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REVIEW

Respiratory sounds in healthy people: A systematic review

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Computerised respiratory sound analysis;
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Adventitious respiratory sound;
Healthy population

Summary
Background: There is a lack of systematised information on respiratory sounds of healthy people. This impairs health professionals from differentiating respiratory sounds of healthy people from people with respiratory diseases, which may affect patients' diagnosis and treatment. Therefore, this systematic review aimed to characterise respiratory sounds of healthy people.
Methods: The Web of knowledge, MEDLINE, EMBASE and SCOPUS databases were searched and studies using computerised analyses to detect/characterise respiratory sounds in healthy people were included. Data were extracted using a structured table-format.
Results: Sixteen cross-sectional studies assessing respiratory sounds in 964 subjects (aged 1day-70yrs) were included: 13 investigated normal respiratory sounds (frequency, intensity and amplitude) and 3 adventitious respiratory sounds (crackles and wheezes). The highest sound frequencies were observed at the trachea (inspiration: 447—1323 Hz; expiration: 206—540 Hz). Women (444—999 Hz) and infants (250—400 Hz) presented the highest frequencies at maximum power. Inspiratory sounds were more intense at the left posterior lower lobe (5.7—76.6 dB) and expiratory sounds at the trachea (45.4—85.1 dB). Nevertheless, studies establishing direct comparisons between inspiratory and expiratory sounds showed that inspiratory sounds presented the highest intensities ($p < 0.001$). Amplitude was higher at the left upper anterior chest (1.7 ± 0.8 V) and lower at the right posterior lower lobe (1.2 ± 0.7 V). Crackles were the adventitious respiratory sound most frequently reported.
Conclusions: Respiratory sounds show different acoustic properties depending on subjects' characteristics, subjects' position, respiratory flow and place of recording. Further research with robust study designs, different populations and following the guidelines for computerised respiratory sound analysis are urgently needed to build evidence-base.

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Contents

Introduction

Respiratory auscultation performed with a conventional stethoscope is an assessment method used by many health professionals to evaluate and monitor patients with respiratory diseases [1,2]. In clinical practice, respiratory diseases may be diagnosed when normal respiratory sounds (NRS) are perceived as having frequencies and intensities that differ from normal [3] or when adventitious respiratory sounds (ARS) are present, namely crackles and wheezes [4,5]. Current research have been reporting on the potential of ARS to provide useful clinical information, as they are directly related to movement of air, changes within lung tissue and morphology and presence of secretions [6]. It is also known that different sections of the airways produce ARS with different characteristics (i.e., their duration and frequency varies; more proximal airways produce coarser crackles and higher frequency wheezes [4,7—9]), which can aid to localise the respiratory problem within the tracheobronchial tree. However, as the detection of ARS is usually performed with conventional stethoscopes, the correct interpretation of these sounds is critically dependent on the experience and hearing ability of the users [10], their knowledge about the range of frequencies and intensities that can be found in NRS and ARS [3] and their capacity to use the same nomenclature and memorise different sound patterns [11]. Furthermore, it can also be influenced by the stethoscope properties [12].

To overcome these limitations, research efforts are being conducted to automatically detect, quantify and characterise respiratory sounds, namely through computerised respiratory sound analysis [13]. Computerised respiratory sound analysis consists on recording subjects' respiratory sounds with an electronic device and then analysing and classifying the acoustic signal based on specific characteristics [14]. This innovative approach is being continuously updated with the use of electronic methods of signal transduction, conditioning, amplification and algorithms for a precise and automatic detection/classification of NRS and ARS [15—17]. However, reports on the classification of computerised respiratory sounds in healthy subjects are dispersed in the literature, unclear and mixed with findings from non-computerised respiratory sound analyses [18,19]. The lack of systematised information impairs health professionals from using this objective technology in their clinical practice and its use could potentially enhance patients' diagnosis treatment and monitoring.

Thus, the purpose of the present systematic review was to characterise respiratory sounds of healthy people through the use of computerised respiratory sound analysis.

Methods

Information sources and search strategy

A systematic electronic literature search was conducted from February to April 2013 on the following electronic databases: Pubmed (1950—2013), Science Direct (1823—2012), Web of Knowledge (1970—2012) and Scopus (1960—2013). A previous search was conducted in the Cochrane database to exclude the existence of reviews with the same purpose as the present one. Search terms were based on a combination of the following keywords: ("healthy people" OR "healthy population" OR "normal people" OR "normal population" OR healthy OR child*) AND ("computerised analyses" OR "digital auscultation" OR "electronic auscultation" OR "automatic auscultation") AND ("breath sounds" OR "lung sounds" OR "respiratory sounds" OR "added lung sounds" OR "abnormal lung sounds" OR "adventitious lung sounds" OR "adventitious respiratory sounds" OR crackl* OR wheez* OR frequenc* OR duration OR amplitude OR intensity OR "sound spectrum"). The search terms were limited to titles and abstracts. The reference lists of the selected articles were scanned for other potential eligible studies. Additionally, a weekly update was conducted until June 2013.

Eligibility criteria and study selection

Articles were included if they: i) used computerised respiratory sound analysis to characterise respiratory sounds in healthy adults or children; ii) were experimental (participants are randomly assigned to experimental or control groups), quasi-experimental (participants are not randomly assigned to experimental or control groups) or observational studies (studies observing human behaviour) [20,21]; iii) were full-text papers published in scientific journals or in conference proceedings; and iv) were written in English, Spanish, French or Portuguese. Articles were excluded if the study i) was conducted in animals; ii) aimed to validate algorithms or instruments for sound acquisition; or iii) aimed to verify the stability of respiratory sounds. Book chapters, review papers, abstracts of communications or meetings, letters to the editor, commentaries to articles, unpublished work and study protocols were not considered suitable and, therefore, were also excluded from this study.

This systematic review was reported using the systematic review method proposed by the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) [22,23].

Data collection process

Two reviewers independently assessed all potential studies identified as a result of the search strategy. A consensus method concerning the selection and inclusion of studies was used to solve any disagreements. The studies were selected based on their titles and abstracts. When the title, abstract and keywords were relevant for the scope of the review, the full-text article was downloaded and read carefully to decide its inclusion in the final report.

Quality assessment

The quality of the included studies was assessed with a checklist adapted by Petticrew and colleagues [24] based on the 'Crombie criteria' for the assessment of cross-sectional studies [25], according to previous systematic reviews [26]. The checklist provides a list of 8 questions to measure the study quality based on research design, recruitment strategy, response rate, sample representativeness, measures and statistics used and power. Quality was assessed independently by two reviewers. To determine the consistency of the quality assessment performed by the two reviewers, an inter-rater agreement analysis using the Cohen's kappa was performed. The value of Cohen's kappa ranges from 0 to 1 and can be categorised as slight (0.0–0.20), fair (0.21–0.40), moderate (0.41–0.60), substantial (0.61–0.80) or almost perfect ($\geq$0.81) agreement [27]. This statistical analysis was performed using PASW Statistics (version 18.0, SPSS Inc., Chicago, IL). Disagreements between raters were further resolved through discussion.

