (OMAHI ≥ 10); high-risk for OSA (PSQ score ≥ 8); slow-risk for OSA (PSQ score < 8)	152	[2–17]			
Hanif et al.[30]		OSA	Mild or Non OSA (AHI < 15) ; Moderate-severe OSA (AHI ≥ 15)	1366 (642:724)	45.9 ± 14.8	30.9 ± 8.7		15.5 ± 19.3
Lin et al.[31]	Asians	OSA	OSA (AHI ≥ 5) who had at least two of symptoms: snoring, daytime sleepiness, witnessed breath-holding during sleep or unrefreshed sleep	38 (38:0)	40.7 ± 10.3 [22–62]	27.5 ± 4.1		50.9 ± 27.7
Monna et al.[32]	Caucasian	Non-OSA and OSA	Non-OSA: AHI < 15; OSA: 15 ≥ AHI	280 (280:0)	59.2 [40–75]	27 [18.3–35.1]	40.3 [34–48]	23.7 [0.5–99.5]
Ohmura et al.[33]	Japanese	Non-OSA and OSA	non OSA: AHI < 5, n = 5; mild OSA: 15 > AHI ≥ 5, n = 5; moderate OSA: 30 > AHI ≥ 15, n = 11; severe OSA: AHI ≥ 30, n = 16	37 (28:9)	57.5 ± 13.1 [30–86]	Non-OSA: 23.2 ± 2.6; OSA: 26.3 ± 5.1	Non-OSA: 38.4 ± 3.5; OSA: 38.5 ± 4.4	Non-OSA: 3.5 ± 1.0; OSA: 38.3 ± 25.9

(continued)

Table 2. Continued.

Study	Ethnic	OSA groups	Diagnostic criteria	Participant (male:female)	Age Mean ± SD [range]	BMI (kg/m^2)	Neck circumference	AHI (events/hour)
Ozdemir et al.[34]	Turkish	Non-OSA and OSA	Non-OSA: subjects with simple snoring-diagnosed subjects after PSG (AHI < 5); OSA: AHI ≥ 5	106 (61:45)	Non-OSA: 42.42 ± 7.44; OSA: 50.79 ± 9.07	Non-OSA: 26.11 [18.93–42.97]; OSA: 32.30 [25.40–52]		
Tyler et al.[35]	Caucasian, Asian, Oceanian, Middle Eastern and African	Non-OSA and OSA	non OSA: OAHI <1, $n = 10$; mild OSA: 5 > OAHI ≥ 1, $n = 15$; moderate OSA: 10 > OAHI ≥ 5, $n = 15$; severe OSA: OAHI ≥ 10, $n = 51$	91 (57:34)	4.4 ± 4.7 [0.05–16.02]			AHI: 21.0 ± 20.0; OAHI: 15.6 ± 16.5

Study	Scanner	Scanning process	Landmarks	Measure ments	Main findings	Conclusions
Banabilh et al.[26]	3D stereophotogrammetry (3dMD, USA)	The patient sat upright, 175 cm from four camera pods, and captured images in <2 ms.	9	Principal component analysis	There was a significant difference in facial shape between the two groups (OSA: AHI ≥5), accounting for 50% of the total shape change ($p < 0.05$). The difference was mainly in the buccosubmandibular regions of the face, indicating an increase in volume of 7–22% ($p < 0.05$) for the OSA group.	Craniofacial obesity in the bucco-submandibular regions is associated with OSA and may provide valuable screening information to identify patients with undiagnosed OSA.
Collier et al.[27]	3dMD head motion system (3dMD, USA)	The subject wore a hair cap and sat in the machine, adopting a natural head posture.	16	39 (24 linear measurements; 13 angles; 2 surfaces)	The following parameters ($p < 0.5$) could predict the OAHI: sex, BMI, neck-depth (Nd)/ mandibular-length (Ml), mandibular-width angle, Nd euclidean distance/surface distance and the interaction terms between sex and Nd/Ml, sex and Nd and BMI and Nd. The interaction between sex and Nd/Ml showed a steeper linear course in females. With a	Measurements involving the width of the face and addressing the soft tissue in the upper neck were found to have a significant relation with OSA severity. There were remarkable differences between obesity status and genders.

