

Noncontact respiration monitoring techniques in young children: a scoping review

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Abstract

Pediatric sleep-related breathing disorders, or sleep-disordered breathing (SDB), cover a range of conditions including obstructive sleep apnea (OSA), central sleep apnea (CSA), sleep-related hypoventilation disorders, and sleep-related hypoxemia disorder. Pediatric SDB is often underdiagnosed, potentially due to difficulties associated with performing the gold standard polysomnography (PSG) in children. This scoping review aims to: 1) provide an overview of the studies reporting on safe, noncontact monitoring of respiration in young children; 2) describe the accuracy of these techniques, and 3) highlight their respective advantages and limitations. PubMed and EMBASE were searched for studies researching techniques in children <12 years old. Both quantitative data and the quality of the studies were analyzed. The evaluation of study quality was conducted using the QUADAS-2 tool. A total of 17 studies were included. Techniques could be grouped into bed-based methods, ultra-wideband (UWB) radar, Doppler radar, video, infrared (IR) cameras, garment-embedded sensors, and sound analysis. Most either measured respiratory rate (RR) or detected apneas; five aimed to do both. Noncontact sleep monitoring techniques are safe, but accuracy data of these techniques is limited, and large heterogeneity exists regarding study quality and stage. Motion artifacts affect accuracies of apnea detection. Sleep respiration analysis could benefit from sleep stage classification and breathing sound analysis. Further research is crucial to facilitate easily accessible and safe non-contact methods for respiration monitoring in a home setting.

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Abstract

Pediatric sleep-related breathing disorders, or sleep-disordered breathing (SDB), cover a range of conditions including obstructive sleep apnea (OSA), central sleep apnea (CSA), sleep-related hypoventilation disorders, and sleep-related hypoxemia disorder. Pediatric SDB is often underdiagnosed, potentially due to difficulties associated with performing the gold standard polysomnography (PSG) in children. This scoping review aims to: 1) provide an overview of the studies reporting on safe, noncontact monitoring of respiration in young children; 2) describe the accuracy of these techniques, and 3) highlight their respective advantages and limitations. PubMed and EMBASE were searched for studies researching techniques in children <12 years old. Both quantitative data and the quality of the studies were analyzed. The evaluation of study quality was conducted using the QUADAS-2 tool. A total of 17 studies were included. Techniques could be grouped into bed-based methods, ultra-wideband (UWB) radar, Doppler radar, video, infrared (IR) cameras, garment-embedded sensors, and sound analysis. Most either measured respiratory rate (RR) or detected apneas; five aimed to do both. Noncontact sleep monitoring techniques are safe, but accuracy data of these techniques is limited, and large heterogeneity exists regarding study quality and stage. Motion artifacts affect accuracies of apnea detection. Sleep respiration analysis could benefit from sleep stage classification and breathing sound analysis. Further research is crucial to facilitate easily accessible and safe non-contact methods for respiration monitoring in a home setting.

Introduction

Sleep-related breathing disorders, or sleep-disordered breathing (SDB), cover a range of conditions including obstructive sleep apnea (OSA), central sleep apnea (CSA), sleep-related hypoventilation disorders, and sleep-related hypoxemia disorder¹. The most common type of SDB, OSA, has a prevalence of 1-4% among children, although a large variation between 0.1 and 13% exists due to varying diagnostic criteria². With OSA being only one type of SDB, total SDB prevalence must be higher.

Overnight polysomnography (PSG) is considered the gold standard for diagnosing sleep-disordered breathing (SDB) in children³. However, PSG poses challenges as it is expensive, time-consuming⁴, and can be particularly challenging in children⁵. In addition, the “first night effect” is a well-known pitfall of studying breathing disorders using PSG⁶. Pediatric SDB is typically known to be underdiagnosed⁷. This underdiagnosis could partly be due to the aforementioned problems in performing a PSG at a young age. This highlights the

demand for prompt, easy and reliable diagnosis using safe, non-contact methods for respiration monitoring in a home setting.