Data extraction and synthesis of results

Data from the included articles were extracted in a structured table-format comprising the following topics: publication details (first author, year of publication); study design; characteristics of the participants (total number, age and gender), data collection protocol (subjects' position and anatomic sites, place and duration of the recordings), target respiratory flows, recording device, sound analysis (sound filters and algorithms applied and sampling rate) outcome measures and findings.

Results

Study selection

The databases search identified 1445 records. After duplicates removal, 1408 records were screened for relevant content. During the title, abstract and keyword screening, 1379 articles were excluded. The full-text of 29 potentially relevant articles was assessed and 27 articles were excluded due to the following reasons: i) did not assess computerised respiratory sounds ($n = 6$); ii) did not included healthy people ($n = 9$); iii) studies were conducted in animals ($n = 1$); iv) were written in German ($n = 1$); v) aimed to validate algorithms ($n = 5$); vi) did not present quantitative data on respiratory sounds ($n = 1$); and vii) analysed artificial respiratory sounds (e.g. sound producer, web source) ($n = 4$). Therefore, 2 original articles were included. The search for relevant articles within the reference list of the included and excluded papers by full-text analysis retrieved 14 additional studies. Therefore, a total of 16 studies were included in this review (Fig. 1).

Quality assessment

The quality of the included studies, using the 'Crombie criteria', is presented in Table 1. All studies had an appropriate research design and used objective measures. Five studies failed to report the recruitment strategy used [3,28–31]. As no study reported dropouts, the response rate indicator was considered in all studies. Studies presented the appropriate statistical analyses, however, they did not use representative samples or justified their sample size. Evidence of bias was not considered to be present, despite the use of convenience samples. The inter-rater agreement was almost perfect ($k = 0.873$; 95% confidence interval = 0.616–1.00; $p = 0.001$).

Study characteristics

Studies included in this review ranged from 1983 to 2008 and used cross-sectional methodologies. A total of 964 healthy subjects (68% male) participated in the studies, 169 were smokers and 258 non-smokers. Most subjects were adults (n = 909; 94%; 18–70 years old) and 6% (n = 54) were children (ages ranged from 1 day to 13 years old).

Three studies provided information on ARS (frequency, number and position in the breathing cycle [31–33]) and thirteen on NRS (frequency [3,18,34–38], intensity [6,18,28–30,34,36,39] and amplitude [40]). Respiratory sounds were recorded mainly from the posterior chest (right and left) [3,18,28–36,38–41], 5 studies recorded from the anterior chest [28,30,32,34,40], 6 from the trachea [29,31,33,35,38,39] and 1 from the nasal cavity [37]. Recordings were performed with the subjects standing [3,28,29,40], lying [18,31,33,36] or sitting [6,30,38,39], with different recording devices such as conventional [3,30,33,37,40], electret [28,31,32] and condenser [35] microphones, piezoelectric contact sensors [6,29,34,35,38], sound transducers [18] and contact accelerometers [39].

Eleven studies controlled subjects' respiratory flows at different targets from 0.015 to 3 l/s using pneumotacographs [18,28–30,34–36,38–41]. In two other studies subjects were asked to breath normally [3] or deeper than normal [3,33].

To analyse the sound data, studies applied different filters (50–2240 Hz), sample rates (4000–12,000 Hz) and

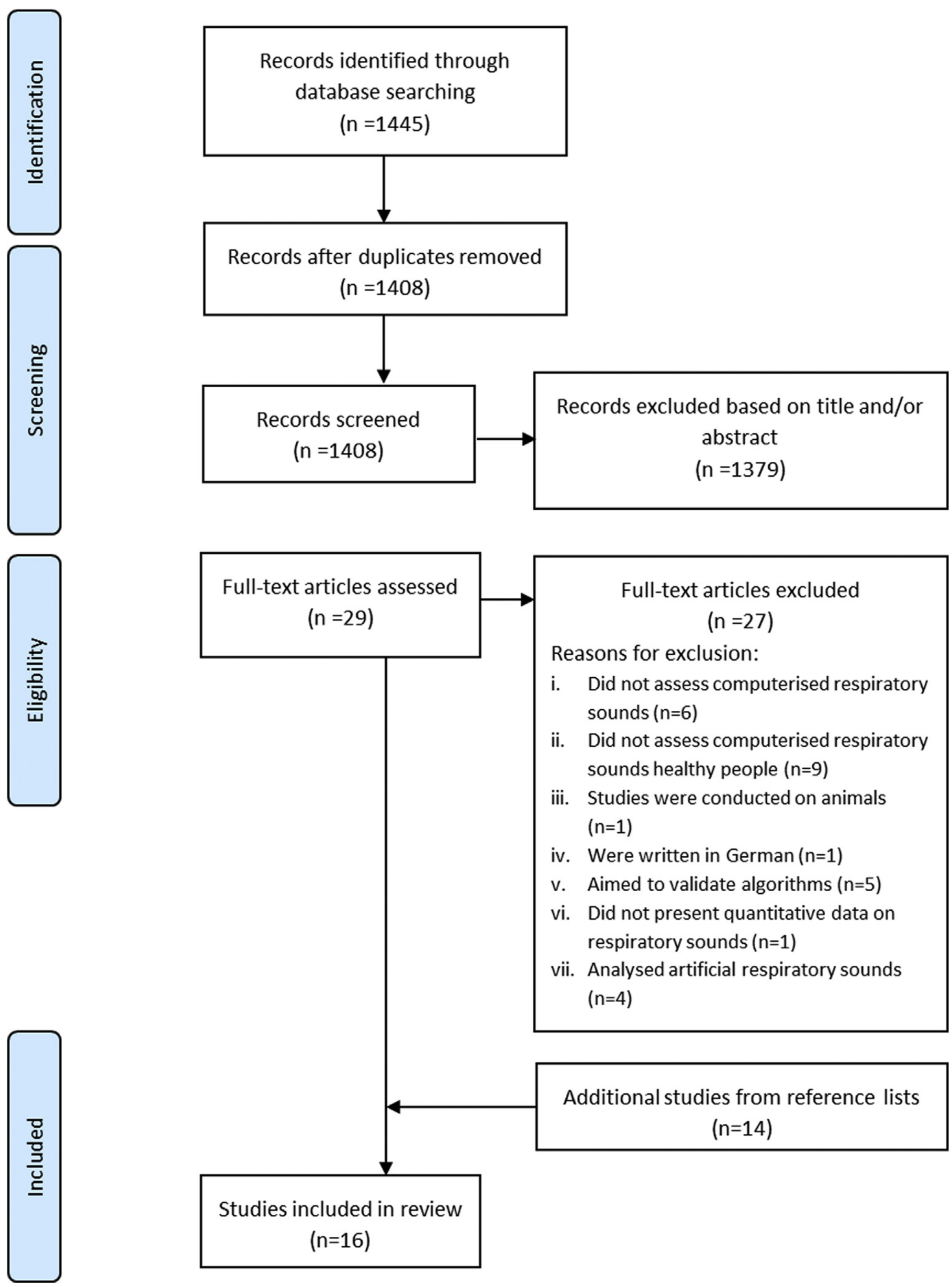

Figure 1 PRISMA flow diagram of the included studies.

