Reference equations for oscillometry and their differences among populations: a systematic scoping review

Andy Deprato[1], Giovanni Ferrara[2], Mohit Bhutani[2], Lyle Melenka[3], Nicola Murgia[4], Omar S. Usmani[5,6], Paige Lacy[2] and Subhabrata Moitra[2]

[1]Faculty of Kinesiology, Sport, and Recreation, University of Alberta, Edmonton, AB, Canada. [2]Alberta Respiratory Centre and Division of Pulmonary Medicine, Dept of Medicine, University of Alberta, Edmonton, AB, Canada. [3]Synergy Respiratory and Cardiac Care, Sherwood Park, AB, Canada. [4]Dept of Medicine, University of Perugia, Perugia, Italy. [5]Airways Disease Section, National Heart and Lung Institute, Imperial College London, London, UK. [6]Royal Brompton Hospital, London, UK.

Corresponding author: Subhabrata Moitra (moitra@ualberta.ca)

Shareable abstract (@ERSpublications)
Our scoping review on adult oscillometric reference equations describes divergence in model construction and variations between the same population-based equations, thus warranting careful selection of oscillometric reference values in clinical practice. https://bit.ly/38a0xwn

Cite this article as: Deprato A, Ferrara G, Bhutani M, *et al*. Reference equations for oscillometry and their differences among populations: a systematic scoping review. *Eur Respir Rev* 2022; 31: 220021 [DOI: 10.1183/16000617.0021-2022].

Received: 31 Jan 2022
Accepted: 16 May 2022

Abstract

Respiratory oscillometry is gaining global attention over traditional pulmonary function tests for its sensitivity in detecting small airway obstructions. However, its use in clinical settings as a diagnostic tool is limited because oscillometry lacks globally accepted reference values. In this scoping review, we systematically assessed the differences between selected oscillometric reference equations with the hypothesis that significant heterogeneity existed between them. We searched bibliographic databases, registries and references for studies that developed equations for healthy adult populations according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A widely used Caucasian model was used as the standard reference and compared against other models using Bland–Altman and Lin's concordance correlational analyses. We screened 1202 titles and abstracts, and after a full-text review of 67 studies, we included 10 in our analyses. Of these, three models had a low-to-moderate agreement with the reference model, particularly those developed from non-Caucasian populations. Although the other six models had a moderate-to-high agreement with the standard model, there were still significant sex-specific variations. This is the first systematic analysis of the heterogeneity between oscillometric reference models and warrants the validation of appropriate equations in clinical applications of oscillometry to avoid diagnostic errors.

Introduction

Pulmonary function tests (PFTs) are the most common method used to assess, diagnose and grade the severity of respiratory diseases [1–3]. These tests require forced breathing manoeuvres and substantial patient cooperation, thus limiting their use in paediatric, elderly and frail populations [4]. Moreover, spirometric manoeuvres must be repeated to achieve accurate and reproducible results [5], making it an exhaustive test to perform, particularly in patients with advanced lung conditions and limited abilities [4]. Since DuBois *et al.* [6] established the first forced oscillation technique (FOT), respiratory oscillometry has become an alternative diagnostic tool for respiratory disease. Respiratory oscillometry, formerly known as FOT, delivers external small amplitude oscillations (sinusoidal, random, impulse train or pseudorandom signals based on the device) in either pressure (P) or flow (V') superimposed on spontaneous tidal breathing to stimulate the respiratory system without imparting any physical stress to patients [7, 8]. It can be administered to all patients, does not require any special breathing manoeuvres or patient cooperation and has a higher sensitivity and capacity to detect small airway obstruction even before any such changes are detected by spirometry [9, 10].

The accuracy of PFTs in assessing respiratory health is based on validated reference values [1, 2, 11]. However, unlike globally accepted reference equations for spirometry [12], reference equations for oscillometric indices are diverse and were developed from country-specific populations [13–15]. At present, the oscillometric reference equations developed by Oostveen *et al*. [16] are most commonly used as the standard model for adults. Nevertheless, these models have several limitations. First, these equations were developed only in Caucasian populations, while they are used indiscriminately by most oscillometry manufacturers and clinicians across the world. Validation of those reference equations in other populations or ethnic groups is rarely performed. Thus, the reference range of indices is not standardised for each population of interest, which may lead to an erroneous calculation of relative (percentage of predicted) values. Second, those models were constructed from measurements using five different instruments that could have possible instrument-wise variations in signal processing, optimisation and signal-to-noise ratio (interference). And third, participants in that study were recruited from four different countries; despite having the same ethnicity, possible anthropometric heterogeneity between populations could have a significant influence on oscillometric measurements, and this has not been properly addressed. Moreover, despite the availability of some population-specific reference equations [15–24], most of these equations are either based on a relatively small sample size [15, 16, 18, 19, 21, 22, 24], include an inappropriate sample selection (*e.g.* current or former smokers) [22, 24] or are mathematically complex [23].