To address the limitations of PSG, various monitoring systems, including actigraphy and oximetry, have been proposed. However, the widespread use of these systems is often hindered by the need for wiring sensors to the body. An easy-to-set-up noncontact system for home monitoring would allow more accessible respiration monitoring and would overcome the challenges of attaching wearables or wiring to the child. Safe, easy-to-use systems could be used for different purposes, including screening for SDB, long-term monitoring and treatment evaluation.

Past reviews have focused on home-based, but not specifically unobtrusive, respiration monitoring (e.g. Bertoni and Isaiah⁸), or have focused solely on measuring respiratory rate (RR) in neonates⁹. To our knowledge, no reviews have been conducted to identify contactless methods for respiration monitoring during sleep in young children.

The aim of this scoping review is threefold: (1) to provide an overview of the studies reporting on safe noncontact monitoring of respiration in young children; (2) to describe the accuracy of the techniques, and (3) to highlight the advantages and limitations of each technique.

Methods

For this scoping review, a systematic search of scientific literature was executed.

Information sources and search strategy

First, an explorative Cochrane search was performed on July 13, 2023 to identify any existing reviews on noncontact respiration monitoring methods in children. To this extent, the keywords “child*” “monitor*” and “breath*” were used for a search in titles, abstracts and keywords. No reviews focusing on noncontact respiration monitoring methods in children were found.

Next, a systematic literature search in PubMed and EMBASE was performed July 13, 2023. The search strings (E-text 1 and 2) included the same terms as the Cochrane search, supplemented with similar terms and synonyms. Terms regarding unobtrusiveness were also included. In this process, a librarian specialized in medical sciences was consulted.

Inclusion and exclusion criteria

For this review, ‘contactless’ also encompassed sensors embedded in natural sleeping attributes, such as mattresses and pajamas. Studies had to at least measure apneas and/or hypopneas or RR. Furthermore, studies had to include, but were not restricted to, children who were <12 years of age. Studies were excluded if obtrusive, contact, prediction or indirect methods were used, if subjects were premature infants, and if subjects were nonhuman. Reviews, conference abstracts, questionnaires and commentaries were also excluded. Lastly, only full-text articles written in English were eligible for inclusion.

Study selection

Following the search, EndNote¹⁰ (Clarivate Analytics, London, UK) was used to remove duplicates, after which the remaining studies were uploaded into Rayyan¹¹ (Rayyan Systems, Inc., Cambridge, MA). Study relevance was assessed by title and abstract screening, after which full-text articles were read to determine eligibility based on the inclusion and exclusion criteria. This was done independently by two reviewers (ML and RG), and any disagreements were discussed until consensus was reached. If no consensus was reached, disagreements were resolved by discussing them with a third reviewer (JD). This, however, did not occur. Finally, the reference lists as well as the citations of all included papers were checked to identify additional eligible studies.

Data extraction and synthesis

Outcome data that was aimed to extract from the studies included data on the accuracy, safety, and reliability of the proposed methods. The results were summarized in a narrative synthesis.

Quality assessment

The quality of the included studies was assessed using the Quality Assessment of Diagnostic Accuracy Studies-2 (QUADAS-2) tool¹². The QUADAS-2 tool allows analysis of the risk of bias and applicability specific to diagnostic accuracy reviews. Four domains were included: patient selection, index test, reference standard, and flow and timing. The risk of bias and applicability concerns were reported as low, high or unclear. The tool was adapted to fit the purposes of this review. The number of study participants was taken into consideration in the quality assessment. If less than ten study participants were included, the risk of bias caused by patient selection was assessed to be high. A risk of bias was assessed to be unclear if the researchers did not provide enough information to evaluate the risk. If no reference standard was used, both the risk of bias of the reference standard and of the flow and timing were assessed to be high risk.

Results

The database search yielded 1414 articles, of which 1058 were left after removal of duplicates. For an overview of the selection process, see the PRISMA figure in Figure 1 . After assessment of relevance and eligibility, 14 studies were included. After checking the references and citations, three additional studies were included (E-text 3).

