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REVIEW ARTICLE

Pediatrics

# Are obstructive sleep apnea and sleep improved in response to multidisciplinary weight loss interventions in youth with obesity? A systematic review and meta-analysis

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## Abstract

**Background** Pediatric obesity is closely associated with obstructive sleep apnea (OSA) and short sleep duration. While multidisciplinary weight loss interventions are recommended for pediatric obesity management, the evidence for their effects on OSA severity and overall sleep in youth have not been systematically examined.

**Objectives** To conduct a systematic review and meta-analysis investigating the effects of multidisciplinary weight loss interventions on OSA severity and prevalence, and on overall sleep health in youth with obesity.

**Methods** A systematic search of interventional studies (participants age range: 10–19 yrs) was performed using PubMed, CENTRAL and Embase, from inception to May 2019. The quality of the evidence was assessed using the Cochrane risk of bias tool.

**Results** Ten studies were included by the end of the screening process. Ninety percent of the included studies reported a decrease in OSA prevalence post-intervention, and OSA was normalized for 46.2–79.7% of the youth. The meta-analysis comprising seven longitudinal studies revealed significant reductions in apnea–hypopnea index (effect size: −0.51, 95%CI −0.94 to −0.08, $p = 0.019$), and oxygen desaturation index (effect size: −0.28, 95%CI = −0.50 to −0.05, $p = 0.016$). Seventy-five percent of the studies reported improved sleep duration in youth with OSA.

**Conclusions** Evidence suggests that multidisciplinary weight loss interventions result in improvements in OSA severity and sleep duration in youth with obesity. Future randomized controlled trials are warranted to better assess and understand the independent implications of weight loss, fat mass decrease and chronic exercise on OSA and sleep health in this population.

## Introduction

Obstructive sleep apnea (OSA) represents a chronic condition characterized by complete or partial upper airway obstruction during sleep [1]. Prevalence rates of both OSA and obesity are growing worldwide among children and adolescents [2]. In 1999, Redline et al. already observed a 4- to 5-time higher risk of presenting sleep-disordered breathing among 2–18

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years old children and adolescents with obesity compared with normal-weight ones [3]. The prevalence of OSA reaches 33–61% in youth with obesity [4–8], while it represents 1–3% in the general pediatric population [9–11]. OSA has been found to alter sleep quality [12] while obesity has been found to be associated with shorter sleep duration and impaired sleep architecture [8, 13–16].

Through different pathways, OSA and obesity have both been found to be involved in the development of metabolic disorders, leading to an increased risk of cardiovascular disease [17, 18]. Indeed, breathing disorders during sleep are associated with sleep fragmentation [12] and intermittent hypoxia [19], leading to sympathetic overactivity [20, 21] and an over-production of radical oxygen species [22]; these disturbances have been reported to be involved in the development of type 2 diabetes, hypertension, and dyslipidemia [23]. Concomitantly, adipose tissue dysfunction generally observed in pediatric obesity, has been incriminated in the development of insulin resistance [24, 25] which, in turn, has a major impact on the metabolism of triglyceride-rich lipoproteins and free-fatty acids, favoring the pro-atherogenic state [26].

Although several treatment options are available for OSA in the general population, its management in youth with obesity remains challenging [27–29]. Adenotonsillectomy, an operation to remove both the adenoids and tonsils, has for instance shown low success in treating OSA in youth with obesity [28, 30–32]. In addition, continuous positive airway pressure (CPAP) adherence in youth with OSA is relatively poor [29, 33, 34]. Interestingly, surgical weight loss interventions have been shown effective in improving OSA severity [4, 35]. In their study, Kalra et al. observed a normalized OSA in 90% of their patients aged between 13 and 18 years after a gastric bypass surgery inducing a mean weight loss of 58 kg, over 5 months [4]. In a larger sample composed of 98 adolescents with obesity, Alqahtani et al. reported a 81% normalization of OSA after sleeve gastrectomy surgery [35]. Since the use of bariatric surgery among children and adolescents is debatable and must follow strict supervision and recommendations [36], multidisciplinary weight loss interventions are encouraged in youth with obesity as a first treatment approach [37].

While the evidence regarding the efficacy of multidisciplinary interventions to improve obesity [38], metabolic profile [39], and functional capacities [40] is compelling, less is known regarding their effect on OSA and overall sleep health in children and adolescents with obesity. Hence, the objective of this systematic review and meta-analysis is to examine the effects of multidisciplinary weight loss interventions on OSA severity and prevalence as well as on overall sleep characteristics in youth with obesity. We hypothesized that multidisciplinary weight loss interventions would be effective in reducing OSA indicators such as the apnea–hypopnea index (AHI), oxygen desaturation index (ODI) and obstructive AHI (OAHI), and in improving sleep duration and sleep architecture (rapid-eye movement (REM) sleep and non-REM sleep).

## Methods

This systematic review and meta-analysis protocol was registered in the International Prospective Register of Systematic Reviews (PROSPERO; registration number CRD42019131640), and was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).

### Search strategy

The participants, interventions, comparisons, outcomes, and study design (PICOS) framework [41] were followed to determine the research question, plan the search strategy, and refine the screening approach and eligibility criteria.

Studies providing pre- and post-multidisciplinary weight loss interventions results for OSA and overall sleep in youth were searched using PubMed, CENTRAL, and Embase. The following search combination on PubMed and CENTRAL was used: ("Sleep Apnea Syndromes" (MeSH) AND "Weight loss" (MeSH) AND "Diet" (MeSH) AND "Behavior Therapy" (MeSH) OR "Life Style" (MeSH) AND "Obesity (MeSH) OR "Pediatric Obesity" (MeSH)). On Embase, the following search combination was used: ('obesity'/exp AND ('sleep disordered breathing'/exp OR 'sleep'/exp) AND ('behavior therapy'/exp OR 'weight loss program'/exp OR 'diet therapy'/exp OR 'body weight loss'/exp) AND ([adolescent]/lim OR [young adult]/lim) AND [embase]/lim NOT ([embase]/lim AND [medline]/lim)). The searches on PubMed, CENTRAL, and Embase respectively identified 460, 55, and 326 publications. All searches were conducted between February 1st and May 10th, 2019. Additional searches were performed from the reference lists of the selected literature.

Based on the selection criteria, screening by title and abstract was independently performed by two authors (JR and DT). Disagreement between authors was resolved by discussion and, if needed, a third author's final decision was solicited. Full manuscripts of potential studies were obtained and screened for the final inclusion and data extraction following the same procedure.

### Study selection criteria

Randomized controlled trials (RCTs) and uncontrolled interventional studies were eligible to be included upon

meeting the following criteria: (a) patients aged between 10 and 19 years; (b) supervised multidisciplinary intervention including both diet and exercise training; (c) no use of CPAP; and (d) providing pre- and post-intervention results of at least one of the most common OSA parameters (AHI or ODI). The exclusion criteria were as follows: (a) case reports, reviews and cross-sectional studies; (b) current or previous surgical interventions for obesity (bariatric surgery); (c) secondary obesity (Prader Willi syndrome and Down's syndrome), asthma and polycystic ovary syndrome; and (d) trials reported in other languages than English or French. Gray literature, book chapters, dissertations, and conference abstracts were also excluded.

### Data synthesis

One of the primary outcomes of interest was AHI, defined by the American Academy of Sleep Medicine (AASM) [1] as the number of apnea (airflow reduction ≥ 90%) and hypopnea (airflow reduction ≥ 30%, associated with ≥3% fall in oxygen saturation and/or arousal) per hour of sleep, each episode lasting at least the duration of two breaths. The other primary outcomes were ODI (defined as the number of oxygen desaturations per hour than or equal 3%), obstructive apnea–hypopnea index (OAHI), body mass index (BMI), BMI $z$-score and fat mass, homeostasis model assessment of insulin resistance ($HOMA_{IR}$), and peak of oxygen consumption ($VO_{2peak}$). As secondary outcomes, we included total sleep time (TST), percentage of REM sleep and percentage of Non-REM sleep stage 1 (N1), sleep stage 2 (N2), and sleep stage 3 (N3), all measured by polysomnography.

### Meta-analysis procedure

The statistical analyses were conducted using Stata software (StataCorp, College Station, US). For descriptive analyses, data were presented as mean and standard-deviation or median and interquartile range, according to statistical distribution. Furthermore, the data included: sample size, pre- and post-intervention AHI, and ODI values. Two of the authors extracted the studies independently and any disagreement was discussed, and a common decision taken. Studies were selected if they met all the inclusion criteria previously detailed and if their design was judged satisfactory [42]. The mean standardized differences were calculated to determine effect sizes estimated using random-effects model that accounts for true variation in effects occurring from study to study, as well as random error within single studies. This random effect model was preferred over a fixed-effect approach as some experimental parameters such as the measurement of AHI and ODI had wide variation, which is better considered with the random-effects model during analysis. Means and standard-deviations were compiled when available, or estimated using Hozo et al. [43] when median and interquartile range were reported. The standard-deviation of the difference between time-points evaluation (T0 and T1) was estimated using the formula: $\sqrt{\left(\left(SD_{T0}^2 + SD_{T1}^2\right) - \left(2 \times 0.5 \times SD_{T0} \times SD_{T1}\right)\right)}$. The effect sizes were interpreted according to Cohen such as <0.2 as trivial, 0.2–0.3 as small, 0.5–0.8 as moderate, and >0.8 as large [44]. A negative effect size value indicates decreased AHI or ODI in response to the multidisciplinary weight loss program while a positive effect size indicates that AHI or ODI increased. The $I^2$ index was used to calculate heterogeneity with 25%, 50% and 75% respectively indicating low, moderate and high heterogeneity [45]. Finally, sensitivity analyses were conducted to assess how including and excluding studies influenced our results. More precisely, the sensitivity analyses were performed to measure the impact of high heterogeneity, methodological quality estimated too low and publication bias assessed using funnel plots. In absence of bias, studies should be distributed evenly around the mean effect size because of random sampling error. Statistical significance was set at $p < 0.05$ in a $Z$-test analysis. The $Z$-tests were used to examine if effect sizes were significantly different from zero.

## Results

### Search results

The systematic search yielded 841 studies and two additional records were identified through other sources. After removal of duplicates and screening by title and abstract, 11 eligible full texts were evaluated for the final inclusion in the review. The flowchart of the search and selection of studies is shown in Fig. 1. A total of ten uncontrolled interventional studies were selected for inclusion [7, 8, 46–53]. No RCT was found. In addition, for the study of Siegfried et al. we excluded eight patients aged 20 years or older [46]. Thanks to the presentation of every single data of each participant in the article, we were able to recalculate every result after exclusion of these subjects.