Table 1 Quality assessment of cross sectional studies.

Author and year	Appropriate research design?	Appropriate recruitment strategy?	Response rate?	Is sample representative? (all clinic populations)	Objective and reliable measures?	Power calculation/ justification of numbers?	Appropriate statistical analysis?	Evidence of bias?	Quality indicators Met (MS = 8)
Kraman, 1983	√	√			√		√	Convenience sample	4
Kraman, 1984	√				√		√	Convenience sample	3
Hidalgo, 1991	√				√		√	Convenience sample	3
Bettencourt, 1994	√	√			√		√	Convenience sample	4
Malmberg, 1994	√	√			√		√	Convenience sample	4
Malmberg, 1995	√	√			√		√	Convenience sample - suspected to have coronary heart disease	4
Gavriely, 1995	√	√			√		√	Convenience sample	4
Gavriely, 1996	√				√		√	Convenience sample - not stated from where were recruited	3
Pasterkamp, 1996a	√	√			√		√	Convenience sample	4
Pasterkamp, 1996b	√	√			√		√	Convenience sample	4
Kompis, 1997	√				√		√	Convenience sample	3
Jones, 1999	√	√			√		√	Convenience sample	4
Kiyokawa, 2002	√	√			√		√	Convenience sample	4
Murphy, 2004	√	√			√		√	Convenience sample	4
Seren, 2005	√	√			√		√	Convenience sample	4
Murphy, 2008	√				√			Convenience sample	2

MS: maximal score.

Table 2 Characteristic of the respiratory sounds of healthy people.

Study, Year	Type of study	Participants	Data collection protocol	Target flows	Recording device	Sound analyses	Outcomes measures	Findings
Kraman, 1983	Cross-sectional	9 adults (2 smokers). 20-37yrs 5M:4F	-Subjects were in a stand position -Records were made from the back of the thorax (5 cm from the spine and 4 cm above the point of just detectable diaphragmatic dullness, and 1 cm lateral to this point) and from the upper left and right anterior chest (at the midsternum in the 2nd intercostal space, 1 cm lateral to this point and on opposite sides of the sternum, 8 cm apart, in the left and right 2nd intercostal spaces).	Targets flows of at least 2 l/s. Only flow rates above 1.3 l/s were analysed.	Phonopneumography 2 microphones	-Band pass-filtered between 200 and 625 Hz - sampling: 5000 Hz	NRS: - Amplitude	**Inspiratory Sounds** RUAC: 1.3 ± 0.7 V LUAC: 1.7 ± 0.8 V RPLL: 1.2 ± 0.7 V LPLL: 1.4 ± 0.8 V
Kraman, 1984	Cross-sectional	4 adults (1 smoker) 27–38yrs 5M:0F	- Subjects were in a stand position - Records were made from the chest, over the second right intercostal space and mid clavicular line and approximately 6 cm from the spine, immediately below the lower edge of the right scapula. - 20 consecutive breathing cycles were taken	Targets flows between 1.2 and 4 l/s.	2 electret microphone	- High pass filtered at 200 Hz - sampling: 5000 Hz	NRS: - Intensity	**Inspiratory Sounds** RUAC: 68.6 ± 5.7 dB LUAC: 79.1 ± 4.3 dB RPLL: 72.8 ± 3.5 dB LPLL: 76.6 ± 2.1 dB
Hidalgo, 1991	Cross-sectional	G1:35 children 0–13yrs 18M:17F G2: 5 non-smoking adults 34–43yrs 3M:2F	- Subjects were in a stand position - Inside a double-walled acoustic chamber - Records were made from the chest wall over the RPLL at a distance of 0.7 cm.	Children breathed spontaneously Adults breathed at an increased depth and rate	1 air coupled microphone	-Low-pass filter at 2000 Hz - Sampling: 4096 Hz - 12-bit resolution - FFT. - TEWA - Automatic detection	NRS: - Frequency	**Inspiratory sounds** RPLL Children vs Adults F25: 125 ± 6 Hz; 139 ± 15 Hz, $p = 0.02$ F50: 169 ± 14 Hz; 194 ± 26 Hz, $p = 0.03$ F75: 252 ± 19 Hz; 277 ± 34 Hz, $p = 0.11$ F95: 527 ± 52 Hz; 467 ± 45 Hz, $p = 0.02$ F25, F50, F75 differed significantly from children aged 0–3yrs and adults ($p < 0.005$)

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Table 2 (*continued*)

Study, Year	Type of study	Participants	Data collection protocol	Target flows	Recording device	Sound analyses	Outcomes measures	Findings
								F95 differed significantly from children aged >9yrs and adults ($p < 0.05$) F25, F50, F75 decreased significantly with age and height ($p < 0.001$).
Bettencourt, 1994	Cross-sectional	15 adults	- Records were made from eight sites anteriorly, 24 laterally, and 18 posteriorly.	NS	Electret microphone connected to the diaphragm of a Littman stethoscope	- Band pass-filtered between 80 and 2000 Hz TEWA	ARS: - Wheeze - Crackle	All chest locations: Wheeze:0; Crackle:1; Late insp: 1 ± 2; Fine: 1 ± 2 Upper chest: Crackle: 7 ± 26%; Wheeze: 0% Right chest: Crackle: 23 ± 37%; Wheeze: 0%
Malmberg, 1994	Cross-sectional	6 non-smoking adults 22–31yrs 3M:3F	- Subjects were in a sitting position - In a quiet room - Records were made from the chest wall over the RPLL and from the trachea. - 4–6 consecutive breathing cycles were taken	Targets flow of 1.25 l/s;	Phonopneumography 1 air-coupled condenser microfone with a preamplifier 1 piezoelectric contact sensor	- High pass filter at 100 Hz - 13-bit resolution - sampling: 12000 Hz - overlapped segment method	NRS: - Frequency	**Inspiratory sounds** Trachea F_{max}: 93 ± 12 Hz F50: 447 ± 186 Hz RPLL F_{max}: 106 ± 10 Hz F50: 142 ± 8 Hz **Expiratory sounds** Trachea F_{max}: 99 ± 8 Hz F50: 540 ± 174 Hz RPLL F_{max}: 104 ± 6 Hz F50: 131 ± 6 Hz
Malmberg, 1995	Cross-sectional	11 non-smoking adults 44–66yrs 11M:0F	- Records were made from the chest wall over the RPLL, approximately 10 cm below the margin of the scapula and 15 cm to the right of the spine and from the trachea at the right side of the cricothyroid cartilage. - 8–10 consecutive breathing cycles were taken	Targets flow of 1.25 l/s; Only sound samples of inspiratory sounds that occurred at flows from 1.0/s to target flow were used	Phonopneumography 1 coupled condenser microfone 1 piezoelectric contact sensor	- High pass filter at 50 Hz - 13-bit resolution - sampling: 12000 Hz - FFT	NRS: - Frequency	**Inspiratory sounds** Trachea F_{max}: 154 ± 157 Hz F50: 766 ± 178 Hz F75: 1323 ± 192 Hz RPLL F_{max}: 117 ± 18 Hz F50: 206 ± 14 Hz F75: 301 ± 33 Hz