The methods researched in the included studies were bed-based methods, ultra-wideband (UWB) radar, Doppler radar, video, infrared (IR) cameras, garment-embedded with sensors, and sound analysis. Some studies used a combination of sensors. The main study characteristics are summarized in Table 1 . The accuracies of the researched techniques are summarized in Table 2 and the advantages and limitations of the techniques are summarized in Table 3 .

Bed-based methods

The techniques that monitor breathing using sensors embedded in a bed were based on pressure sensors, vibration sensors, load cells, microphones, electromagnetic sensors, piezoelectric sensors, and electromechanical film. Arimoto et al.¹³, embedded these sensors in a sheet-like device, the SD-101(Kenzmedico co. Ltd., Saitama, Japan). Norman et al.^{14,15} and Collaro et al.¹⁶ evaluated the Sonomat (Sonomat, Balmain, Australia), a thin mattress overlay with embedded sensors and microphones. and So et al.¹⁷ used the TaidoSensor (Sumitomo Riko Company Limited, Nagoya, Japan), a rubber sheet made of piezoelectric material. Lee et al.¹⁸ embedded load cells in a bed frame and used their sensors to obtain a ballistocardiogram (BCG), from which the cardiac and respiration cycle, and thereby the RR, could be obtained. So et al.¹⁷ Norman et al.^{14,15} and Collaro et al.¹⁶ aimed to detect apneas/hypopneas, and So et al.¹⁷ aimed to continuously measure RR and were also able to detect characteristic breathing patterns such as deep breathing and apneas. Lee et al.¹⁸ and Arimoto et al.¹³ used analytical software for automatic respiration monitoring, although the latter performed a manual correction since software was not yet available for measurements in children. Norman et al.^{14, 15} researched the validity of the Sonomat (Sonomat) in children, and Collaro et al.¹⁶ aimed to do so for children with Down Syndrome. The Sonomat (Sonomat) contains four vibration sensors and two room sound microphones. Both Norman et al.¹⁴ and Collaro et al.¹⁶ used the combination of signals to differentiate between obstructive, central, and mixed apneas and compared these results with PSG.

UWB Radar

Kim et al.¹⁹, de Goederen et al.⁵, Huang et al.²⁰, and Ziganshin et al.²¹ researched ultra-wideband (UWB) radar for respiration monitoring. Huang et al.²⁰ and Ziganshin et al.²¹ aimed to detect apneas, while de Goederen et al.⁵ and Kim et al.¹⁹ used their system to measure RR. De Goederen et al.⁵ used the RR for sleep stage classification.

Doppler radar

Fox et al.²² used Doppler radar with analytical software for actimetry and compared their method with an actimetry watch.

Video

Al-Naji and Chahl²³ used a video camera to monitor RR and used video magnification technique to do so.

IR camera

Both Al-Naji et al.²⁴ and Bani Amer et al.²⁵ used an IR camera in their research. Al-Naji et al.²⁴ used the Kinect v2 (Microsoft, Redmond, WA) sensor, which has three optical sensors: an RGB camera, IR sensor, and IR projector, that provide an RGB image, IR image and depth image. These signals were used to measure RR. Simulated apneas were detected as well. Bani Amer et al.²⁵ aimed to detect central, obstructive and mixed apneas. Both authors used software for signal analysis.

Garments

Two studies embedded sensors inside a garment; Gramse et al.²⁶ in the MamaGoose (MMG) pajamas (Verhaert Design and Development, Kruibeke, Belgium), Ranta et al.²⁷ in the NApping PAnTs (NAPPA) diaper cover (BABA Center, Helsinki, Finland). Both used an algorithm for RR monitoring, and Gramse et al.²⁶ detected apneas based on visual examination of the abdominal and thoracic respiration signals. No reference standard was used for respiration signals.