### Risk of bias and quality assessment

The Cochrane risk of bias tool [54] was used to assess risk of bias (Table 1). Two authors independently estimated risks of bias for each included study. Selection, performance, detection attrition, and reporting bias were assessed. Any disagreements were discussed with a third co-author

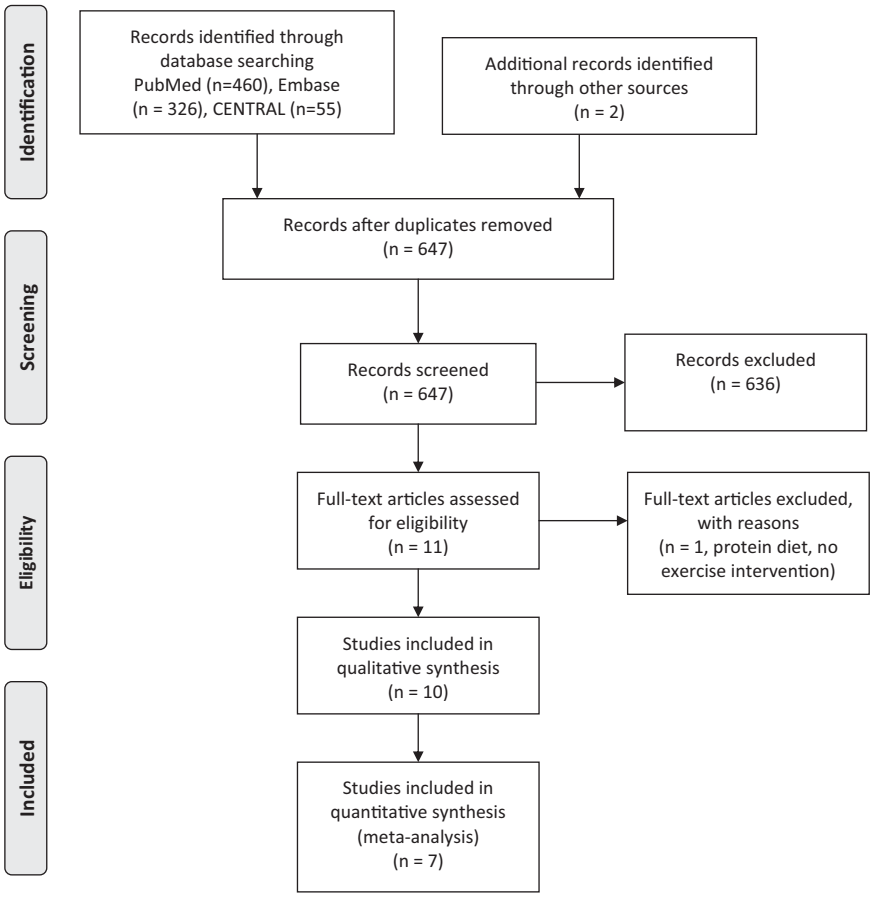



**Fig. 1** Flow diagram of the description of the screening, selection, and inclusion process

**Table 1** Cochrane risk of bias

| First author | Random Sequence Generation | Allocation concealment | Blinding of participants and personnel | Blinding of outcome assessment | Incomplete outcome data | Selective outcome reporting |
|---|---|---|---|---|---|---|
| Siegfried et al. [46] | High risk | NR | High risk | High risk | Low risk | Low risk |
| Verhulst et al. [47] | High risk | NR | High risk | High risk | High risk | High risk |
| Van Hoorenbeeck et al. [48] | High risk | NR | High risk | High risk | High risk | High risk |
| Van Hoorenbeeck et al. [49] | High risk | NR | High risk | High risk | Moderate risk | Low risk |
| Van Eyck et al. [50] | High risk | NR | High risk | High risk | Moderate risk | Low risk |
| Corgosinho et al. [51] | High risk | NR | High risk | High risk | Moderate risk | Moderate risk |
| Corgosinho et al. [52] | High risk | NR | High risk | High risk | Low risk | Low risk |
| Roche et al. [8] | High risk | NR | High risk | High risk | Low risk | Moderate risk |
| Roche et al. [7] | High risk | NR | High risk | High risk | Low risk | Low risk |
| Roche et al. [53] | High risk | NR | High risk | High risk | Moderate risk | Low risk |

NR = not reported

until a consensus was reached. No study was excluded on the basis of risk of bias.

## Population description

The description of participants and interventions of all included studies is reported in the Table 2. The total sample was composed of 962 participants (342 youth identified with OSA, 620 without OSA). Among the ten studies, all included boys and girls in their analysis, with the total sample being 35.4% of boys [7, 8, 46–53]. Verhulst et al., Van Hoorenbeeck et al. and Van Eyck et al. included youth aged between 10 and 19 years [47–50], Siegfried et al. and Corgosinho et al. included youth aged between 14 and 19 years [46, 51, 52] and Roche et al. included youth aged between 11 and 18 years [7, 8, 53]. Every study included exclusively obese participants [7, 8, 46–53].

## OSA prevalence and sex repartition

Siegfried et al. using an AHI≥5 reported a prevalence of OSA of about 20%, 33.3% being boys [46].

**Table 2** Description of participants and interventions

| First author | Study design | Population description *n* (% boys), age, BMI/BMI-z | Definition and prevalence of OSA (%boys with OSA) | T&A history, Tonsillar size | Intervention | Duration (mo) | Sleep assessment method outcomes |
|---|---|---|---|---|---|---|---|
| Siegfried et al. [46] (Germany) | P-U | $N = 30$ (30% boys)[a]<br>Age = 16.8 (14–19)[a]<br>BMI = 44.92 ± 7.50[a] | Criterion = AHI ≥ 5<br>OSA = 20% (33.3% boys)[a] | n/a | Diet (1600 kcal/d)<br>Exercise<br>Psychotherapy | 5.8[a] | **PG**<br>Blood pressure |
| Verhulst et al. [47] (Belgium) | P-U | $N = 61$ (31% boys)<br>Age = 14.8 (10.1–18.3)<br>BMI = 37.5 ± 5.7<br>BMI-z = 2.7 ± 0.4 | Criterion = AHI ≥ 2<br>OSA = 60.7% (46% boys) | **Whole population:** Tonsillectomy: 29.5%<br>Adenoidectomy: 37.7%<br>**OSA group:** Tonsillectomy: 27%<br>Adenoidectomy: 27%<br>Tonsillar size (Brodsky score):<br>**-2≤AHI<5**: 1 (0–5)<br>**-AHI≥5**: 2(0–5) | Diet (1400–1600 kcal/d)<br>Exercise (10 h/w)<br>Psychological support | 5.2 | **PG**<br>Modified Epworth questionnaire<br>WC, WHR |
| Van Hoorenbeeck et al. [48] (Belgium) | P-U | $N = 132$ (31% boys)<br>Age = 15.4 (10.1–18.0)<br>BMI-z = 2.72 ± 0.42 | Criterion = ODI ≥ 2<br>OSA = 39.4% (44.2% boys) | **Whole population:** Tonsils hypertrophy (Brodsky score ≥ 3+): 14.4%<br>**OSA group:** Tonsils hypertrophy 19.2%<br>−**2≤ODI<5**: 20%<br>−**ODI≥5**: 14% | Diet (1400–1600 kcal/d)<br>Exercise (10 h/w)<br>Psychological support | 5.1 | **PG**<br>Inflammatory profile (hs-CRP, lymphocytes, leukocytes, neutrophils) and uric acid |
| Van Hoorenbeeck et al. [49] (Belgium) | P-U | $N = 224$ (33.5% boys)<br>Age = 15.5 (10.1–18.0)<br>BMI-z = 2.74 ± 0.42 | Criterion = ODI ≥ 2<br>OSA = 30.4% (51.5% boys) | n/a | Diet (1400–1600 kcal/d)<br>Exercise (10 h/w)<br>Psychological support | 5.1 | **PG**<br>Metabolic profile (glucose, insulin, $HOMA_{IR}$ and lipid profile), ASAT and ALAT |
| Van Eyck et al. [50] (Belgium) | P-U | $N = 339$ (34.8% boys)<br>Age = 15.4 (10.1–19.1)<br>BMI-z = 2.75 ± 0.42 | Criterion = ODI ≥ 2<br>OSA = 31.9% (53.7% boys) | **Whole population:** Tonsils hypertrophy (Brodsky score ≥ 3+): 17.7%<br>**OSA group:** Tonsils hypertrophy 19.8% | Diet (1400–1600 kcal/d)<br>Exercise (10 h/w)<br>Psychological support | 5.2 | **PG**<br>International Study of Asthma and Allergies in Children (ISAAC) Questionnaire<br>WHR |
| Corgosinho et al. [51] (Brazil) | P-U | $N = 55$ (38.2% boys)<br>Age = 15–19<br>BMI = 37.6 ± 5.3 | Criterion = AHI ≥ 5<br>OSA = 21.9% (n/a) | n/a | Nutritional therapy<br>Exercise training (3 h/w)<br>Psychotherapy | 12 | **PSG**: TST, N-REM, REM<br>Metabolic profile (glucose, insulin, $HOMA_{IR}$ and lipid profile), Adipokines (leptin, adiponectin)<br>Body composition (BOD POD and ultrasound) |
| Corgosinho et al. [52] (Brazil) | P-U | $N = 24$ (75% boys)<br>Age = 15–19<br>BMI = n/a | Criterion = AHI ≥ 5.<br>OSA = 50% (n/a) | n/a | Nutritional therapy<br>Exercise training (3 h/w)<br>Psychotherapy | 12 | **PSG**: TST, N-REM, REM<br>Metabolic profile (glucose, insulin, $HOMA_{IR}$ and lipid profile), Adipokines (leptin, adiponectin)<br>Body composition (BOD POD and ultrasound) |
| Roche et al. [8] (France) | P-U | $N = 24$ (45.8% boys)<br>Age = 14.7 (12–17)<br>BMI = 40.27 ± 6.82<br>BMI-z = 4.71 ± 0.95 | Criterion = OAHI ≥ 2<br>OSA = 58.3% (50% boys) | n/a | Nutritional education (2300–2500 kcal/day)<br>Exercise training (5 h/w)<br>Psychological support | 9 | **PSG**: TST, N-REM, REM<br>WC, HC, WHR<br>Body composition (bioimpedance)<br>Maximal aerobic capacities |
| Roche et al. [7] (France) | P-U | $N = 23$ (43.5% of boys)<br>Age = 14.7 (12–17)<br>BMI = 40.12 ± 6.93<br>BMI-z = 4.68 ± 0.95 | Criterion = OAHI ≥ 2<br>OSA = 56.5% (46% boys) | **Whole population:** Tonsillectomy: $n = 4$/20 (20%)<br>Tonsillar size (Friedman's scale):<br>0: $n = 6$ (30%)<br>1: $n = 3$ (15%)<br>2: $n = 6$ (30%)<br>3: $n = 5$ (25%)<br>4: $n = 0$ (0%)<br>**OSA group:** Tonsillectomy: $n = 2$/11 (18.1%)<br>Tonsillar size:<br>0: $n = 3$ (27.3%)<br>1: $n = 2$ (18.2%)<br>2: $n = 2$ (18.2%)<br>3: $n = 4$ (36.4%)<br>4: $n = 0$ (0%) | Nutritional education (2300–2500 kcal/day)<br>Exercise training (5 h/w)<br>Psychological support | 9 | **PSG**: TST, N-REM, REM<br>WC, HC, WHR<br>Body composition (bioimpedance)<br>Metabolic (glucose, insulin, $HOMA_{IR}$,) adipokine and inflammatory profiles (leptin, adiponectin, CRP)<br>Maximal aerobic capacities |
| Roche et al. [53] (France, Brazil) | P-U | $N = 50$ (38% of boys)<br>Age = 15.8 ± 1.5 (11–18)<br>BMI = 38.01 ± 6.14<br>BMI-z = 2.37 ± 0.34 | Criterion = AHI ≥ 2<br>OSA = 40% (55% boys) | n/a | Nutritional education (2300–2500 kcal/day)<br>Exercise training (3–5 h/w)<br>Psychological support | 9–12 | **PSG**: TST, N-REM, REM<br>WC, body composition (bioimpedance, BOD POD)<br>Cardiometabolic profile (blood pressure, glucose, insulin, $HOMA_{IR}$ and lipid profile), Maximal aerobic capacities |