Gavriely, 1995	Cross-sectional	353 subjects (166 smokers) M: 44 ± 11yrs F: 40 ± 11yrs. 272M:81F	- In a quiet room. - Records were made from the right anterior chest at the mid clavicular line in the second intercostal space, and in the RPLL and LPLL at the eighth to tenth intercostal spaces in the mid scapular line	Targets flows of 1 l/s	Phonopneumography 3 piezoelectric contact sensors	- Band pass-filtered between 75 and 2000 Hz - sampling: 4000 Hz - 12-bit resolution - FFT - Regression lines	NRS: - Frequency - Intensity	**Inspiratory sounds** (males) RUAC − A_{high}: −13.6 ± 1.8 dB/oct; A_{low}: −6.3 ± 6.4 dB/oct; F_{int}: 160 ± 45 Hz; P_{int}: 53 ± 28; F_{max}: 822 ± 247 Hz RPLL − A_{high}: −14.1 ± 1.9 dB/oct; A_{low}: −0.0 ± 14.6 dB/oct; F_{int}: 155 ± 39 Hz; P_{int}: 68 ± 61; F_{max}: 760 ± 227 Hz LPLL − A_{high}: −15.2 ± 2.6 dB/oct; A_{low}: −5.0 ± 7.0 dB/oct; F_{int}: 160 ± 17 Hz; P_{int}: 53 ± 41; F_{max}: 736 ± 201 Hz **Inspiratory sounds** (females) RUAC − A_{high}: −12.9 ± 1.7 dB/oct; A_{low}: −5.8 ± 5.6 dB/oct; F_{int}: 182 ± 52 Hz; P_{int}: 48 ± 21; F_{max}: 999 ± 265 Hz RPLL − A_{high}: −13.8 ± 2.0 dB/oct; A_{low}: −5.4 ± 5.2 dB/oct; F_{int}: 157 ± 15 Hz; P_{int}: 71 ± 32; F_{max}: 843 ± 133 Hz LPLL − A_{high}: −14.7 ± 2.6 dB/oct; A_{low}: −6.8 ± 1.4 dB/oct; F_{int}: 157 ± 16 Hz; P_{int}: 74 ± 29; F_{max}: 885 ± 247 Hz **Expiratory sounds** (males) RUAC − A_{high}: −14.9 ± 12.7 dB/oct;

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Table 2 (*continued*)

Study, Year	Type of study	Participants	Data collection protocol	Target flows	Recording device	Sound analyses	Outcomes measures	Findings
								A_{low}: −11.4 ± 14.0 dB/oct; F_{int}: 184 ± 81 Hz; P_{int}: 25 ± 22; F_{max}: 604 ± 123 Hz RPLL − A_{high}: −19.7 ± 5.1 dB/oct; A_{low}: −6.5 ± 7.1 dB/oct; F_{int}: 150 ± 16 Hz; P_{int}: 32 ± 45; F_{max}: 419 ± 112 Hz LPLL − A_{high}: −18.8 ± 4.4 dB/oct; A_{low}: −6.7 ± 5.9 dB/oct; F_{int}: 155 ± 30 Hz; P_{int}: 23 ± 17; F_{max}: 426 ± 87 Hz **Expiratory sounds** (females) RUAC − A_{high}: −13.4 ± 1.9 dB/oct; A_{low}: −4.7 ± 7.7 dB/oct; F_{int}: 173 ± 52; P_{int}: 28 ± 14; F_{max}: 794 ± 142 Hz RPLL − A_{high}: −20.3 ± 4.2 dB/oct; A_{low}: −5.3 ± 7.1 dB/oct; F_{int}: 147 ± 21 Hz; P_{int}: 30 ± 14; F_{max}: 420 ± 60 Hz LPLL − A_{high}: −17.7 ± 3.8 dB/oct; A_{low}: −8.0 ± 1.0 dB/oct; F_{int}: 140 ± 18 Hz; P_{int}: 44 ± 9; F_{max}: 444 ± 52 Hz
Gavriely, 1996	Cross-sectional	6 adults 29–70yrs 6M:0F	- Subjects were in a stand position; - In a quiet room	Targets flows of 0.5, 1.0, 1.5, 2.0, 2.5 and	Phonopneumography 3 piezoelectric contact sensors	- Band pass-filtered	NRS: - Intensity	**Inspiratory sounds** TR: 60.8 ± 37.7 dB; RUAC: 4.7 ± 2.2 dB;

			- Records were made from the trachea, right anterior chest at the mid clavicular line in the second intercostal space, and in the RPLL and LPLL at the eighth to tenth intercostal spaces in the mid scapular line - Over 10 consecutive breathing cycles were taken	3.0 l/s		between 75 and 2000 Hz - Sampling: 4800 Hz - 12-bit resolution - FFT		RPLL: 4.3 ± 1.6 dB; LPLL: 5.7 ± 1.7 dB RPLL and LPLL differed significantly ($p < 0.05$) RUAC and LPLL differed dignificantly ($p < 0.05$) **Expiratory sounds** TR: 85.1 ± 54.1 dB; RUAC: 2.3 ± 1.3 dB; RPLL: 1.9 ± 0.8 dB; LPLL: 2.5 ± 0.9 dB RPLL and LPLL differed significantly ($p < 0.05$)
Pasterkamp, 1996a	Cross-sectional	G1: 10 infants 1 ± 0.5days 5M:5F G2: 9 children 7 ± 0.8yrs 4M:5F G3: 10 non-smoking adults 30 ± 3.6yrs 5M:5F	Infants - Subjects were in a prone position; - In a quiet room - Records were made from the chest over the RPLL, below the scapula and approximately 2 cm lateral to the spine. Children and Adults - Subjects were in a prone position; - In the respiration acoustic laboratory - Records were made on the chest, over the RPLL, below the scapula and approximately 3—5 cm lateral to the spine.	Infants breathed spontaneously Children and adults had targets flow of 0.015 and 0.03l/s/kg ± 20% tolerance.	Phonopneumography 1 sound transducer	- Low-pass filtered at 2400 Hz - Sampling: 10.24 Hz - 12-bit resolution - FFT - Logarithmic transformation	NRS: - Frequency - Intensity	**Low flows (15 ml/s/kg):** - Inspiratory Sounds intensity < 100 Hz — Infants: 3.4 ± 2.6 dB; Children: 3.2 ± 2 dB; Adults: 1.5 ± 2.9 dB, $p < 0.05$ - Inspiratory sounds intensity < 300 Hz - Infants: 14.4 ± 3.7 dB Children: 15.1 ± 1.5 dB; Adults: 11.4 ± 3.2 dB, $p = 0.028$ **High flows (30 ml/s/kg ± 20%):** - Inspiratory Sounds intensity < 100 Hz - Children: 8.0 ± 4.1 dB;

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Table 2 (*continued*)