Sound analysis

Emoto et al.²⁸ used an artificial neural network to determine snoring/breathing episodes (SBEs) based on microphone recordings. Norman et al.¹⁵ compared the signals from the Sonomat (Sonomat) microphones with the mat as a whole. Breathing sounds and pattern prior to body movement were used to differentiate between spontaneous and respiration-induced body movement.

Quality assessment

Figure 2 shows the risk of bias and applicability concerns about each domain for the individual studies. In the figure, the colors green, yellow and red correspond to low, unclear and high risk of bias, respectively.

Eight studies included less than ten study participants. This, and the lack of information about the enrollment of study participants or exclusion criteria, increased the risk of bias in the patient selection.

Only Arimoto et al.¹³, Norman et al.¹⁴ and Collaro et al.¹⁶ compared their techniques with PSG and Ranta et al.²⁷ compared their garment with capnography. These authors all described the process of patient sampling and of index and reference test interpretation.

Both Fox et al.²² and So et al.¹⁷ included children and adults in their study population. In both of these studies, children <12 years old were the minority of the study population, which raises applicability concerns. These concerns also apply to the study by Kim et al.¹⁹ who evaluated their UWB radar device at the NICU. Although the neonates were clinically stable and full-term, this also raises concerns regarding applicability to our review question.

Discussion

Safe, noncontact techniques

The primary objective of this scoping review was to investigate the methods that have been studied for safe and noncontact monitoring of respiration in young children. The included studies explored various approaches, including bed-based methods, UWB radar, Doppler radar, video, IR cameras, garment-embedded sensors, and sound analysis. Among the 17 studies reviewed, the majority focus on monitoring either RR or apneas, while five studies aimed to do both. None of the studies reported safety risks. For very high-power UWB radar systems, there could be concerns for interference with other radiofrequency devices and safety,

but such high powers are not reached in UWB radar in the medical field²⁹. Liu et al.³⁰ have outlined that RR measurement methods can be derived from other physiological signals, respiration movements or airflow. Notably, most of the techniques investigated relied on software for signal analysis, offering advantages such as faster and more objective analysis compared to manual assessment.

In the study conducted by Lee et al.¹⁸, ballistocardiography was employed to derive RR. Notably, this technique offers the potential to detect other physiological parameters that generate motion, including snoring and limb movements^{31,32}. This capability opens up the possibility of assessing additional sleep characteristics such as REM sleep, as demonstrated by Kortelainen et al.³³. However, it is important to note that research on these measurements has predominantly concentrated on adults.

Accuracy

The second aim of this review was to describe the accuracy of the techniques. Because the monitoring techniques would mostly function as a screening tool for SDB, sensitivity is an important measure of accuracy. Only Norman et al.¹⁴, Collaro et al.¹⁶ and Bani Amer et al.²⁵ provided the sensitivity of their techniques (82%, 85% and 94% respectively).

RR measurement accuracies found by Al-Naji and Chahl²³, Kim et al.¹⁹ and Ranta et al.²⁷ fall within an accuracy of ± 2 breaths per minute. These researchers used different types of methods, namely video, UWB radar, and a garment-embedded sensor, respectively.

Not all studies explicitly described the impact on motion artifacts. However, the authors that did, were not able to monitor respiration. Interestingly, Bani Amer et al.²⁵ claimed that their measurements with an IR sensor did not have any effect of motion artifacts. A conventional apnea monitor was used as a reference standard, but it was not specified what type of monitor this was. It is known that different respiration measurement techniques, such as methods that measure chest and abdominal wall movements, are also subject to motion artifacts.³⁴ It would be interesting to see the performance validated against PSG.

Most authors removed data containing motion artifacts from the signal for apnea detection. Although this is not a problem for apnea detection in adults, children can experience apneas during body movements that last a long time¹³. Therefore, the ability of a technique to monitor respiration during movement would enable more accurate measurements. For Doppler radar, efforts have been made to fight the problem of motion artifacts. Li and Lin³⁵ researched a method using two radar sensors, and Gu et al.³⁶ used a hybrid radar-camera system for random body movement cancellation.