Data presented as mean ± standard deviation, or as median (interquartile)

*AHI* apnea-hypopnea index, *ALAT* alanine aminotransferases, *ASAT* aspartate aminotransferase, *BMI* body mass index, *BMI-z* BMI z-score, *CRP* C-reactive protein, *hs-CRP* high sensitivity CRP, *HC* hip circumference, $HOMA_{IR}$ homeostasic model assessment of insulin resistance, *mo* months, *N-REM* Non rapid-eye movement sleep, *OAHI* obstructive apnea-hypopnea index, *ODI* oxygen desaturation index, *OSA* obstructive sleep apnea, *P* prospective, *PG* polygraphy, *PSG* polysomnography, *REM* rapid-eye movement sleep, *TST* total sleep time, *T&A* tonsillectomy & adenoidectomy, *U* uncontrolled, *WC* waist circumference, *WHR* waist-to-hip ratio

[a]Recalculated results after exclusion of eight participants aged 20 years or older

Corgosinho et al. using the same cut-off, reported respectively a prevalence of OSA of 21.9% [51] and 50% [52], the sex repartition being not reported. Using an AHI ≥ 2, Verhulst et al. reported a prevalence of OSA of 60.7%, 46% being boys [47], and Roche et al. of 40%, 55% being boys [53]. Using an OAHI ≥ 2, Roche et al. respectively reported a prevalence of OSA of 58.3% [8] and 56.5% [7], with 50% [8] and 46% of boys [7]. Using an ODI ≥ 2, Van Hoorenbeeck et al. reported in 2012 a prevalence of OSA of 39.4% with 44.2% being boys [48], and in 2013, a prevalence of OSA of 30.4% with 51.5% being boys [49]. Using the same threshold, Van Eyck et al. observed a prevalence of OSA of 31.9%, 53.7% being boys [50].

## Tonsillectomy and adenoidectomy history, and tonsillar size

Among the ten included studies, only two reported information about tonsillectomy and/or adenoidectomy history [7, 47] and four studies assessed tonsillar size at the time of the study [7, 47, 48, 50]. In the study by Roche et al., only four participants had a history of tonsillectomy, of which two had OSA and two were classified as Non-OSA [7]. As for Verhulst et al., they found no difference in tonsillectomy prevalence between participants without OSA (AHI < 2), with mild OSA (2 ≤ AHI < 5) and those with moderate-to-severe OSA (AHI≥5), while they observed that the number of participants who had a history of adenoidectomy decreased over the three groups [47].

Considering tonsillar size, Verhulst et al. and Van Hoorenbeeck et al. did not observe any significant difference in terms of tonsillar size and tonsils hypertrophy between subjects without OSA, with mild OSA or with moderate-to-severe OSA, respectively [47, 48]. Van Eyck et al. found a similar proportion of tonsils hypertrophy between participants with and without OSA, while Roche et al. found a slightly higher proportion of tonsils hypertrophy among participants with OSA, compared with their counterparts without OSA [7, 50].

## Studies design

### Duration of the intervention

The ten included studies are interventional and without control group [7, 8, 46–53], none is a RCT. Four studies proposed an intervention comprised between 4 and 7 months [47–50], one proposed an intervention from 3 to 9 months [46], two proposed a 9-month intervention [7, 8], two a 12-month intervention [51, 52], and one proposed an intervention from 9 to 12 months [53].

## Main outcomes

### Sleep and sleep respiratory parameters assessment

Among the ten studies, Siegfried et al., Verhulst et al., Van Hoorenbeeck et al., and Van Eyck et al. used polygraphy recordings [46–50]. On the other hand, Corgosinho et al. and Roche et al. assessed sleep using polysomnography recordings [7, 8, 51–53]. Corgosinho et al. performed the polysomnography in a sleep laboratory and had an habituation night while Roche et al. had no habituation night and performed ambulatory polysomnography [7, 8, 51–53].

Regarding the outcomes used to define OSA, Siegfried et al., Verhulst et al., Corgosinho et al., and Roche et al. used AHI [46, 47, 51–53], while Van Hoorenbeeck et al. and Van Eyck et al. used ODI [48–50]. Finally, two studies used OAHI [7, 8].

Regarding the retained threshold to diagnose OSA, Siegfried et al. and Corgosinho et al. used a cut-off of AHI ≥ 5 [46, 51, 52], while Verhulst et al. and Roche et al. used a cut-off of AHI ≥ 2 [47, 53]. Van Hoorenbeeck et al. and Van Eyck et al. used ODI ≥ 2 [48–50] and finally, two studies used OAHI ≥ 2 [7, 8]. Through polysomnographic recordings, Corgosinho et al. and Roche et al. measured sleep duration (TST), N1, N2, N3, and REM sleep stages [7, 8, 51–53].

One study assessed excessive daytime sleepiness through a modified Epworth questionnaire [47], another proposed the International Study of Asthma and Allergies in Childhood (ISAAC) questionnaire in order to assess respiratory allergies [50].

### Anthropometric parameters and body composition, cardiometabolic and inflammatory profiles and cardiorespiratory fitness

The methodological details related to the evaluation of body composition, anthropometric parameters, cardiometabolic and inflammatory profiles and cardiorespiratory fitness are presented in Table 2.

## Diet and exercise training

Four studies proposed a dietary restriction (1400–1600 kcal/day), associated with 10 h of various sports, swimming and extra physical activities per week [47–50]. One study proposed a dietary restriction (1600 kcal/day) with aerobic physical exercise such as swimming, hiking, biking, cross-country skiing, and with resistance training [46]. The weekly dose of exercise was not specified. Two studies proposed a nutritional therapy set at the levels recommended for the dietary reference intake for participants with low physical exercise, combined with exercise-training

program performed three times a week [51, 52]. This program included 30 min of exercise training (running on a moto-driven treadmill) plus 30 min of resistance training per session. Three studies proposed a nutritional education associated with total daily calorie intake controlled at about 2300–2500 kcal/day and physical training [7, 8, 53]. The latest consisted of exercise at least five times/week for 45–60 min, including an interval training program alternating 4 min of moderate work (50% of $VO_{2peak}$) and 1 min of intense work (85% of $VO_{2peak}$). Moderate and high intensity activities such as walking, swimming, cycling, climbing and group games were performed 3 times/week [7, 8, 53].

## Main results

Table 3 details the results related to OSA, BMI, sleep duration and architecture, cardiometabolic and inflammatory profiles, cardiorespiratory fitness, and main associations.

### Sleep and sleep respiratory parameters

According to the results in the whole population, Siegfried et al., Corgosinho et al., and Roche et al. [8, 46, 51, 53] reported no modification of AHI at the end of the intervention. In addition, Roche et al. reported no modification of ODI and OAHI while Van Hoorenbeeck et al. reported a decrease of ODI [7, 8, 48, 53].

Regarding polysomnographic data in the whole population, two studies did not observe modification in TST [51, 53] while two other ones reported an increase of TST [7, 8]. The four studies reported an increase of REM sleep (%) and no change in N2 [7, 8, 51, 53], and two of them showed a decrease of N3 and an increase of N1 [7, 8], while the two others did not report modification of N3 and N1 proportions [51, 53].

In the OSA group, Siegfried et al. reported no modification of AHI at the end of the intervention, despite OSA was normalized for 50% of the subjects [46]. In a study, Roche et al. did not observe any modification of AHI, OAHI, and ODI [8]. In a second study, they reported a decrease of OAHI along with 46.2% of normalized OSA, while ODI was not changed [7]. In a third study, Roche et al. did not found a decrease of ODI, while OAHI and AHI were decreased, and OSA was normalized for 55% of the participants [53].

Verhulst et al., Van Hoorenbeeck et al., and Corgosinho et al. observed a decrease of AHI in the OSA group, the latest being normalized in 61.9%, 76% and 66.6% of the participants, respectively [47, 49, 52]. Two studies reported a decrease of ODI [47, 49]. Van Hoorenbeeck et al. and Corgosinho et al. reported that OSA was respectively normalized in 70.7 and 58.3% of the participants [48, 51]. Despite Van Eyck et al. reported that OSA was normalized in 79.7% of their sample, they did not report final values of either ODI or AHI [50].

Regarding polysomnographic data, three studies reported an improvement of sleep duration [7, 8, 52], and one did not observe any modification [53]. No change in N2 nor in N1 proportions was observed [7, 8, 52, 53].

Two studies reported N3 decrease [7, 8] while two other did not find any change [52, 53]. Two studies reported an increase in REM sleep [8, 53] while two others did not [7, 52].