Study, Year	Type of study	Participants	Data collection protocol	Target flows	Recording device	Sound analyses	Outcomes measures	Findings
								Adults: 9.2 ± 2.6 dB, $p < 0.05$ - Inspiratory Sounds intensity > 100 Hz- Children: 8.4 ± 1.7 dB; Adults: 9.7 ± 1.5 dB, $p = 0.107$ - Expiratory sounds 8/10 adults: F: 760 −1.735 Hz; Int: 5.4 −18.5 dB 9/9 children: F: 1040 −1595 Hz; Int: 6.3 −20.4 dB - Both Inspiratory and expiratory sounds F_{hi} was not different between children and adult ($p > 0.05$). Infants had higher F_{max} than either children or adults ($p < 0.01$). F_{hi} was not different among groups ($p = 0.176$) F_{lo}- infants: 126 ± 36 Hz; Children: 57 ± 38 Hz; Adults:79 ± 66 Hz, $p = 0.016$ Adults had lower F_{lo} and higher F_{hi} with increased flows

								($p < 0.05$). Children showed the same changes but also higher F_{max}, ($p < 0.05$).
Pasterkamp, 1996b	Cross-sectional	6 non-smoking adults 29–34yrs 6M.0F	- Subjects were in a sitting position - Records were made from the front the RPLL and at the trachea	Targets flows between 1.3 and 1.7 l/s.	Phonopneumography 2 contact accelerometers	- Band pass-filtered bellow 50 Hz - sampling: 10240 Hz - 12-bit resolution - FFT	NRS: - Intensity	**Inspiratory sounds** (>100 Hz) Trachea: 38.67 ± 1.02 dB RPLL: 17.17 ± 1.47 dB **Expiratory sounds** (>100 Hz) Trachea: 45.33 ± 1.58 dB RPLL: 11.50 ± 0.92 dB
Kompis, 1997	Cross-sectional	4 non-smoking adults 30–39yrs 4M:0F	- Subjects were in a sitting position - In the sound proof chamber - Records were made from the front chest and the back of the thorax	Targets flows of 2 l/s. Only flow rates within ±20% of the target flow were analysed.	Phonopneumography 16 microphones	- Band pass-filtered between 100 and 2000 Hz - sampling: 10240 Hz	NRS: - Intensity	**Average difference between inspiratory/ expiratory sounds** 150–300 Hz: 10.5 dB 300–600 Hz: 12.4 dB 600–1200 Hz: 11.4 dB **Compariso between the left and right hemithorax** Inspiratory Sounds (Front; Back): 150–300 Hz: −4 dB; 3.5 dB 300–600 Hz: −1.3 dB; 4.6 dB 600–1200 Hz: −0.9 dB; 3.4 dB Expiratory Sounds (Front; Back): 150–300 Hz: −4.3 dB; −5.7 dB 300–600 Hz: −2.6 dB; 2.1 dB 600–1200 Hz: −3.0 dB; 1.8 dB
Jones, 1999	Cross-sectional	11 aldults 16–26yrs 6M:5F	- Subjects were side lying and seated; - Records were made from the RPLL and the LPLL at the	Targets flows between 1.5 and 2 l/s.	Phonopneumography 3 microphone attached to 3 stethoscope chest	- sampling: 5000 Hz	NRS: - Intensity - Frequency	**Inspiratory sounds** Sitting (RPLL, LPLL) PI: 20.7 ± 6.3 dB, 25.6 ± 4.3 dB,

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Table 2 (*continued*)

Study, Year	Type of study	Participants	Data collection protocol	Target flows	Recording device	Sound analyses	Outcomes measures	Findings
			eighth intercostal spaces in the mid scapular line - Over 5 consecutive breathing cycles were taken		piece			$p = 0.016$ F_{max}: 244 ± 51.9 Hz, 253 ± 22.9 Hz F_{mean}: 439.5 ± 96.8 Hz; 439.9 ± 107.2 Hz Left side lying (RPLL, LPLLL) PI: 15.7 ± 4.3 dB, 23.5 ± 5.1 dB, $p = 0.000$ F_{max}: 201.6 ± 57.6 Hz, 240.6 ± 31 Hz F_{mean}: 427.5 ± 126.9 Hz; 434.2 ± 109.1 Hz Right side lying (RPLL, LPLL) PI: 22.7 ± 4.2 dB, 19.7 ± 7.2 dB F_{max}: 278.4 ± 42.3 Hz, 236.6 ± 158 Hz F_{mean}: 429.5 ± 80.9 Hz; 445.6 ± 146.3 Hz **Expiratory sounds** Sitting (RPLL, LPLL) PI: 8.3 ± 3.2 dB, 10.2 ± 4.9 dB F_{max}: 192.6 ± 130.9 Hz, 172.6 ± 76.9 Hz F_{mean}: 552.5 ± 164.9 Hz; 516.1 ± 169.2 Hz Left side lying(RPLL, LPLL) PI: 8.7 ± 7.0 dB, 9.3 ± 6.5 dB F_{max}: 155.7 ± 77.5 Hz,

								148.5 ± 37.2 Hz F_{mean}: 532.1 ± 199.9 Hz; 386.7 ± 106.4 Hz Right side lying(RPLL, LPLL) PI: 11.2 ± 4.5 dB, 6.8 ± 4.2 dB F_{max}: 167.5 ± 69.4 Hz, 199.2 ± 146 Hz F_{mean}: 436.3 ± 156.8 Hz; 480.1 ± 144.13 Hz
Kiyokawa et al., 2002	Cross-sectional	5 non-smoking adults 21—50yrs 3M:2F	- Subjects were in a sitting position - In a body plethysmograph - Records were made from the chest over the RUPC, RPLL and LPLL - Over 5 consecutive breathing cycles were taken	Targets flows of 1.2 ± 0.2 l/s.	Phonopneumography 2 contact sensors in each recording site	- 12-bit resolution - Sampling 10240 Hz;	NRS: - Intensity	**Inspiratory sounds** RUAC 75—150 Hz: 10.0 ± 2.9 dB 150—300 Hz: 19.8 ± 5.0 dB 300—600 Hz: 25.2 ± 5.2 dB RPLL 75—150 Hz: 13.7 ± 2.7 dB 150—300 Hz: 20.9 ± 3.0 dB 300—600 Hz: 20.7 ± 3.9 dB LPLL 75—150 Hz: 12.7 ± 3.9 dB 150—300 Hz: 20.1 ± 3.7 dB 300—600 Hz: 23.2 ± 4.3 dB **Expiratory sounds** RUAC 75—150 Hz: 7.9 ± 4.8 dB 150—300 Hz: 16.9 ± 6.5 dB 300—600 Hz: 21.1 ± 8.9 dB RPLL

(*continued on next page*)

Table 2 (*continued*)