Existing reviews on oscillometric techniques [25–30] have not systematically studied the heterogeneity between existing oscillometric reference models. In this scoping review, we aim to systematically assess the variability between existing adult reference equations for oscillometry by evaluating their agreement and biases with the most widely used standard model.

Methods

Scoping review approach and design

The main purpose of a scoping review is to synthesise an interpretable yet broad overview of available evidence without aiming to answer a single research question. Owing to our primary outcome, we decided to follow a scoping review study design for greater methodological flexibility while still incorporating components of a systematic review. We conducted this review based on previously described methodology [31] and according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) extension for scoping reviews [32]. The protocol was submitted to the Open Science Framework [33].

Eligibility criteria and outcomes of interest

Studies were included in our analyses if they developed oscillometric reference equations for respiratory resistance (R_{rs}) and respiratory reactance (X_{rs}) in healthy adults (⩾18 years old). Healthy individuals were defined as participants who did not report any chronic respiratory diseases such as asthma or chronic obstructive pulmonary disease (COPD), tuberculosis, recent respiratory infections, cardiovascular disease, obesity or current pregnancy. Studies were excluded if they 1) were not written in English, 2) were not published in a peer-reviewed journal, 3) had not mentioned the inclusion/exclusion criteria properly, 4) did not have clearly defined variables or included smokers and 5) were not available as full texts.

Because there are several oscillometric indices, it is difficult to consider all of them in a single review. Therefore, we selected three principal indices of airway impedance: total airway resistance (R_5), central airway resistance (R_{20}) and total airway reactance (X_5). These indices were chosen because they are used most often in clinical diagnosis and clinical trials [34]. In studies in which resistance and reactance values at 5 Hz and 20 Hz were not available, we accepted values from the closest frequencies (*i.e.* 6 Hz and 19 Hz). Additionally, we also considered area under the reactance curve (AX) if it was included in studies. We also considered demographic data including height, weight, age and ethnicity or country of origin of the study. Where height and weight were not reported, we considered body mass index to allow us to compare these reference equations. Variables were extracted only from studies included in the final analysis.

Search strategy and study selection

We searched the bibliographic databases MEDLINE (1946 to present *via* Ovid), Embase, PubMed, Scopus, Web of Science Core Collection and Cochrane Database of Systematic Reviews (Cochrane Library) and registries such as Cochrane Registries (Cochrane Library) and the International Prospective Register of Systematic Reviews (PROSPERO) up to November 15, 2021. The first 100 results of a Google Scholar search, hand searches, contact with study authors and bibliographies from included studies, known reviews or texts were also considered. Full search strategies are included in the supplementary material.

All identified studies were uploaded to systematic review management software (Covidence, Melbourne, Australia). After duplicates were removed, one author (AD) reviewed all titles and abstracts. Two authors (AD and SM) then independently reviewed full texts of all potentially eligible studies and identified additional documents through citations or hand searches. A third author (PL) adjudicated any disagreements, and some eligible studies were further excluded from analyses if they 1) did not develop oscillometric reference equations, 2) were only abstracts or preprints, 3) were duplicate studies, 4) had ineligible oscillometric parameters for this current analysis or 5) had an ineligible population.

Statistical analysis

We performed a set of analyses to compare different reference equations identified in our search. Using an imaginary dataset of age, height and weight for 50 men and 50 women, we created R_{rs} and X_{rs} values for each reference equation. We also created AX values for studies where available. Because one of the included studies [23] used quantile regression, we only used prediction equations of 50th quantile to create imaginary R_{rs}, X_{rs} and AX values for the specific study. We used Spearman's rank-order correlation to find associations between different equations for oscillometric indices separately for men and women. Because height was the common demographic variable in all reference equations included in our review, we also assessed sex-stratified correlations between height and the oscillometric indices. Considering that