### Anthropometric parameters and body composition, cardiometabolic and inflammatory profiles, and cardiorespiratory fitness

The Table 3 details all the results related to anthropometric parameters and body composition changes, cardiometabolic and inflammatory profiles as well as cardiorespiratory fitness.

### Main associations

At baseline, three studies assessed potential relations between obesity and OSA [8, 46, 47]. Roche et al. failed to find a relation between OAHI and BMI or BMI *z*-score or fat mass [8]. Similar results were reported by Siegfried et al. who did not find any relation between anthropometric parameters and respiratory parameters during sleep, either at the start of the intervention, either for the difference at discharge [46]. Verhulst et al. by contrast, reported, first, a positive correlation between waist-to-hip ratio and AHI in the whole population at baseline, and second, a positive correlation between baseline AHI and relative decrease in BMI *z*-score controlled for gender, age and basal BMI *z*-score [47]. Corgosinho et al. reported a positive association between decrease in fat mass and decrease in respiratory events and respiratory disturbance index (RDI) [51].

Considering tonsillar size, Van Hoorenbeeck et al. reported a higher prevalence of tonsils hypertrophy in the group of participants with residual OSA, compared to those with normalized OSA [48]. Roche et al. observed in a smaller sample size of participants a higher percentage of larger tonsillar size in participants with residual OSA compared to their counterparts with normalized OSA [7]. On the other hand, Verhulst et al. and Van Eyck et al. did not find any statistical difference of tonsillar size and tonsils hypertrophy prevalence between residual and normalized OSA participants [47, 50].

Regarding cardiometabolic data, Siegfried et al. reported a correlation between basal BMI and diastolic blood pressure [46]. Van Hoorenbeeck et al. observed a positive

**Table 3** Results related to OSA, BMI, sleep duration and architecture, cardiometabolic and inflammatory profiles, cardiorespiratory fitness, and main associations

| First author | AHI | ODI | OAHI | BMI/BMI z-score/FM | Normalized OSA | Sleep duration and architecture | Cardiometabolic and inflammatory profiles Cardiorespiratory fitness | Main associations |
|---|---|---|---|---|---|---|---|---|
| Siegfried et al. [46] (Germany) | **Whole population**: ↔ 3.8 ± 4.6 to 3.5 ± 3.2[a](ns) **OSA group:** ↔ 10.3 ± 7.1 to 6.3 ± 5.3[a] (ns) | n/a | n/a | **Whole population:** ↓ BMI: 44.9 ± 7.5 to 35.5 ± 6.8[a] ($p < 0.001$) **OSA group:** ↓ BMI: 47.8 ± 13.6 to 36.4 ± 13.2[a] ($p < 0.001$) | 3/6 (50%)[a] | n/a | **Whole population:** $DBP_{mmHg}$: ↓ 89.3 ± 13.6 to 79.8 ± 8.8[a] ($p < 0.01$) **OSA group:** $DBP_{mmHg}$: ↔ 94.0 ± 8.2 to 83.0 ± 9.7[a] (ns) | ■ Correlation between basal BMI and DBP.<br>■ No correlation between anthropometric parameters and respiratory parameters either at the start or for the difference at discharge. |
| Verhulst et al. [47] (Belgium) | **OSA group:** ↓ 3.8 (2.2–58.3) to 1.9 (0.6–27.7) ($p < 0.01$) | **OSA group:** ↓ 2.5 (0.4–26.1) to 1.2 (0.0 –7.9) ($p < 0.001$) | n/a | **OSA group:** −24 kg (11.0–48.0) = relative decrease in BMI-z of 34.8% (16.2–76.3%) | 13/21 (61.9%) | n/a | n/a | ■ Overall, correlation between WHR and AHI at baseline.<br>■ Correlation between baseline AHI & relative decrease in BMI-z controlled for gender, age and basal BMI-z.<br>■ At baseline, similar tonsillar size between subjects without OSA, with mild OSA and those with moderate-to-severe OSA.<br>■ No difference in tonsillar size between subjects with normalized and residual OSA. |
| Van Hoorenbeeck et al. [48] (Belgium) | n/a | **Whole population:** ↓ 1.6 (0.0–26.1) to 0.96 (0.0–7.9) ($p < 0.001$) | n/a | **Whole population basal:** BMI-z: 2.7 ± 0.4 **OSA group:** BMI-z: 2.7 to 1.9 | 29/41 (70.7%) | n/a | **Whole population:** $Leukocytes_{mm^3}$: ↑ 6.28 (3.61–12.63) to 6.65 (3.51–11.49) ($p < 0.01$) $Neutrophils_{mm^3}$: ↑ 3.15 (1.37–8.59) to 3.32 (1.04-8.71) ($p < 0.05$) $Lymphocytes_{mm^3}$: ↑ 2.19 (1.25–3.97) to 2.43 (1.30–3.97) ($p < 0.001$) $hs\text{-}CRP_{mg/dl}$: ↓ 0.29 (0.02–1.80) to 0.14 (0.01–2.40) ($p < 0.001$) $Uric\ Acid_{mg/dl}$: ↓ 6.6 (4.2–13.0) to 5.0 (3.1–8.3) ($p < 0.001$) | ■ Linear association between UA and ODI after adjusting for BMI-z.<br>■ Linear association of RDI with leukocytes and lymphocytes.<br>■ Association between hs-CRP and BMI z-score.<br>■ Improvements in UA concentrations associated with decrease of RDI & ODI after adjusting for relative BMI-z decrease.<br>■ Lowering of hs-CRP not associated to improvements in sleep or anthropometric parameters.<br>■ At baseline, similar prevalence of tonsils hypertrophy between subjects without OSA, with mild OSA and with moderate-to-severe OSA.<br>■ Post-intervention, higher prevalence of tonsils hypertrophy in subjects with residual OSA compared to those with normalized OSA. |
| Van Hoorenbeeck et al. [49] (Belgium) | **OSA group:** ↓ 2.2 (0.0–58.3) to 0.9 (0.0–27.7) ($p < 0.001$) | **OSA group:** ↓ 2.9 (2.0–36.1) to 0.9 (0.0–10.8) ($p < 0.001$) | n/a | **Whole population:** ↓ BMI-z: 2.7 ± 0.4 to 1.9 ± 0.6 ($p < 0.001$) **OSA group:** ↓ BMI-z: 2.8 ± 0.4 to 1.9 ± 0.7 ($p < 0.001$) | 38/50 (76%) | n/a | **Whole population:** $Glucose_{g/L}$: ↔ 0.84 (0.57–1.14) to 0.83 (0.69–1.00) (ns) $HOMA_{IR}$: ↓ 3.0 (0.7–11.5) to 1.9 (0.8–8.4) ($p < 0.001$) $Total\ Chol_{g/L}$: ↓ 1.47 (0.66–3.60) to 1.37 (0.88–3.98) ($p < 0.001$) $HDL\text{-}C_{g/L}$: ↑ 0.42 (0.21–0.78) to 0.43 (0.25–0.73) ($p < 0.001$) $TG_{g/L}$: ↓ 0.75 (0.37–3.44) to 0.70 (0.25–2.41) ($p < 0.001$) $ASAT_{mg/dL}$: ↓ 26 (14–227) to 19 (11–84) ($p < 0.001$) $ALAT_{mg/dL}$: ↓ 27 (8-512) to 18 (6-171) ($p < 0.001$) **OSA group:** $Glucose_{g/L}$: ↔ 0.85 (0.70–1.14) to 0.84 (0.69–0.99) (ns) $HOMA_{IR}$: ↓ 2.9 (1.4–11.5) to 2.1 (1.1–8.4) ($p < 0.01$) $Total\ Chol_{g/L}$: ↓ 1.43 (0.85–2.47) to 1.30 (0.89–1.82) ($p < 0.01$) $HDL\text{-}C_{g/L}$: ↑ 0.40 (0.28–0.60) to 0.42 (0.29–0.56) ($p < 0.05$) $TG_{g/L}$: ↓ 0.73 (0.41–3.44) to 0.64 (0.33–2.41) ($p < 0.01$) $ASAT_{mg/dL}$: ↓ 29 (14–223) to 19 (11–32) ($p < 0.001$) $ALAT_{mg/dL}$: ↓ 30 (12–99) to 18 (10–42) ($p < 0.001$) | ■ Linear association between basal HDL-C and $SaO_2$ after correction for age, sex, and BMI-z.<br>■ No significant correlation between metabolic improvements and improvements in sleep parameters. |