When presenting data on a new monitoring technique, it is essential to provide comprehensive information on accuracy to establish its validity and reliability. This includes describing the validation methods used to assess the performance of the technique, such as comparisons with established reference standards or expert evaluations. Geographical validation is also crucial to ensure the generalizability of the results across different populations or settings. Additionally, reporting metrics such as receiver operating characteristics (ROC) curves, sensitivity, specificity, positive predictive value, negative predictive value, and F1 score can further demonstrate the accuracy of the monitoring technique. These metrics allow for an in-depth analysis of the technique's ability to correctly identify and distinguish between various physiological parameters or conditions. Furthermore, providing information on any potential limitations or sources of error associated with the monitoring technique is important for a comprehensive evaluation. This may include factors such as signal quality, potential interference, or specific conditions under which the technique may yield less accurate results.

Advantages and limitations of the techniques

Most researched methods were easy to set up, except those involving load cells in a bed frame, which would be more challenging in a domestic setting compared to a mattress or mattress overlay. Both bed-based methods and UWB radar demonstrated potential for movement tracking in addition to monitoring RR and detecting apneas. It is expected that all techniques, except sound analysis, would enable movement tracking, which is valuable for accurately measuring sleep duration, fragmentation, and assessing the impact of SDB. Combining

sleep-wake classification with apnea detection allows a more precise estimation of the apnea-hypopnea index (AHI) compared to estimating sleep time based on time spent in bed. Arimoto et al.¹³, who took the time in bed as sleeping time, found an underestimation of 10-15% of AHI compared to PSG. Several studies have compared AHI calculations using UWB radar with PSG in adults. Zhou et al.³⁷ found a sensitivity and specificity of the AHI measured with UWB radar were 0.95-1 and 0.96 – 1, respectively, depending on the AHI cut-off values. Kang et al.³⁸ found that using UWB radar, three types of apnea (central, obstructive, and mixed) and hypopneas could be detected in adults. The authors concluded that UWB radar could be used as a screening tool for sleep apnea. If these results can be achieved in adults, there is reason to believe this is also possible in children.

Bed-based techniques and video analysis were found to be able to measure respiration in children in any sleeping position, allowing more accurate real-life measurements in children. Gramse et al.²⁶, who integrated strain sensors in a pair of pajamas, found that more signals were out of range in prone and side positions compared to supine positions. Authors researching radar-based monitoring did not specify the effect of sleeping position. In a radar-based vital sign monitoring study by Turppa et al.³⁹, larger errors in RR measurements in lateral sleeping positions were found compared to prone and supine positions. Not only the sleeping position influence the measurements, but the location and direction in which the radar is facing also play a significant role in measurement accuracy. Therefore, it would be valuable to explore various experimental setups in this context.

The added value of sound recording has been studied by Emoto et al.²⁸ and Norman et al.¹⁵ Apart from using breathing sounds for the classification of obstructive, central and mixed apneas, Norman et al.¹⁵ found that measuring snoring and stertor allows assessment of partial upper airway obstruction, providing more information compared to identifying discrete obstructive apnea/hypopnea events. In addition to this, snoring and breathing sounds have recently been researched for the estimation of sleep-wake activity and sleep quality parameters in adults. A study by Dafna et al.⁴⁰ found they could differentiate between sleep and wake based on breathing sounds, with a sensitivity of 92.2% and a specificity of 56.6% compared to PSG. In another study, by Akhter et al.⁴¹, breathing sounds were used to differentiate between REM and non-REM sleep, with a sensitivity of 92% and a specificity of 81% compared to PSG, indicating that these results could also be achievable in children.

Limitations

Three out of the 17 studies included in this review were retrieved from the reference lists of the other studies. This highlights the heterogeneity of terminology in this field of research. Four studies compared their method to the gold standard. Across the studies, different measures for accuracy were used, or no accuracies were determined. In addition to that, within groups of methods, different types of sensors and analytical algorithms were used, complicating the comparison between methods. The development of different sensors and algorithms, however, is not only logical in the current state of the art, but also essential for the field's progress, reflecting the diversity of use cases, promoting innovation, and allowing for tailored solutions to meet the unique needs in various clinical scenarios.