Study, Year	Type of study	Participants	Data collection protocol	Target flows	Recording device	Sound analyses	Outcomes measures	Findings
								75–150 Hz: 10.5 $\pm$ 2.9 dB 150–300 Hz: 15.0 $\pm$ 4.1 dB 300–600 Hz: 8.8 $\pm$ 6.1 dB LPLL 75–150 Hz: 7.9 $\pm$ 4.0 dB 150–300 Hz: 10.2 $\pm$ 3.9 dB 300–600 Hz: 9.4 $\pm$ 4.6 dB
Murphy, 2004	Cross-sectional	100 adults 69 $\pm$ 7yrs 52M:48F	- Subjects were in a supine position; - Records were made from the trachea and from the back of the torax - Two 20″ measurements were taken	Subjects breathed more deeply than normal, with their mouths open	1 regular microphone 14 microphones incorporated into a soft foam pad	- Crackle counter - Wheeze and rhonchus detector	ARS: - Wheeze - Crackle	**Inspiratory Sounds** Wheeze: Patients With Wheeze: 3 Crackle: Patients With Crackle: 28%; mean nBC: 2 $\pm$ 4 F: 387 $\pm$ 91 Hz **Expiratory sounds** Wheeze; Patients With Wheeze: 1 Crackle: Patients With Crackle: 9%; mean nBC: 4 $\pm$ 3; F: 402 $\pm$ 104 Hz
Seren, 2005	Cross-sectional	30 non-smoking adults 18–45yrs 13M:17F	- Records we made 0.5 cm inside the nostril of the nasal cavity *via* a 2-cm-long nasal prope.	NS	1 microphone with amplifier	- 16-bit resolution - Sampling: 44.1 Hz - FFT.	NRS: - Frequency	**Expiratory Sounds** Right Nose vs Left Nose HIS: 1254 $\pm$ 10.3 Hz vs 1375 $\pm$ 18.5 Hz, $p > 0.05$ LIS: 2453 $\pm$ 22.2 Hz vs 2234 $\pm$ 21.1 Hz, $p < 0.05$.
Murphy, 2008	Cross-sectional	334 participants	- Records were made from the back and lateral bases of the thorax - 6 microphones on the posterior right base, 6 on the	NS	16 microphones incorporated into a soft foam pad	Algorithm analyses acoustic energy versus time and detects wheezes,	ARS: - Wheeze - Crackle	**Inspiratory Sounds** Wheeze: Average wheeze rate (%):0 $\pm$ 4; Patients who wheeze

		posterior left base, 1 on the right lateral base, 1 on the left lateral base and 1 over the trachea		rhonchi and crackles	for >4% of the inspiration: 2% Among these patients, average wheeze frequency: 300 ± 136 Hz Crackle: Average crackle/breath:1 ± 2 Patients with over 2 crackles/breath: 16 Among these patients, average crackle frequency: 371 ± 88 Hz **Expiratory sounds** Wheeze: Average wheeze rate (%):1 ± 5; Patients who wheeze for >4% of the inspiration: 2% Among these patients, average wheeze frequency: 309 ± 122 Hz Crackle: Average crackle/breath:1 ± 1 Patients with over 2 crackles/breath: 8 Among these patients, average crackle frequency: 337 ± 106 Hz

Data are Mean ± Standard Deviation.

A_{high}: high frequency regression lines; A_{low}: low frequency regression lines; ARS: adventitious respiratory sounds; F: frequency; FFT: fast fourier transformation; F_{hi}: High frequencies; F_{int} = frequency at intersection of low and high frequency regression lines; F_{lo}: Low frequencies; F_{max}: frequency at maximum power; F_{mean}: mean frequency; HIS: higher intensity sound; Int: intensity; LIS: lower intensity sound; LPLL: left posterior lower lobe; RMS: total spectral power; NRS: normal respiratory sounds; NS: not stated; nBC: number per breathing; P_{int} = power at intersection of low and high frequency regression lines; RUAC: right upper anterior chest; LUAC: left upper anterior chest; RUPC: right upper posterior chest; RPLL: right posterior lower lobe; TEWA: time expanded waveform analysis; TR: trachea; Yrs: years.

Table 3 Resume table — Respiratory sounds characteristics of healthy people.

				Variables					
FEMALE	A	Place	BP	F25 (Hz)	F50 (Hz)	F75 (Hz)	F95 (Hz)	F_{max} (Hz)	F_{mean} (Hz)
		RUAC	ins					999 ± 265	
			exp					794 ± 142	
		RPLL	ins					843 ± 133	
			exp					420 ± 60	
		LPLL	ins					885 ± 247	
			exp					444 ± 52	
MALE	A	RUAC	ins					822 ± 247	
			exp					604 ± 123	
		RPLL	ins					760 ± 227	
			exp					419 ± 112	
		LPLL	ins					736 ± 201	
			exp					426 ± 87	
BOTH	I	RPLL	ins						
	C	RPLL	ins	125 ± 6	169 ± 14	252 ± 19	527 ± 52		
			exp					1.040 to 1.595	
	A	TC	ins		447 to 766	1323 ± 192		93 to 154	
			exp		540 ± 174			99 ± 8	
		RUAC	ins						
			exp						
		LUAC	ins						
			exp						
		RPLL	ins	139 ± 15	194 to 206	277 to 301	467 ± 45	106 to 244	439.5 ± 96.8
			exp		131 ± 6			104 to 1.735	552.5 ± 164.9
		LPLL	ins					253 ± 22.9	439.9 ± 107.2
			exp					172.6 ± 76.9	516.1 ± 169.2

A: Adults; A_{high}: high frequency regression lines; A_{low}: low frequency regression lines; Amp: amplitude; BP: breathing phase; C: Children; exp: expiration; F: frequency; F_{max}: frequency at maximum power; F_{mean}: mean frequency; F25: frequency at 25% of inspiratory/expiratory spectral power; F50: frequency at 50% of inspiratory/expiratory spectral power ; F75: frequency at 75% of inspiratory/expiratory spectral power; F95: frequency at 95% of inspiratory/expiratory spectral power; I: Infants; Int: intensity; ins: inspiration; LPLL: left posterior lower lobe; LUAC: left upper anterior chest; RPLL: right posterior lower lobe; RUAC: right upper anterior chest; RUPC: right upper posterior chest; TR: trachea.

resolutions (12—16 bits). Algorithms based on fast Fourier transformation [3,18,29,34,35,37,39], time-expanded wave-form analysis [3,32], overlapped segment method [38] and automatic sound detection [3,31,33] were used to automatically detect and characterise NRS and ARS.

Nine studies did not provide information about gender [31,32], smoking status [29,31,32,33,36], subjects' position [32,34,35,37], target respiratory flows [31,32,37], filters [32,33] or sampling rates [28,30,32,33,36,40] applied for sound analysis.

Synthesis of results

Pooling the results was not possible due to the large heterogeneity in respiratory sounds nomenclature and differences in measurement protocols. Instead a synthesis per NRS (frequency, intensity and amplitude) and ARS characteristics was performed (see Table 2).

Normal respiratory sounds

- Frequency

The frequency of NRS was investigated in seven studies. Hidalgo et al. (1991) reported significant differences in the sound frequency at the right posterior lower lobe (RPLL) between children and adults at 25% (125 ± 6 Hz; 139 ± 15 Hz, $p = 0.02$), 50% (169 ± 14 Hz; 194 ± 26 Hz, $p = 0.03$) and 95% (527 ± 52 Hz; 467 ± 45 Hz, $p = 0.02$) of the inspiratory spectral power (F25, F50 and F95). Furthermore, F25, F50 and F75 decreased significantly with subjects' age and height ($p < 0.001$) [3]. Two other studies analysed inspiratory F50 and F75 in adults at the RPLL and trachea [35,38] and reported that F50 showed lower values (142—766 Hz) than F75 (301—1323 Hz). Expiration was only analysed by one study at F50 [38] and no studies reported on expiratory F75. Therefore, comparisons cannot be established. The highest sound frequencies were observed at the trachea, where the values for inspiration reached 447—766 Hz at F50 [35], [38] and 1323 ± 192 Hz at F75 [35]. Values were slightly lower for expiratory sounds at F50 (540 ± 174 Hz) [38].