**Table 3** (continued)

| First author | AHI | ODI | OAHI | BMI/BMI z-score/FM | Normalized OSA | Sleep duration and architecture | Cardiometabolic and inflammatory profiles Cardiorespiratory fitness | Main associations |
|---|---|---|---|---|---|---|---|---|
| Van Eyck et al. [50] (Belgium) | **OSA group basal:** 3.1 (0.2-58.3) | **OSA group basal:** 3.0 (2.0-36.1) | n/a | **OSA group:** BMI-z: 2.8 ± 0.4. Decrease in BMI-z of 32% | 63/79 (79.7%) | n/a | n/a | ■ Respiratory allergy and basal ODI associated with higher risk for residual OSA.<br>■ At baseline, similar prevalence of tonsils hypertrophy between subjects without OSA and those with OSA.<br>■ No difference in prevalence of tonsils hypertrophy between subjects with normalized and residual OSA. |
| Corgosinho et al. [51] (Brazil) | **Whole population:** ↔ 0.3 (0–16.5) to 0.2 (0–17.5) (ns) | n/a | n/a | **Whole population:** ↓ BMI: 37.6 ± 5.3 to 33.8 ± 5.9 ($p < 0.05$) $FM_{\%}$: 47.1 ± 5.1 to 39.7 ± 6.7($p < 0.05$) | 7/12 (58.3%) | **Whole population:** $TST_{min}$: ↔ 401.8 ± 70.1 to 404.1 ± 70.2 (ns) $N1_{\%}$: ↔ 6.7 ± 4.1 to 6.0 ± 2.8 (ns) $N2_{\%}$: ↔ 49.2 ± 8.2 to 47.1 ± 8.3 (ns) $N3_{\%}$: ↔ 25.9 ± 7.7 to 26.9 ± 8.1 (ns) $REM_{\%}$: ↑ 18.2 ± 5.8 to 19.2 ± 5.9 ($p < 0.05$) | **Whole population:** $Glucose_{g/L}$: ↔ 0.91 ± 0.08 to 0.92 ± 0.07 (ns) $HOMA_{IR}$: ↔ 3.6 (1.2–16) to 2.7 (0.7–22) (ns) Total $Chol_{g/L}$: ↓ 1.70 ± 0.34 to 1.60 ± 0.29 ($p < 0.05$) HDL-$C_{g/L}$: ↑ 0.44 ± 0.09 to 0.47 ± 0.10 ($p < 0.05$) LDL-$C_{g/L}$: ↓ 1.02 ± 0.29 to 0.95 ± 0.25 ($p < 0.05$) $TG_{g/L}$: ↓ 1.19 ± 0.72 to 0.93 ± 0.44 ($p < 0.05$) $Leptin_{ng/mL}$: ↓ 54.1 ± 28.3 to 24.95 (1.8–99.2) ($p < 0.05$) $Adiponectin_{ng/mL}$: ↑ 3.4 (0.3–12.8) to 4.3 (2.4–21.6) ($p < 0.05$) | ■ Correlation between Δfat mass and Δrespiratory events and ΔRDI. |
| Corgosinho et al. [52] (Brazil) | **OSA group:** ↓ 11.6 (6.2–22.6) to 2.3 (0.4–13.8) ($p < 0.05$) | n/a | n/a | **OSA group:** ↓ BMI: 38.5 (30.7–48.5) to 31.3 (27.0–48.8) ($p < 0.05$) $FM_{\%}$: 47.6 (37.8–53.5) to 41.1 (26.3-48.0) ($p < 0.05$) | 8/12 (66.6%) | **OSA group:** $TST_{min}$: ↑ 376 (243–433) to 411 (244–466) ($p < 0.05$) $N1_{\%}$: ↔ 8.9 (3.9–16.5) to 6.9 (3.5–10.6) (ns) $N2_{\%}$: ↔ 44.2 (36.2–68.1) to 48.4 (38.6–61.0) (ns) $N3_{\%}$: ↔ 25.8 (14.5–37.7) to 26.0 (11.5–34.4) (ns) $REM_{\%}$: ↔ 19.1 (4.6–25.8) to 21.3 (9.8–31.0) (ns) | **OSA group:** $Glucose_{g/L}$: ↔ 0.93 (0.84–1.17) to 0.92 (0.84–1.19) (ns) $HOMA_{IR}$: ↔ 4.1 (2.6–16.1) to 3.2 (1.6–22.1) (ns) Total $Chol_{g/L}$: ↓ 1.81 (0.99–2.39) to 1.59 (0.92–2.30) ($p < 0.05$) HDL-$C_{g/L}$: ↔ 0.42 (0.28–0.57) to 0.40 (0.29–0.60) (ns) LDL-$C_{g/L}$: ↔ 1.17 (0.56–1.45) to 0.91 (0.53–1.62) (ns) $TG_{g/L}$: ↔ 1.04 (0.58–2.46) to 0.87 (0.48–1.83) (ns) $Leptin_{ng/mL}$: ↓ 40.27 (28.82–97.01) to 19.29 (9.17–96.90) ($p < 0.05$) $Adiponectin_{ng/mL}$: ↔ 3.14 (1.87–5.53) to 3.65 (2.49–4.92) (ns) | n/a |
| Roche et al. [8] (France) | **Whole population:** ↔ 2.7 ± 3.4 to 2.3 ± 2.5 (ns) **OSA group:** ↔ 4.2 ± 3.9 to 3.1 ± 3.1 (ns) | **Whole population:** ↔ 3.9 ± 4.1 to 4.0 ± 3.5 (ns) **OSA group:** ↔ 5.5 ± 4.8 to 4.6 ± 4.4 (ns) | **Whole population:** ↔ 2.4 ± 2.5 to 2.1 ± 2.5 (ns) **OSA group:** ↔ 3.7 ± 2.6 to 3.0 ± 3.0 (ns) | **Whole population:** ↓ BMI: 40.3 ± 6.8 to 35.3 ± 5.7 ($p < 0.001$) BMI-z: 4.7 ± 1.0 to 4.0 ± 1.1 ($p < 0.001$) $FM_{\%}$: 39.3 ± 5.2 to 34.2 ± 5.2 ($p < 0.01$) **OSA group:** ↓ BMI: 42.4 ± 7.7 to 36.4 ± 6.7 ($p < 0.001$) BMI-z: 5.0 ± 1.1 to 4.2 ± 1.3 ($p < 0.001$) $FM_{\%}$: 39.9 ± 6.1 to 34.1 ± 5.1 ($p < 0.05$) | n/a | **Whole population:** $TST_{min}$: ↑ 451.2 ± 30.4 to 485.5 ± 48.5 ($p < 0.05$) $N1_{\%}$: ↑ 5.0 ± 2.8 to 7.2 ± 2.5 ($p < 0.01$) $N2_{\%}$: ↔ 54.0 ± 4.6 to 52.4 ± 6.6 (ns) $N3_{\%}$: ↓ 21.1 ± 4.8 to 18.0 ± 4.4 ($p < 0.001$) $REM_{\%}$: ↑ 19.9 ± 3.2 to 22.4 ± 3.9 ($p < 0.05$) **OSA group:** $TST_{min}$: ↑ 441.9 ± 21.9 to 494.9 ± 47.6 ($p < 0.01$) $N1_{\%}$: ↔ 5.7 ± 3.2 to 6.3 ± 2.7 (ns) $N2_{\%}$: ↔ 53.4 ± 4.6 to 51.6 ± 7.0 (ns) $N3_{\%}$: ↓ 21.4 ± 5.4 to 19.2 ± 3.1 ($p < 0.05$) $REM_{\%}$: ↑ 19.5 ± 3.3 to 22.9 ± 4.8 ($p < 0.05$) | **Whole population:** Absolute $VO_{2peak}$: ↑ 2.5 ± 0.5 to 2.7 ± 0.6 ($p < 0.01$) $VO_{2peakBW}$: ↑ 22.8 ± 3.2 to 27.7 ± 5.3 ($p < 0.001$) **OSA group:** Absolute $VO_{2peak}$: ↑ 2.5 ± 0.5 to 2.7 ± 0.6 ($p < 0.05$) $VO_{2peakBW}$: ↑ 22.3 ± 2.4 to 27.1 ± 4.5 ($p < 0.01$) | ■ No correlation of OAHI with BMI, BMI-z or FM. |
| Roche et al. [7] (France) | n/a | **Whole population:** ↔ 3.9 ± 4.1 to 3.95 ± 3.3 (ns) | **Whole population:** ↔ 2.4 ± 2.5 to 2.5 ± 2.6 (ns) | **Whole population:** ↓ BMI: 40.1 ± 6.9 to 35.3 ± 5.7 ($p < 0.001$) | 6/13 (46.2%) | **Whole population:** $TST_{min}$: ↑ 451.5 ± 31.1 to 483.6 ± 45.4 ($p < 0.05$) | **Whole population:** $Glucose_{g/L}$: ↔ 0.78 ± 0.06 to 0.79 ± 0.06 (ns) | ■ Baseline association between CRP and BMI controlled for sex, ODI, arousal index, TST and |