This scoping review mainly focused on apnea detection and RR monitoring. It is important to acknowledge that SDB encompasses a larger spectrum, including hypoperfusion and decreasing saturations¹. In order to properly diagnose SDB, these aspects should also be taken into account. Nonetheless, because OSA is the most common and clinically significant type of SDB in children⁴², this review is an important step towards contactless respiration monitoring and SDB screening in children.

Future research

To determine the most promising techniques for noncontact respiration monitoring in children, further research is necessary to compare these techniques against the gold standard PSG. Ideally, these studies should be openly accessible and encompass large cohorts of children across different age groups, encompassing both those with and without comorbidities. This approach will allow for the identification of the most effective techniques tailored to specific patient populations. Additionally, because respiration monitoring techniques

can be used for various objectives, it is important to take into consideration the types of monitoring techniques for specific use. Common objectives include diagnosis or screening of SDB, long-term apnea detection, RR monitoring, or impact assessment of SDB treatment. Future research should focus on identifying both the appropriate monitoring techniques for each application and the adequate signal processing algorithms for those techniques. Techniques should be safe, accurate, reliable and flexible in terms of environment. Studies presenting new monitoring techniques should report important accuracy metrics such as ROC curves, sensitivity, specificity, positive predictive value, negative predictive value and, in case of machine learning algorithms, F1 score. Lastly, to ensure generalizability of the results, it is crucial to validate the techniques.

Conclusion

In conclusion, our scoping review underscores the potential of diverse techniques for non-contact respiration monitoring in children. Yet, limited research volume and substantial heterogeneity spanning study quality, sensors and algorithms prevail.

Motion artifacts persist as a common hurdle in the reviewed studies, compromising apnea detection accuracy. Integrating sleep stage classification would enhance the precision of AHI calculation.

Sleep respiration monitoring research in adults has led to promising outcomes. These encouraging findings warrant further investigation and validation in pediatric populations. It is crucial to conduct studies with large sample sizes, encompassing diverse age groups and including children both with and without comorbidities. Open-source studies would catalyze progress and enable comparative analyses between different techniques.