(continued)

Table 2. Continued.

Study	Scanner	Scanning process	Landmarks	Measure ments	Main findings	Conclusions
					same neck-depth ratio, the OAHI is larger in men.	
Eastwood et al.[28]	3dMD craniofacial scanner system (3dMD LCC, USA)	The patient sat between two cameras with the hair pulled back, images captured within 1.5 ms.	24	25 liner distances; 25 geodesic distance and 10 angles	Combining linear and geodetic measurements into a single prediction algorithm improves accuracy, the sensitivity, specificity, accuracy, and AUC of the algorithm to predict OSA (AHI $\geq$ 5) based on this combination was 97%, 76%, 91% and 0.96. When AHI $\geq$ 10/15 is used to define OSA, the accuracy decreases.	3D photographs of the face have predictive value for OSA and that geodesic measurements enhance this capacity.
Fernandes et al.[29]				8 craniofacial feature scores	When only 3D facial stereophotogrammetry was used and when all tools were assessed simultaneously, sensitivity and specificity varied among clinicians, indicating a low screening ability for 3D stereophotogrammetry, ranging from 0.36–0.90 and 0.10–0.70 and all tools ranging from 0.53–1.0 and 0.01–0.49.	3D facial analysis does not seem predictive for pediatric OSA, alone or combined with the Pediatric Sleep Questionnaire and Craniofacial Index when used by dental specialists.
Hanif et al.[30]	A Structure Sensor from Occipital Inc. attached to an iPad Pro (Apple, USA)	Each scan was performed before or after the PSG and took about 1 min to obtain a complete surface scan.	73	3D mesh scans	When distinguished OSA by AHI $\geq$15, an overall accuracy of 67 $\pm$ 4% was obtained. Sensitivity was 59 $\pm$ 8%, specificity was 72 $\pm$ 5%, and AUC was 65 $\pm$ 4%. When adding clinically relevant demographics and questionnaire scores to the model, an accuracy of 67 $\pm$ 4% was achieved, with sensitivity of 74 $\pm$ 7%, specificity of 63 $\pm$ 7%, and AUC of 69 $\pm$ 3%.	The study created topographic displays of the most important facial features used by the model to predict AHI, showing importance of the neck and chin area.

(continued)

Table 2. Continued.

Study	Scanner	Scanning process	Landmarks	Measure ments	Main findings	Conclusions
Lin et al.[31]	3dMD cranial5 system (3dMD LLC, USA)	Each subject was placed in a natural uprightseated position with a cap to cover their hair.	20	25 (12 lines, 5 angles, 3 areas and 5 volumes)	Mandibular width, neck perimeter size and maxillary volume measurements correlated well with the severity of OSA (AHI $\geq$ 5) using all three imaging methods. A multivariate predictive model in predicting OSA severity by 3dMD was created ($r = 0.523$, $p = 0.058$): AHI $= -193.0 + 64.3\times$ mandibular length $+114.8\times$neck width $+ 41.4\times$ neck perimeter $-18.5\times$cranial area $1 + 0.0038\times$ maxillary volume.	Radiation free 3dMD provided accurate craniofacial measurements of OSA patients, that are highly consistent with CT and less consistent with 2D digital photogrammetry.
Monna et al.[32]	Sense v2 (3D systems, USA)	A mount equipped with bubble levels was used to ensure consistent horizontal head position. The scanning process lasted about 10 min.	7	7 landmarks and 500 semi-landmarks (507 points)	The specificity of OSA diagnosis (AHI $\geq$ 15) obtained by ML analysis of 3D craniofacial shape (56%) was higher than that of the questionnaire (Berlin: 50%; NoSAS: 40%). The sensitivity using ML analysis was 80%, while the NoSAS and BERLIN questionnaires was about 90% and 61%, respectively. The AUC score was further improved when 3D geometric morphometry was combined with patient anthropometry (AUC = 0.75).	3D morphometry combined with machine learning (ML), which already has a discriminative power beyond currently available tools (i.e. NoSAS and BERLIN), is considered to be a efficient, fast, and inexpensive screening tool for OSA.
Ohmura et al.[33]	3D photogrammetry (Shining 3D; EinScan Pro, China)	The device was placed 0.5–2.0 m from the patient in a closed-mouth supine position, and image was captured in about 30 s.	3	Mandibular width (Mw), length (Ml), depth (Md), width length angle (Mwla), and area (Ma)	Mwla was strongly correlated with AHI, it could predict the presence of OSA (AHI $\geq$ 5; AUC: 0.931), (AHI $\geq$ 10; AUC: 0.967). Mwla ($r = 0.73$, $p < 0.01$), Mw ($r = 0.39$, $p < 0.05$), and Md ($r = 0.34$, $p < 0.05$) were significantly correlated with the severity of OSA. And Mwla ($p < 0.01$) and Md ($p < 0.05$) remained independent factors for AHI.	Among the measurements obtained using 3D photogrammetry, Mwla was the most significantly correlated with AHI, regardless of sex and presence of obesity.