**Table 3** (continued)

| First author | AHI | ODI | OAHI | BMI/BMI z-score/FM | Normalized OSA | Sleep duration and architecture | Cardiometabolic and inflammatory profiles Cardiorespiratory fitness | Main associations |
|---|---|---|---|---|---|---|---|---|
| | | **OSA group:** ↔<br>5.5 ± 4.8 to<br>4.5 ± 4.2 (ns) | **OSA group:** ↓<br>3.7 ± 2.6 to<br>2.9 ± 2.95 ($p < 0.05$) | BMI-z: 4.7 ± 1.0 to<br>4.0 ± 1.1 ($p < 0.001$)<br>$FM_{\%}$: 39.4 ± 4.9 to<br>33.4 ± 5.8 ($p < 0.001$)<br>**OSA group:** ↓<br>BMI: 42.3 ± 8.0 to<br>36.4 ± 6.8 ($p < 0.001$)<br>BMI-z: 4.9 ± 1.1 to<br>4.2 ± 1.3 ($p < 0.001$)<br>$FM_{\%}$: 40.0 ± 5.9 to<br>34.1 ± 4.6 ($p < 0.05$) | | $N1_{\%}$: ↑ 4.9 ± 2.8 to<br>7.1 ± 2.5 ($p < 0.05$)<br>$N2_{\%}$: ↔ 53.7 ± 4.4 to<br>52.4 ± 6.3 (ns)<br>$N3_{\%}$: ↓ 21.3 ± 4.8 to<br>18.4 ± 4.3 ($p < 0.05$)<br>$REM_{\%}$: ↑ 20.0 ± 3.2 to<br>22.1 ± 4.3 ($p < 0.05$)<br>**OSA group:** $TST_{min}$: ↑<br>443.2 ± 23.4 to<br>491.8 ± 44.4 ($p < 0.05$)<br>$N1_{\%}$: ↔ 5.7 ± 3.3 to<br>6.2 ± 2.8 (ns)<br>$N2_{\%}$: ↔ 52.8 ± 4.1 to<br>51.6 ± 6.6 (ns)<br>$N3_{\%}$: ↓ 21.8 ± 5.4 to<br>19.9 ± 3.1 ($p < 0.01$)<br>$REM_{\%}$: ↔ 19.7 ± 3.3 to<br>22.4 ± 5.4 (ns) | $HOMA_{IR}$: ↔ 3.9 ± 1.9 to<br>3.8 ± 2.3 (ns)<br>$CRP_{mg/L}$: ↓ 8.46 ± 6.50 to<br>6.11 ± 4.07 ($p < 0.05$)<br>$Leptin_{ng/mL}$: ↓ 65.54 ± 28.65 to<br>43.88 ± 19.74 ($p < 0.001$)<br>$Adiponectin_{ng/mL}$: ↑ 7.55 ± 2.25 to<br>9.24 ± 3.20 ($p < 0.05$)<br>Absolute $VO_{2peak}$: ↑ 2.5 ± 0.5 to<br>2.7 ± 0.6 ($p < 0.001$)<br>$VO_{2peakBW}$: ↑ 22.9 ± 3.1 to<br>27.9 ± 4.9 ($p < 0.001$)<br>$VO_{2peakFFM}$: ↑ 37.5 ± 5.4 to<br>41.6 ± 5.4 ($p < 0.05$)<br>**OSA group:** $Glucose_{g/L}$: ↔<br>0.79 ± 0.05 to<br>0.78 ± 0.06 (ns)<br>$HOMA_{IR}$: ↔ 4.5 ± 2.1 to<br>4.0 ± 2.7 (ns)<br>$CRP_{mg/L}$: ↓ 11.0 ± 7.6 to<br>6.8 ± 4.1 ($p < 0.05$)<br>$Leptin_{ng/mL}$: ↓ 64.56 ± 20.31 to<br>42.16 ± 17.52 ($p < 0.001$)<br>$Adiponectin_{ng/mL}$: ↑ 7.06 ± 2.26 to<br>9.28 ± 3.05 ($p < 0.05$)<br>Absolute $VO_{2peak}$: ↑ 2.5 ± 0.5 to<br>2.7 ± 0.6 ($p < 0.001$)<br>$VO_{2peakBW}$: ↑ 22.5 ± 2.4 to<br>27.5 ± 3.9 ($p < 0.001$)<br>$VO_{2peakFFM}$: ↑ 38.4 ± 6.5 to<br>41.4 ± 4.7 ($p < 0.05$) | $VO_{2peak}$.<br>■ Association between ΔCRP and $\Delta VO_{2peak}$ controlled for sex, ΔBMI, ΔODI, Δarousal index, ΔTST.<br>■ At baseline, higher prevalence of tonsils hypertrophy in participants with OSA compared to those without OSA.<br>■ Post-intervention, higher prevalence of tonsils hypertrophy in subjects with residual OSA compared with those with normalized OSA. |
| Roche et al. [53] (France, Brazil) | **Whole population:** ↔<br>2.7 ± 4.2 to<br>1.6 ± 2.8 (ns)<br>**OSA group:** ↓<br>6.2 ± 4.9 to<br>3.0 ± 3.9 ($p < 0.01$) | **Whole population:** ↔<br>3.5 ± 4.7 to<br>2.6 ± 3.7 (ns)<br>**OSA group:** ↔<br>7.2 ± 5.6 to<br>4.8 ± 4.9 (ns) | **Whole population:** ↔<br>2.5 ± 4.0 to<br>1.5 ± 2.8 (ns)<br>**OSA group:** ↓<br>5.7 ± 4.9 to<br>3.0 ± 3.9 ($p < 0.01$) | **Whole population:** ↓<br>BMI: 38.0 ± 6.1 to<br>33.4 ± 5.8 ($p < 0.001$)<br>BMI-z: 2.4 ± 0.3 to<br>2.0 ± 0.5 ($p < 0.001$)<br>$FM_{\%}$: 44.0 ± 6.0 to<br>37.0 ± 6.1 ($p < 0.001$)<br>**OSA group:** ↓<br>BMI: 39.6 ± 7.3 to<br>34.7 ± 7.0 ($p < 0.001$)<br>BMI-z: 2.5 ± 0.4 to<br>2.1 ± 0.6 ($p < 0.001$)<br>$FM_{\%}$: 42.8 ± 6.5 to<br>36.2 ± 6.5 ($p < 0.001$) | 11/20 (55%) | **Whole population:**<br>$TST_{min}$: ↔ 414.7 ± 69.4 to<br>432.7 ± 54.1 (ns)<br>$N1_{\%}$: ↔ 6.0 ± 3.6 to<br>6.1 ± 2.8 (ns)<br>$N2_{\%}$: ↔ 49.9 ± 6.9 to<br>48.7 ± 6.8 (ns)<br>$N3_{\%}$: ↔ 24.9 ± 6.8 to<br>23.9 ± 7.1 (ns)<br>$REM_{\%}$: ↑ 19.2 ± 4.8 to<br>21.2 ± 5.4 ($p < 0.05$)<br>**OSA group:** $TST_{min}$: ↔<br>413.4 ± 58.2 to<br>440.9 ± 64.4 (ns)<br>$N1_{\%}$: ↔ 6.7 ± 3.8 to<br>6.4 ± 2.5 (ns)<br>$N2_{\%}$: ↔ 48.1 ± 5.4 to<br>48.5 ± 6.8 (ns)<br>$N3_{\%}$: ↔ 24.8 ± 5.8 to<br>22.5 ± 5.1 (ns)<br>$REM_{\%}$: ↑ 20.4 ± 4.0 to<br>22.7 ± 5.0 ($p < 0.05$) | **Whole population:**<br>$Glucose_{g/L}$: ↔ 0.87 ± 0.09 to<br>0.89 ± 0.10 (ns)<br>$HOMA_{IR}$: ↓ 3.8 ± 2.3 to<br>3.5 ± 3.3 ($p < 0.01$)<br>Chol $total_{g/L}$: ↓ 1.61 ± 0.38 to<br>1.54 ± 0.32 ($p < 0.01$)<br>$HDL\text{-}C_{g/L}$: ↑ 0.44 ± 0.09 to<br>0.46 ± 0.09 ($p < 0.05$)<br>$LDL\text{-}C_{g/L}$: ↔ 0.95 ± 0.31 to<br>0.91 ± 0.31 (ns)<br>$TG_{g/L}$: ↓ 1.12 ± 0.70 to<br>0.89 ± 0.40 ($p < 0.001$)<br>$SBP_{mmHg}$: ↓ 120.9 ± 11.1 to<br>114.9 ± 8.7 ($p < 0.01$)<br>$DBP_{mmHg}$: ↓ 74.2 ± 7.0 to<br>71.0 ± 7.1 ($p < 0.01$)<br>$Metscore_{FM}$: ↓ 0.00 ± 0.58 to<br>-0.37 ± 0.59 ($p < 0.001$)<br>MS prevalence: ↓ 72-36% ($p < 0.001$)<br>Absolute $VO_{2peak}$: ↑ 2.8 ± 0.7 to<br>3.0 ± 0.7 ($p < 0.05$)<br>$VO_{2peakBW}$: ↑ 26.1 ± 5.5 to<br>31.5 ± 6.7 ($p < 0.001$)<br>$VO_{2peakFFM}$: ↔ 47.4 ± 10.2 to<br>50.2 ± 10.4 (ns)<br>**OSA group:** $Glucose_{g/L}$: ↔<br>0.87 ± 0.11 to<br>0.87 ± 0.13 (ns)<br>$HOMA_{IR}$: ↔ 4.8 ± 3.2 to<br>4.8 ± 4.8 (ns)<br>Total $Chol_{g/L}$: ↓ 1.64 ± 0.46 to<br>1.52 ± 0.39 ($p < 0.01$)<br>$HDL\text{-}C_{g/L}$: ↑ 0.41 ± 0.09 to<br>0.49 ± 0.09 ($p < 0.05$)<br>$LDL\text{-}C_{g/L}$: ↔ 0.99 ± 0.36 to<br>0.91 ± 0.32 (ns)<br>$TG_{g/L}$: ↓ 1.22 ± 0.91 to<br>0.89 ± 0.43 ($p < 0.01$)<br>$SBP_{mmHg}$: ↓ 125.3 ± 11.9 to<br>116.8 ± 8.5 ($p < 0.05$)<br>$DBP_{mmHg}$: ↓ 74.0 ± 8.2 to | n/a |

**Table 3** (continued)

| First author | AHI | ODI | OAHI | BMI/BMI *z*-score/FM | Normalized OSA | Sleep duration and architecture | Cardiometabolic and inflammatory profiles<br>Cardiorespiratory fitness | Main associations |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | 69.5 ± 8.6 ($p < 0.05$)<br>$Metscore_{FM}$: ↓ 0.17 ± 0.67 to<br>-0.24 ± 0.80 ($p < 0.001$)<br>MS prevalence: ↓ 85–40% ($p < 0.05$)<br>Absolute $VO_{2peak}$: ↑ 2.9 ± 0.7 to<br>3.1 ± 0.7 ($p < 0.01$)<br>$VO_{2peakBW}$: ↑ 25.7 ± 5.4 to<br>31.1 ± 6.0 ($p < 0.001$)<br>$VO_{2peakFFM}$: ↑ 46.2 ± 11.4 to<br>49.3 ± 10.6 ($p < 0.05$) | |

Data presented as mean ± standard deviation, or as median (interquartile)

*AHI* apnea–hypopnea index, *ALAT* alanine aminotransferases, *ASAT* aspartate aminotransferase, *BMI* body mass index, *BMI-z* BMI z-score, *DBP* diastolic blood pressure, *FM* fat mass, *Total Chol* total cholesterol, *HDL-C* high density lipoprotein cholesterol, $HOMA_{IR}$ homeostatic model assessment of insulin resistance, *hs-CRP* high sensitivity C-reactive protein, *LDL-C* low density lipoprotein cholesterol, $MetScore_{FM}$ continuous cardiometabolic risk score, *MS* metabolic syndrome, *N1* stage 1 sleep, *N2* stage 2 sleep, *N3* stage 3 sleep, *OAHI* obstructive apnea-hypopnea index, *ODI* oxygen desaturation index, *OSA* obstructive sleep apnea, *RDI* respiratory disturbance index, *REM* rapid-eye movement sleep, $SaO_2$ oxygen saturation, *SBP* systolic blood pressure, *TST* total sleep time, *TG* triglycerides, *UA* uric acid, *Absolute* $VO_{2peak}$ peak of oxygen consumption (L/min), $VO_{2peakBW}$ peak of oxygen consumption relative body weight (mL/min/KG), $VO_{2peakFFM}$ peak of oxygen consumption relative to fat-free mass (mL/min/$KG_{FFM}$), *WHR* waist-to-hip ratio, ↔ no change, ↓ decrease, ↑ increase, *ns* not significant

[a]Recalculated results after exclusion of eight participants aged 20 years or older

association between basal high-density lipoprotein cholesterol (HDL-C) and $SaO_2$, after correction for age, sex, and BMI *z*-score [49]. Nevertheless, the same authors did not find any association between metabolic improvements and improvements in sleep parameters.

Considering inflammatory profile and oxidative stress, Van Hoorenbeeck et al. reported that high-sensitivity c-reactive protein (hs-CRP) was associated with BMI *z*-score at baseline [48]. A similar result was reported by Roche et al. who observed a strong association between CRP and BMI, after adjusting for sex, ODI, arousal index, TST, and $VO_{2peak}$ [7]. On the other hand, Van Hoorenbeeck et al. also reported that RDI was positively associated with leukocytes and lymphocytes at baseline, and that ODI was associated with uric acid after adjusting for BMI *z*-score [48]. Post-intervention, the same authors observed that improvements in uric acid concentrations were associated with decrease of RDI and ODI. Nevertheless, the lowering of hs-CRP observed by the authors was not associated to improvements in sleep or anthropometric parameters [48]. By contrast, Roche et al. reported a strong association between decrease of CRP and $VO_{2peak}$ improvement post intervention, after adjusting for age, sex, decreased BMI, decreased ODI and arousal index, and improved TST [7].