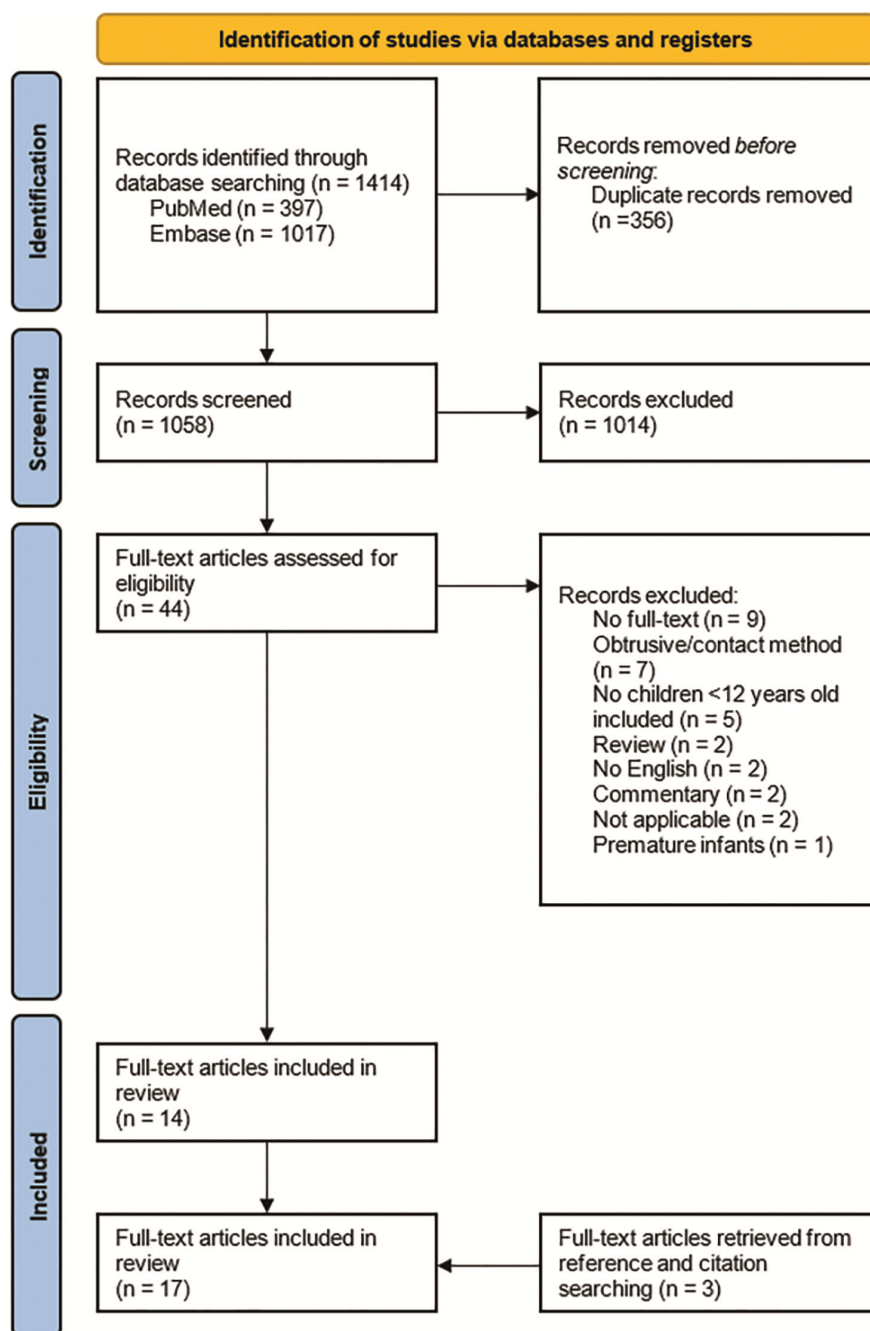
By addressing these research gaps, we can pave the way for improved monitoring approaches that provide accurate and reliable assessment of respiratory parameters in children. Such advancements would greatly contribute to the diagnosis and management of sleep-related breathing disorders in pediatric populations, ultimately elevating the overall health and well-being of children.

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		Risk of bias				Applicability concerns			Number of included subjects
		Patient selection	Index test	Reference standard	Flow and timing	Patient selection	Index test	Reference standard	
Bed-based methods	Arimoto et al. (2011)	?	+	+	-	+	+	+	107
	Norman et al. (2017)	+	+	+	+	+	+	+	76
	Collaro et al. (2023)	+	-	+	?	+	+	+	50
	So et al. (2011)	-	-	-	-	-	-	-	6
	Lee et al. (2015)	-	+	?	+	+	+	+	2
UWB radar	De Goederen et al. (2021)	+	?	+	-	+	-	+	40
	Kim et al. (2019)	-	+	+	+	-	+	+	6
	Huang et al. (2015)	-	+	-	?	+	+	-	1
	Ziganshin et al. (2010)	-	-	-	-	+	-	-	1
Doppler radar	Fox et al. (2007)	-	+	-	+	-	+	-	20
Video	Al-Naji and Chahl (2016)	-	?	-	+	+	+	+	1
IR camera	Al-Naji et al. (2017)	-	+	?	+	+	-	-	5
	Bani Amer et al. (2010)	?	+	?	+	+	+	+	20
Garments	Ranta et al. (2021)	+	+	-	+	+	+	+	24
	Gramse et al. (2003)	-	-	-	-	+	-	-	7
Sound analysis	Emoto et al. (2018)	?	+	?	+	+	-	-	20
	Norman et al. (2019)	+	-	-	+	+	-	+	231
-	High	?	Unclear	+	Low				

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