(continued)

Table 2. Continued.

Study	Scanner	Scanning process	Landmarks	Measure ments	Main findings	Conclusions
Ozdemir et al.[34]	Artec 3D scanners	3D facial scanning procedure were performed on the same day as the PSG.	12	66 interlandmark distances	No statistically significant difference in terms of general shape of face was found between the two group (OSA: AHI ≥ 5). There were significant differences between the groups in some of the interlandmark distances: 11% of the interlandmark distances were greater in OSA, which are concentrated in the nasal region. And 29% were greater in non-OSA, but it is not concentrated in a specific region.	OSA is a multifactorial clinical entity, the etiology of OSAS is too diverse and complex to be explained by a simple relationship established between craniofacial morphology and the development of the disease.
Tyler et al.[35]	3D facial imaging; 3DMD software (3dMD LLC, USA)	Patient positioning requires mouth closure and their top jaw aligned with their bottom jaw, with a hairnet.	3	3 (1 angle)	The logarithm of age and sex had a significant effect on facial convexity, while excluding OSA. Ordinal logistic regression taking into consideration growth (age, weight, and height), sex, and ethnicity with OSA severity showed that facial convexity was associated with OSA severity ($p = 0.0022$); an increasing angle of convexity increased the tendency to be classified as having severe OSA.	Infancy had an added impact of on changes of facial convexity with age. And differences in facial convexity were present among groups with OSA severity adjusted for growth, sex, and ethnicity.

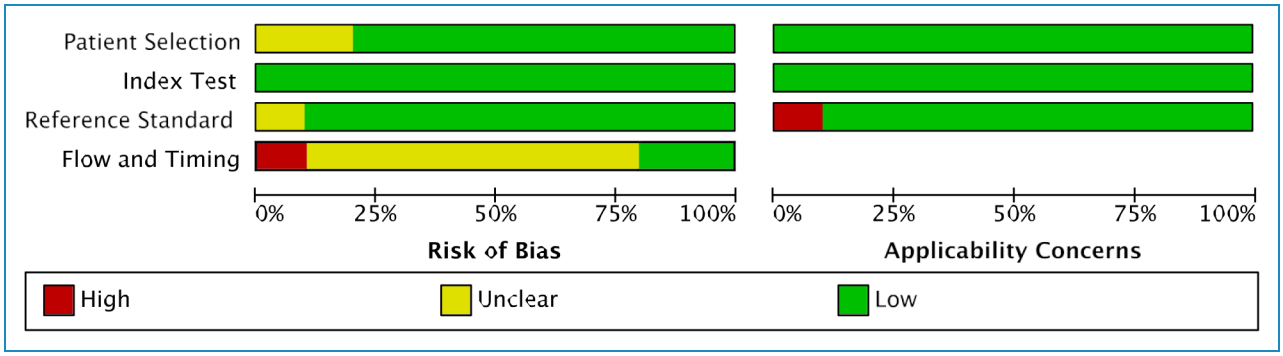

Figure 2. Risk of bias and application.