### Meta-analysis

Six of the ten included studies provided pre- and post-intervention results for AHI. The effect size ranged from −1.89 to −0.11. Results of the meta-analysis revealed a mean effect size of multidisciplinary weight loss intervention to improve AHI of −0.51 (95% CI = −0.94 to −0.08, $p = 0.019$; Fig. 2a) (the mean effect size for AHI was −0.24 (95% CI = −0.47 to −0.01, $p = 0.04$ after removal of the study from Corgosinho et al.). Results for heterogeneity among these studies were as follows: $I^2 = 64.1\%$; $p = 0.016$.

Five of the ten included studies presented pre- and postintervention results regarding ODI with an effect size ranging from −0.51 to −0.20. Results of the meta-analysis revealed a mean effect size of the intervention to reduce ODI of −0.28 (95% CI = −0.50 to −0.05, $p = 0.016$; Fig. 2b). Results for heterogeneity among these studies were as follows: $I^2 = 0.0\%$; $p = 0.959$.

## Discussion

The present paper systematically reviewed available evidence for the effects of multidisciplinary weight loss interventions on OSA severity, prevalence, and sleep parameters in youth with obesity. We also conducted meta-analyses when possible to determine whether such interventions can improve OSA in this population.

After a careful selection process, ten studies were systematically reviewed, representing a total population of 962 participants aged between 10 and 19 years [7, 8, 46–53]. All these studies enrolled both boys and girls (35.4% of the total analyzed sample was composed of boys) [7, 8, 46–53] while 342 youth were identified with OSA at baseline against 620 without.

According to our systematic review, it first appears that the prevalence of OSA shows a large inter-study variation [7, 8, 46–53], this variation being certainly explained by the retained cut-off for OSA detection. Indeed, Siegfried et al. reported a prevalence of 20% of OSA in their population, using a cut-off of AHI ≥ 5, while Verhulst et al. reported 60.7% of OSA, using an AHI ≥ 2 [46, 47]. On the other hand, three studies used ODI ≥ 2 for OSA detection [48–50], which is not commonly used for the diagnosis of OSA [1].

These methodological discrepancies highlight the lack of consensus regarding the diagnosis of OSA. While the American Academy of Sleep Medicine currently allows the use of both the pediatric and adult criteria for respiratory events scoring in adolescents [1], experts in the field keep failing to decide which cutoff of AHI should be used for OSA detection in children and adolescents with obesity. This lack of consensus explains why cutoffs vary between studies, ranging from AHI ≥ 1 [55], >1.5 [56], ≥2 [47] to ≥5 [51]. As illustrated by our results, this is of importance as it favors important disparities between studies when it comes to the prevalence of OSA in this population, which might in turn lead to inconsistent results regarding the effect of multidisciplinary weight loss interventions on OSA. Importantly, half of the included studies in the present systematic review completed polysomnography [7, 8, 51–53], with the other half using polygraphy to diagnose OSA [46–50].

## Effects of multidisciplinary weight loss interventions on OSA and sleep

In the present systematic review, 90% of the included studies reported a decrease of OSA prevalence post intervention [7, 46–53]. The smallest change was reported by Roche et al. who found that 46.2% of subjects initially diagnosed with OSA were normalized post intervention [7]. By contrast, Van Eyck et al. reported 79.7% of normalized OSA in their study [50]. Considering the other studies, OSA was normalized for 50–76% of the subjects [46–49, 51–53]. This is important to note that while some studies did not report significant decrease of AHI or ODI, they still observed OSA normalization among their participants [7, 53]. These results are confirmed by the meta-analysis, showing significant effects of multidisciplinary weight loss interventions on OSA severity through AHI and ODI reduction (Fig. 2).

Interestingly, a recent study providing a 6-to-12month family-centered approach for the management of obesity in children and adolescents (10–20 interventions regarding lifestyle changes) reported beneficial effects on OSA severity, the latter being normalized in 44% of the participants after one year [57]. In this study involving 62 youth initially suffering of OSA, defined as AHI ≥ 2 using polygraphy, weight loss was associated with AHI decrease, independently of sex, age, tanner stage, or tonsils size by the end of the protocol. Unfortunately, this same study could not be included in this systematic review since it did not meet the inclusion criteria.

In the present systematic review, three of the four studies also assessing sleep within their subgroups of youth with OSA reported improved sleep duration [7, 8, 52]. One study reported that sleep duration was increased by 53 min [8], another by 49 min [7], and the last one by 35 min [52]. The fourth study did not report significant improvement of sleep duration, while the latter was increased from about 413–441 min [53].

Considering sleep architecture, two studies observed decreased N3% [7, 8] and two reported increased REM% [8, 53]. Interestingly, similar changes in sleep architecture were reported in youth with obesity following a 12-week training exercise alone, without weight loss [16] or following a 12-week high protein diet inducing weight loss [58]. Regarding sleep duration, the study of Mendelson et al. found improved sleep duration following the program of exercise training, while Willi and colleagues did not report these data [16, 58]. Although our systematic approach seems to suggest that multidisciplinary weight loss interventions can effectively improve sleep duration in youth with OSA, it also points out the lack of available evidence, which did not allow us to perform a meta-analysis.

## Role of tonsillectomy and adenoidectomy history and tonsils hypertrophy

Enlarged tonsils and adenoids are recognized as a main factor of OSA in pediatrics, and tonsillectomy and adenoidectomy represent the first line of treatment for OSA [59]. However, in youth with obesity, residual OSA following surgery is usually reported [60]. Among the ten included studies, only two reported tonsillectomy and/or adenoidectomy history [7, 47]. As such, Roche et al. found a similar distribution of participants without and with OSA, who had undergone tonsillectomy previously [7]. When comparing participants without OSA, with mild OSA and with moderate-to-severe OSA, Verhulst et al. did not find a significant difference in tonsillectomy prevalence among the groups, but reported a decrease in adenoidectomy prevalence over the three groups, respectively [47]. If this result may suggest a potential relationship between OSA severity and adenoids in youth with obesity, the same

authors and two other studies, however, reported similar tonsillar size and/or similar prevalence of tonsils hypertrophy between participants without OSA, with mild and with moderate-to-severe OSA, suggesting a greater effect of obesity than tonsils hypertrophy on OSA pathophysiology in this population [47, 48, 50]. Post intervention, two of these studies did not report differences in tonsillar size and in the prevalence of tonsils hypertrophy (as defined by a Brodsky score ≥ 3+) between participants with normalized and residual OSA [47, 50], while Van Hoorenbeeck et al. and Roche et al. found a greater proportion of tonsils hypertrophy in youth with residual OSA [7, 48]. We do acknowledge the importance of assessing tonsillar size and of recording adenotonsillectomy history in youth with obesity. However, the lack of data on that aspect in the publications reviewed did not allow us to investigate a potential additive effect of tonsils hypertrophy on OSA severity at baseline. It could also be that a multidisciplinary weight loss intervention may not be as effective in youth with obesity who present with tonsils hypertrophy. In addition, the few studies reporting tonsillectomy and adenoidectomy history did not allow us to perform comparisons between OSA participants with residual OSA after surgery, from those who did not have surgery. This clearly needs to be considered when interpreting the results of the present systematic review and meta-analysis.

## Role of weight loss and fat mass decrease

While the ten included studies reported a significant weight loss [7, 8, 46–53], nine of them also observed a decrease of the OSA prevalence at the end of the multidisciplinary weight loss interventions [7, 46–53]. Regarding body composition, five studies assessed this parameter and reported significant decrease of fat mass [7, 8, 51–53]. Interestingly, Siegfried et al. did not find a significant correlation between weight loss and OSA decrease, while Corgosinho et al. found some correlations between fat mass decrease and respiratory events and RDI decrease [46, 51]. Considering the impact of fat mass on OSA pathophysiology [61], measure of fat mass might be a better indicator than BMI in order to assess the effects of fat and fat loss on OSA severity. For instance, Canapari et al. showed that visceral adiposity, as measured by magnetic resonance imaging (MRI) at L4, in youth with obesity, was a significant predictor of the OSA severity independently of BMI [61]. In obese subjects, OSA might be partly due to fat infiltration of the upper airway structures and tongue, associated to the subcutaneous fat deposits in cervical regions [27, 62, 63]. In addition, abdominal or visceral adiposity increases the respiratory load and decreases intrathoracic volumes and diaphragm excursion, promoting breathing disorders in the supine position [27]. Then, measures of fat localization (upper airway, visceral, and subcutaneous) might be relevant indicators to predict OSA improvements.

In adults, several RCTs assessed the impact of weight loss reached through a diet on OSA severity, and reported that a weight loss from 10 to 16% could reduce AHI by 20–50% [64–66]. In children and adolescents with obesity, weight loss achieved through a diet alone is not currently recommended, which could partly explain why both uncontrolled longitudinal and RCTs studies assessing this approach on OSA severity are scarce. Considering sleep quality, one study assessed the effects of a 12-week high protein diet inducing weight loss on sleep architecture in adolescents with obesity [58]. The authors reported decreased N3% and increased REM% following the diet. The data regarding sleep duration were however not presented in this study, and respiratory parameters were not monitored.

## Role of exercise

While all selected studies induced significant weight loss, they also included exercise program [7, 8, 46–53], and the role of exercise alone on sleep and OSA severity deserves further attention.

There is to our knowledge only one study to date that questioned the effects of exercise training alone on sleep parameters in adolescents with obesity [16]. In their work, Mendelson et al. assessed the effects of a 12-week exercise training program, without weight loss, on sleep parameters [16]. Despite numerous sleep improvements, the authors failed to observe any decrease of the AHI severity. It is however important to note that the authors did not individually assess OSA severity, while it might have been normalized in some subjects despite the absence of mean AHI decrease within the whole population. Regarding sleep parameters, the authors reported improved sleep duration, along with increased REM%, and decreased N1% [16]. If further studies are needed, these results seem to suggest a positive effect of exercise alone, independently of weight loss, on sleep health in youth with obesity. This seems to be in line with the actual literature available in adults, and especially with some recent systematic reviews and meta-analyses questioning the effects of exercise alone on OSA and sleep health [67, 68]. Iftikhar et al., for instance, reported that supervised exercise training non-associated with CPAP use had a significant effect on AHI independently of changes in BMI [67]. More recently, a meta-analysis performed by Aiello and colleagues reported favorable effects of both supervised and unsupervised exercise programs on AHI in patients with OSA, independently of exercise modality, duration, frequency or CPAP use [68].