Frequency at maximum power (F_{max}) was studied in inspiratory and expiratory sounds at trachea, right upper anterior chest (RUAC), RPLL and left posterior lower lobe (LPLL). Inspiratory F_{max} presented values between 93 and

Int (dB)	A_{high} (dB/oct)	A_{low} (dB/Oct)	Int (<100 Hz) (dB)	Int (>100 Hz) (dB)	Int (<300 Hz) (dB)	Int (75–150 Hz) (dB)	Int (300–600 Hz) (dB)	Amp (V)
	−12.9 ± 1.7	−5.8 ± 5.6						
	−13.4 ± 1.9	−4.7 ± 7.7						
	−13.8 ± 2	−5.4 ± 5.2						
	−20.3 ± 4.2	−5.3 ± 7.1						
	−14.7 ± 2.6	−6.8 ± 1.4						
	−17.7 ± 3.8	−8 ± 1						
	−13.6 ± 1.8	−6.3 ± 6.4						
	−14.9 ± 12.7	−11.4 ± 14						
	−14.1 ± 1.9	−0±14.6						
	−19.7 ± 5.1	−6.5 ± 7.1						
	−15.2 ± 2.6	−5 ± 7						
	−18.8 ± 4.4	−6.7 ± 5.9						
			3.4 to 8.0		14.4 ± 3.7			
			3.2 ± 2	8.4 ± 1.7	15.1 ± 1.5			
6.3 to 20.4								
60.8 ± 37.7				38.67 ± 1.02				
85.1 ± 54.1				45.33 ± 1.58				
4.7 to 68.6					19.8 ± 5.0	10 ± 2.9	25.2 ± 5.2	1.3 ± 0.7
2.3 ± 1.3					16.9 ± 6.5	7.9 ± 4.8	21.1 ± 8.9	
79.1 ± 4.3								1.7 ± 0.8
4.3 to 72.8			1.5 to 9.2	9.7 to 17.17	11.4 to 20.9	13.7 ± 2.7	20.7 ± 3.9	1.2 ± 0.7
1.9 to 18.5				11.50 ± 0.92	15.0 ± 4.1	10.5 ± 2.9	8.8 ± 6.1	
5.7 to 76.6					20.1 ± 3.7	12.7 ± 3.9	23.2 ± 4.3	1.4 ± 0.8
2.5 to 10.2					10.2 ± 3.9	7.9 ± 4	9.4 ± 4.6	

154 Hz at trachea [35,38], 822–999 Hz at RUAC [34], 106–843 Hz at RPLL [3,18,34,35,36,38] and 236.6–885 Hz at LPLL [34,36]. Expiratory F_{max} presented values of 99 ± 8 Hz at trachea [38], between 604 and 794 Hz at RUAC [34], 104–420 Hz at RPLL [18,34,36,38] and 172.6–480.1 Hz at LPLL [34,36]. Frequency at maximum power were significantly higher in women than in man ($p < 0.05$) [34] and infants than in adults ($p < 0.01$) [18].

When assessed in different positions, the inspiratory F_{max} recorded over the right lung reached its highest in the dependent side-lying position (278.4 ± 42.3 Hz), was lower in sitting (244.5 ± 51.9 Hz) and the lowest value was found in the nondependent side-lying position (201.6 ± 57.6 Hz) ($p < 0.001$) [36]. No significant differences were found at the left lung.

One study recorded expiratory nasal sounds and analysed their frequency during the higher and lower intensity of sound. Their findings indicate that, for lower intensity of sound, frequencies of the right nose (2453 ± 22.2 Hz) were significantly higher from those at left nose (2234 ± 21.1 Hz) ($p < 0.05$) [37].

- Intensity

Eight studies investigated the intensity of NRS at trachea, RUAC, RPLL, LPLL and LUAC. Inspiratory intensities presented values between 38.67 and 60.8 dB at trachea [29,39], 4.7–68.6 dB at RUAC [28,29,34], 4.3–72.8 dB at RPLL [18,28,29,34,36,39], 5.7–76.6 dB at LPLL [6,28,29,30,34,36] and of 79.1 ± 4.3 dB at LUAC [28]. Expiratory intensities presented values of 2.3 ± 1.3 dB at RUAC [29,34], between 45.4 and 85.1 dB at trachea [29,39], 1.9–11.2 dB at RPLL [18,29,34,36] and 2.5–10.2 dB at LPLL [29,34,36].

Two studies compared the intensity of respiratory sounds at different frequencies (150–600 Hz) between inspiration and expiration [6,30] and found that inspiratory sounds were louder than expiratory ($p < 0.001$) in all frequency bands. Also, the difference between the two respiratory phases was high in the range of frequencies of 300–600 Hz in both studies [6,30]. The intensity of inspiratory sounds recorded over the posterior left chest wall was found to be higher than the right chest wall (left 25.6 dB vs right 20.7 dB; $p < 0.05$) [30, 36].

When comparing different positions of sound recording, the sound intensity of both lungs was higher in sitting than in nondependent side-lying (inspiration: 20.7–25.6 dB vs 15.7–19.7 dB; expiration 8.8–10.2 dB vs 6.8–8.7 dB; $p < 0.05$). However, no significant differences were found when comparing the sitting with the dependent side-lying position (inspiration: 20.7–25.6 dB vs 22.7–23.5 dB; expiration 8.8–10.2 dB vs 9.3–11.2 dB). In side-lying, the dependent side had higher intensities than the nondependent side (inspiration: 22.7–23.5 dB vs 15.7–19.7 dB; expiration 9.3–11.2 dB vs 6.8–8.7 dB; $p < 0.05$) [36].

The sound intensity increased with higher frequencies and flows and differed significantly among infants, children and adults ($p < 0.05$) [18], i.e., high flows implied lower sound intensity of infants and children than adults and vice-versa [18]. Respiratory sounds intensity was higher in men and smokers, although these results were not statistically significant [34].

- Amplitude

Respiratory sounds amplitude was analysed in two studies [34,40], however only one presented SI units, allowing interpretation [40]. Kraman (1983) studied the amplitude at different chest locations (RUAC, LUAC, RPLL and LPLL) and presented mean values between 1.2–1.7 V, being higher at LUAC and lower at RPLL [40].