relatively low precision and accuracy. One of the included studies evaluated the diagnostic value of structured light scanners, with results indicating relatively low accuracy.[32] Conversely, 8 studies employing stereophotogrammetry yielded promising results in predicting OSAHS due to its excellent precision in measuring craniofacial morphology.[26–28,31–35] Stereophotogrammetry accurately reproduces the face's surface geometry and maps realistic color and texture data onto the geometric shape, leading to lifelike renderings.[43] Thus, it appears that 3D optical devices based on stereophotogrammetry are optimal for predicting OSAHS. Moreover, another study assessed OSAHS occurrence using a recently developed RGB-D camera.[30] The RGB-D camera, introduced in 2010, provides both color images and per-pixel depth images of objects through active physical measurement.[44] The results indicated that the developed model achieved comparable accuracy to two experts and outperformed one. Therefore, when stereophotogrammetry is not feasible due to limitations such as cost and resources, an RGB-D camera may serve as an alternative for measuring craniofacial morphology and predicting OSAHS prevalence and severity with acceptable precision and reasonable accuracy.

The potential of 3D optical devices in predicting OSAHS has garnered significant attention as emerging tools compared to traditional approaches. Although polysomnography remains the gold standard for OSAHS diagnosis, its widespread adoption is hindered by barriers in many countries, including high costs and long wait times for public health services.[45] Similarly, only a limited number of hospitals have the capacity to perform cephalography, Cone beam Computer Tomography (CBCT), and MRI for maxillofacial morphology evaluation. Furthermore, the utilization of these devices circumvents the limitations associated with radiation exposure in cephalometry and CBCT as well as the high expenses linked with MRI. Lin et al. conducted a comparative analysis of the predictive accuracy of 3D optical devices against 2D digital photogrammetry and 3D CT.[31] Their findings indicated that radiation-free 3D optical devices delivered precise craniofacial measurements in OSAHS patients, exhibiting high consistency with CT measurements, while demonstrating poor agreement with 2D digital photogrammetry. While traditional high-resolution scanner systems may be expensive, integrating the method into existing, affordable, off-the-shelf systems could be feasible. Additionally, recently developed RGB-D cameras may offer an alternative for measuring craniofacial morphology and predicting OSAHS prevalence and severity with acceptable precision and reasonable accuracy.

The findings from the present study suggest that 3D optical devices offer a simple, rapid, accurate, and objective means of identifying individuals at high risk of OSAHS, potentially serving as a novel screening tool for widespread use in the general population. Future research avenues could explore additional clinically relevant variables captured by sleep studies to enhance the predictive capabilities of models and improve understanding of OSA phenotypes and their relationship to facial anatomy. Furthermore, the relatively small cohorts in the included studies may not fully encompass the diversity of maxillofacial shapes. With larger cohorts, potential benefits arise, the application of more complex algorithms improved adaptation to nonlinearly separable OSAHS and non OSAHS groups, and the possibility of embedding the method into existing, inexpensive, off-the-shelf systems, potentially reducing costs associated with traditional high-resolution scanner systems. Finally, the measurement can be automated by using the libraries for detection of selected face features in the future to save diagnostic time and decrease human errors and medical specialists presence during the measurement.[46]

The present study has several limitations. Firstly, despite conducting extensive literature searches, only 10 articles met the eligibility criteria, limiting the scope of conclusions. Secondly, considerable heterogeneity was observed among articles assessing the suitability of 3D optical devices for OSAHS screening. This heterogeneity rendered a meta-analysis unfeasible due to differences in the types of 3D optical devices used and variations in outcome characterization and assessment methods. Additionally, inconsistencies were noted in the definition of OSAHS and the

characteristics of participant groups across studies, with some studies lacking specificity in participant diagnosis. Consequently, further high-quality studies with standardized methodologies are warranted before recommending the use of these devices in clinical practice.

Conclusions

Despite the limitations, the utilization of 3D optical devices for OSAHS diagnosis holds significant promise, offering potential improvements in accuracy, cost reduction, and time efficiency. While they cannot replace polysomnography, 3D optical devices play a crucial role in detecting OSAHS patients during large-scale screening initiatives, particularly in regions with limited or inaccessible medical facilities. However, caution is warranted among practitioners when employing these devices in clinical decision-making, as they are still in the early stages of development. Additional clinical data are needed, and detection methods based on 3D optical devices must undergo strict standardization to enhance reliability and effectiveness.

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Data availability: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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