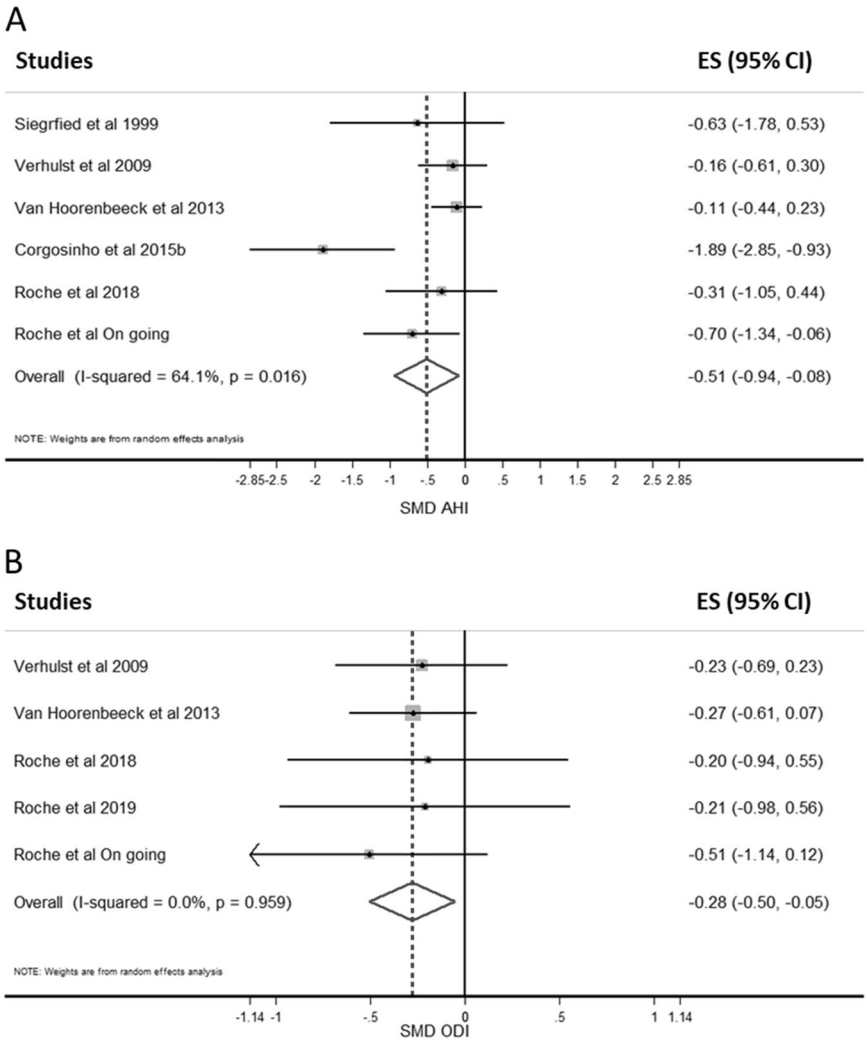



**Fig. 2** Effect size forest plot for the **a** apnea–hypopnea index (AHI) and **b** oxygen desaturation index (ODI) changes in response to the multidisciplinary weight loss intervention (mean ± 95% confidence intervals)

Mechanisms involved in the decrease of OSA through exercise remain to be fully elucidated; however, several hypotheses have been formulated. First, endurance exercise might result in improved upper airway muscle activation to increase upper airway diameter, reduce airway resistance and oppose pharyngeal collapse during sleep [69–72]. Second, exercise training has shown beneficial effects on sleep architecture by improving slow wave sleep (N3) duration in patients with OSA [73, 74]. Breathing is known to be more stable, and airway more resistant to collapse in this stage, probably due to increased genioglossus activity [75]. Then, OSA severity is reduced in N3 sleep stage [76].

## Cardiometabolic, inflammatory, and cardiorespiratory fitness changes

In the present systematic review, four studies reported metabolic profile in their population of youth with OSA [7, 49, 52, 53]. Among these four studies, three did not find any decrease in insulin profile [7, 52, 53], while Van Hoorenbeeck et al. reported a significant decrease of $HOMA_{IR}$ [49]. On the other hand, Corgosinho et al. found a significant decrease in total cholesterol concentrations, and Van Hoorenbeeck et al.and Roche et al. both reported significant decrease of total cholesterol and triglycerides, and increase in HDL-C [49, 52, 53]. Importantly, these results suggest a beneficial effect of multidisciplinary intervention on weight loss (100%) and on OSA normalization (46.2–79.7%) independently of metabolic changes. Moreover, OSA normalization does not seem to require BMI normalization, since subjects remained obese by the end according to six of the ten included studies [7, 8, 46, 51–53].

Interestingly, the two studies who assessed leptin concentrations in participants with OSA reported significant improvement of this parameter, the leptin concentrations being drastically decreased post intervention [7, 52]. Measures of leptin are of interest in the pediatric population with OSA. Indeed, youth with obesity usually experience leptin resistance due to the adipose tissue dysfunction, resulting in

high concentrations of leptin, and promoting systemic inflammation [77–79]. In addition to regulating energy balance and satiety signaling [80], leptin is also implicated in central and peripheral breath control [81, 82] and authors have suggested the implication of leptin resistance in the pathogenesis of OSA [83, 84]. Conversely, multidisciplinary weight loss interventions with exercise and diet are known to have a beneficial effect on the adipose tissue function in youth with obesity [24, 85, 86], promoting decrease in leptin resistance [87]. In this review, the two studies mentioned above found a similar decrease in leptin concentrations in both participants with residual and normalized OSA [7, 52]. This improvement in leptin sensitivity may have also improved the respiratory drive, and thus decreased OSA severity in youth with obesity.

Regarding inflammatory profiles, the two studies assessing this outcome reported similar results; systemic inflammation being associated with the severity of obesity at baseline, among the whole population of youth [7, 48].

Van Hoorenbeeck et al. did not observe significant correlations between hs-CRP lowering and the improvement in OSA nor with improvements in anthropometric parameters post-intervention [48]. On the other hand, Roche et al. found that the CRP concentration decrease was associated with improvements in aerobic capacity, independently of weight loss, sleep duration improvements, and decreased OSA [7]. Yet, OSA represents a pro-inflammatory factor, and obesity seems to explain systemic inflammation rather than OSA at baseline. Considering the implication of aerobic capacities on the inflammatory responses to multidisciplinary interventions, further studies are needed. Indeed, this latter outcome was assessed in 33.3% of the retained studies only, and improved in all of them [7, 8, 53].

## Limitations

Several limitations have to be considered when interpreting the present analysis. First, the important heterogeneity in the methodologies used needs to be considered. Indeed, as pointed out in our systematic approach, the included studies presented a large variability in the measured outcome and cutoff used to diagnose OSA, which might lead to disparities and inconsistent results regarding the effects of the multidisciplinary weight loss interventions. In addition, the age group of the study population was large (10–19 years), and statistical corrections regarding puberty might have been relevant, since puberty influences both metabolic parameters [88] and OSA development [89]. However, only one study provided Tanner stages among the ten studies [7]. Plus, only two studies reported tonsillectomy and/or adenoidectomy history of the participants [7, 47], and four studies assessed tonsillar size of the participants at the time of the study [7, 47, 48, 50]. As enlarged tonsils and adenoids are recognized as a major factor of OSA in pediatrics, and since youth with obesity often have residual OSA following tonsillectomy and/or adenoidectomy [60], it would have been relevant to differentiate OSA participants who never underwent tonsillectomy and/or adenoidectomy, from those who have residual OSA after surgery. As detailed previously, lack of information on this aspect is a limitation of our present analysis. Similarly, only two of the included studies reported information regarding the use of CPAP among their participants [7, 8]. In those two studies, participants who used CPAP were excluded from the analysis. None of the other included studies provided information regarding use of CPAP. As the implementation of CPAP appears as an unavoidable approach when dealing with youth with moderate to severe OSA, we strongly believe this information should be systematically reported in those multidisciplinary interventions. While this can be considered as one of the limitations of the present work, we strongly encourage future studies to clarify this essential information. Also, three studies did not consider dropout subjects when presenting baseline characteristics of their population, which might favor misinterpretations of the results [47, 48, 50]. Finally, the ten retained studies came from four different research groups only, and the same participants might have been including in some studies.

### Implications for OSA and sleep management

All the studies reported here were of significant duration (5–12 months) and highlight a clinical relevance of multidisciplinary weight loss interventions regarding OSA changes and sleep duration improvements. However, RCTs need to be performed in the future in order to better understand the independent implications of weight loss, fat mass decrease and chronic exercise on OSA and sleep changes, and on cardiometabolic and inflammatory improvements in this population. Importantly, we suggest the establishment of a universal consensus regarding the cut-off retained for the diagnosis of OSA in the population of youth with obesity in order to limit disparities between studies when it comes to the prevalence of OSA, and avoid inconsistent results regarding the effect of multidisciplinary weight loss interventions on OSA. In that sense, our research group recently proposed the use of a AHI≥2 for OSA diagnosis in this population; this cutoff corresponding to the threshold from where an important relationship between cardiometabolic risk and AHI was observed [90]. Additionally, the use of complete polysomnography seems of interest in order to better understand the effects of these interventions on sleep architecture. The present systematic review reported decreased N3 and improved REM sleep following interventions, while data in adults suggest

improved N3 sleep following exercise training in patients with OSA [73, 74].

Our results also encourage future studies to systematically perform separate analyses on the whole sample and OSA sample, as well as to compare post-intervention normalized and residual OSA participants, which might provide a better view of the beneficial effects of their intervention. Finally, we also recommend that future studies systematically report tonsillectomy and adenoidectomy history along with tonsillar size of the participants. We also recommend that investigators differentiate OSA participants who never underwent tonsillectomy and/or adenoidectomy, from those who have residual OSA after surgery. Future studies should also clarify whether some of their participants received CPAP treatment.

## Conclusions

This review used a systematic approach and performed a meta-analysis to examine the effects of multidisciplinary weight loss interventions on OSA severity and prevalence as well as on overall sleep parameters in youth with obesity. Although it indicates important beneficial effects of multidisciplinary weight loss interventions on OSA severity, future well-designed randomized controlled trials are warranted to better assess and understand the independent implications of weight loss, fat mass decrease and chronic exercise on OSA and sleep health, in relation to the cardiometabolic and inflammatory profile of children and adolescents with obesity. Meanwhile, multidisciplinary weight loss interventions proposing both diet and exercise training should be recommended for OSA and sleep management.

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### Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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