Adventitious respiratory sounds

Three studies focused on the characteristics of ARS in healthy people. The presence of wheezes were reported in two studies [31,33], however only one reported the characteristics of these sounds [31]. The average wheeze occupation rate varied between 0 and 5% both in inspiration and expiration [31] Mean frequencies were higher in expiratory (309 ± 122 Hz) than in inspiratory wheezes (300 ± 136 Hz) [31]. The three studies reported the presence of crackles [31,32,33]. The number of crackles varied between 1 and 4 per breathing cycle and these were found mainly in the upper and lateral right chest, especially during inspiration [31,32,33]. However, studies differed on the type of crackle reported: Bettencourt (1999) found fine crackles (shorter than 10 ms) whilst Murphy (2004) found course crackles (longer than 10 ms) [32,33]. Crackles were mainly of low frequency, both in inspiration (371–387 Hz) and expiration (337–404 Hz) [31,33].

Discussion

Four main findings emerged from this systematic review: i) respiratory sound characteristics are affected by several factors (e.g., gender, body size, recording place, subjects' position and respiratory flow), ii) sound frequency is higher at the trachea and during expiration; iii) sound intensity is higher at trachea, during inspiration and when the recording is performed with the subject seated or in dependent side-lying, iv) ARS are present in healthy people however, crackles are the most frequently reported.

Studies analysing different populations reported higher respiratory sound frequencies in children and women [18,34]. The mechanism behind these findings is well understood in children and generally attributed to the acoustic transmission through smaller lungs and thinner chest walls [18]. In women, the mechanism is unclear and different explanations are suggested, such as: differences in sound generation and attenuation in the lung parenchyma, differences in impedance matching between the lung and the chest wall, or altered chest wall mass and physical properties [18,34] due to a smaller rib cage size and shorter diaphragm when compared to men [41]. However, these hypotheses need further investigation.

Sounds appeared to be louder in men and in the left hemithorax. It is known that sound intensity is directly dependent on respiratory flow [5,42] and that males present higher respiratory flows than females [43], hence louder sounds. However, the mechanism explaining the differences between the right and left bases of the lungs is not fully understood. Several authors have tried to justify these differences based on the asymmetry of the airways geometry of both lungs [36,44], i.e., left bronchus is smaller and more horizontal than the right and, the major left segmental bronchi is directed more posteriorly than the right due to the heart position [36,44], increasing flow rate and consequently, the sound intensity at the left bronchi. Therefore, health professionals who assess respiratory sounds should be aware of these differences in lung sound intensity that routinely occur between the left and right bases to prevent potential errors in diagnosis and clinical decisions.

As expected, in most studies both frequency and intensity were higher at the trachea, due to its large diameter and the absence of a structure to filter the sound (contrarily to the chest, due to the presence of lung parenchyma), high and turbulent flows are generated, resulting in high frequencies and intensities [45]. However, when assessed in different positions, frequency and intensity evidenced different behaviours: a clear pattern was not found for frequency, whilst intensity was clearly higher in the sitting and in dependent side lying positions. Although frequency did not differ significantly with positioning, it tended to be higher in the right lung for all the positions assessed [36]. Differences in the anatomy of the airways between the two lungs might contribute to explain this finding however, this phenomenon is not explained by the authors or other literature and therefore, more studies are needed to improve our understanding in this field. The results found for the sitting position may be explained by a better ventilation of the dependent part of the lungs in sitting and dependent side-lying positions, due to the mechanical advantage [36,44]. The sitting position results in a deeper breath for the same amount of muscular effort and consequently a higher inspiratory airflow enhancing the intensity of the respiratory sounds [36,44]. The high intensity sounds found in the dependent lung regions were also expectable, as it is known that lower diaphragm contracts more effectively than the upper diaphragm in the side lying position and, therefore, ventilation distributes preferentially to the dependent lung, despite the diminished lung volume [46,47]. Two studies provided information on the sound amplitude, however, in the study of Gavriely et al. (1995) results could not be interpreted due to the lack of SI units [34]. Kraman et al. (1983) [40] showed that mean amplitude was higher at the LUAC and lower at the RPLL but, as this is the only study in the field, this result should be interpreted with caution. In the literature, the difference between intensity and amplitude is not well described and most authors use both terms indistinguishably using different methodologies, limiting the conclusions that can be drawn.

Adventitious respiratory sounds in healthy people were only investigated in three studies [31,32,33] however, inferential statistics was not reported. A reduced number of ARS were found, however, different types of crackles were reported, i.e., fine [32] vs coarse [33]. Subjects' different mean age may explain this difference (49 ± 11yrs [32] vs 69 ± 7yrs [33]). It is known that older people present some degree of physiological degeneration in the respiratory system, diminishing mucociliary function and flow rates [48,49]. This may lead to retention of secretions, generating coarse crackles on the air passage. Only one study reported wheeze characteristics in healthy subjects, however, it did not analyse the type of wheeze found (monophonic/polyphonic). This information may be of potential interest as it is well known that wheeze type is a good predictor of disease severity (polyphonic wheezes indicate a more serious obstruction than monophonic wheezes) [50]. Due to the reduced number of wheezes and fine crackles found in the studies, it is hypothesised that these results may not be indicative of respiratory disease.

It is clear that the study of NRS and ARS provides valuable information about the tracheobronchial tree. However, much research is needed in this area to improve the knowledge on respiratory sounds of healthy people and people with respiratory diseases. This will contribute for enhancing health professionals' knowledge on the respiratory system, enhancing their skills for diagnosis and monitoring of respiratory diseases.

Limitations

Based on the results of this study, we cannot draw strong conclusions on the characteristics of NRS and ARS in healthy people, due to the lack of: i) well designed studies with large samples; ii) similar methodological approaches (body positions for data collection, breathing flow rates and algorithms for sound analysis) and iii) clear definitions of the variables analysed and SI units used. International Computerised Respiratory Sound Analysis (CORSA) guidelines [10,51,52] are available since the year 2000 to standardise the instruments used and procedures of data acquisition and signal processing techniques. However, none of the studies conducted after this year followed these guidelines. Further research, following the CORSA guidelines, is urgently needed to objectively understand the clinical value of the respiratory sound characteristics to diagnose and monitor respiratory patients.

Implications for practice and research

This systematic review summarises the main characteristics of the respiratory sounds of healthy people, in an attempt to improve the current body of knowledge and provide health professionals with the acoustic characteristics expected to be found in healthy people (see Table 3). This review adds clinical value to the results obtained through computerised respiratory sounds analysis and may potentiate its use as an objective respiratory measure. However, more studies with robust designs (e.g., RCT with sample size calculation) and standardised recording/analysis methodologies are urgently needed to enhance respiratory clinical decision making. It would also be of great value the development of systematic reviews focused in summarising the sound characteristics of different respiratory and cardiac diseases. These reviews could be compared with the findings of the present systematic review to clearly define patterns of healthy and pathological respiratory sounds. Finally, the nomenclature related to the sound analysis should be further clarified to enable the dissemination and comparison of the findings from different studies.

Conclusions

Respiratory sounds show different acoustic properties depending on the subject's characteristics and local of sound acquisition. These characteristics need to be well defined in healthy populations to allow objective interpretations of respiratory sounds alterations in people with respiratory diseases. Further research with robust study designs, exploring different children and adult populations and following CORSA guidelines are urgently needed to build evidence-base in this topic.

Conflict of interest statement

The authors have no conflict of interest.

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