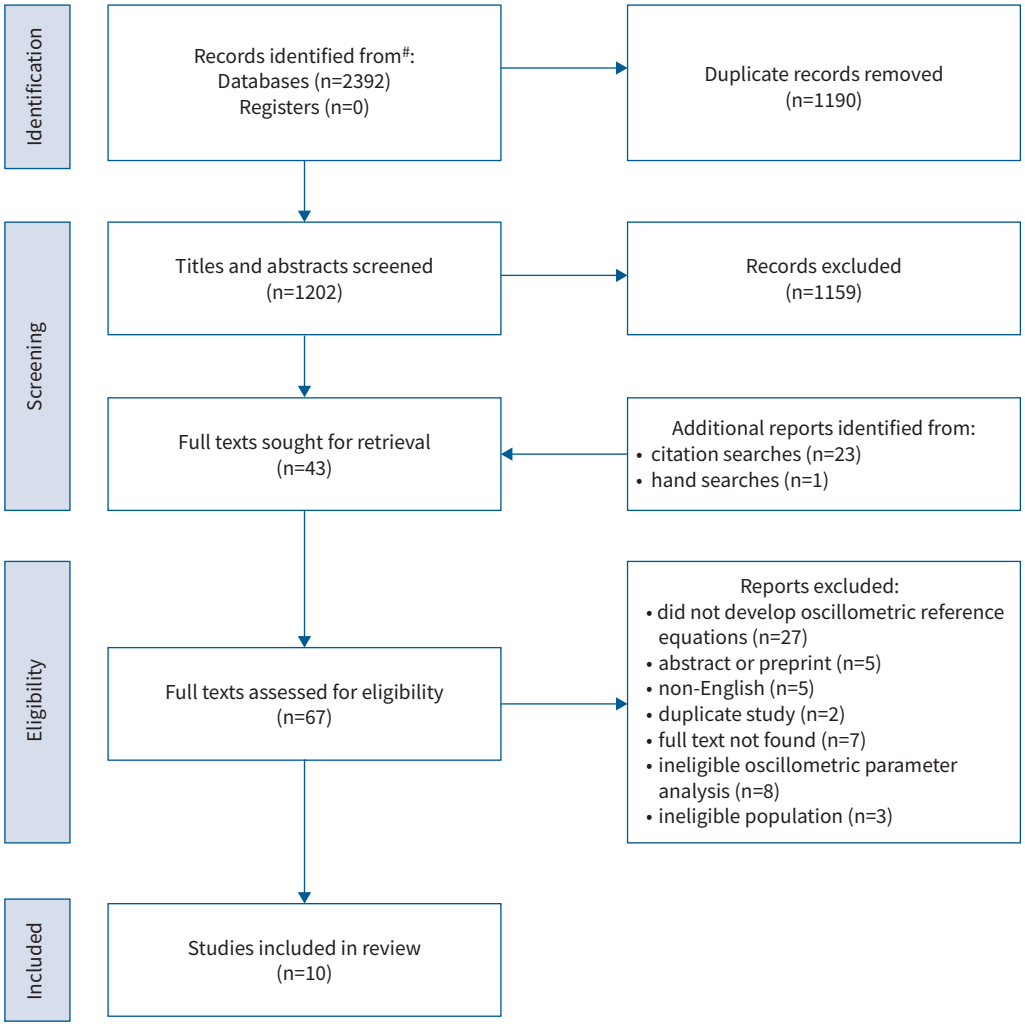

FIGURE 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram for the identification and selection process of studies that developed reference equations for oscillometric parameters of interest. #: MEDLINE: 348 results; Embase: 832 results; PubMed: 348 results; Scopus: 623 results; Web of Science Core Collection: 122 results; Cochrane Database of Systematic Reviews: 19 results; Google Scholar: first 100 results used; Cochrane Protocols: no results; PROSPERO: no results.

the reference equations developed by Oostveen *et al*. [16] are the most widely used prediction models, we investigated the agreement between said equations and all other equations for resistance and reactance indices (R_5/R_6, R_{20}/R_{19}, X_5/X_6 and AX) separately for men and women using Bland–Altman analysis of agreement [35] and Lin's concordance correlation coefficient [36].

Results

Search results

Our search strategy identified 1202 unique studies related to oscillometry. After primary exclusion and scrutiny of titles and abstracts, we considered 67 studies for a full-text review (figure 1). Figure 2 represents the relative number of oscillometric reference equation studies (published in peer-reviewed journals only) identified in our search that were developed for three major ethnic groups in the past 20 years.

Study characteristics

We included 10 studies in the analyses, with the majority being Caucasian-derived (n=6). All eligible studies were cross-sectional in design, with some having comparative groups (*e.g.* patients with respiratory diseases). Studies included instruments generating either impulse or non-impulse signals or both types of instruments, and all developed reference equations for R_5, R_{20} and X_5 (or the respective R_6, R_{19} or X_6). Five studies developed reference equations for AX. Additionally, some studies considered $R_{5–20}$, otherwise known as the frequency dependence of resistance and resonant frequency. Studies that used non-impulse signals also provided equations for resistance values for a wide range of frequencies other than 5 Hz and 20 Hz. Some studies (n=5) included current and/or former smokers. Details of included studies are outlined in table 1 and table 2.

Structure of the reference equations

The construction of reference equations was different between included studies (table 3). In seven of the 10 studies [15–18, 21, 22, 24], either oscillometric indices or demographic variables were mathematically transformed (logarithmic, inverse or exponential function). While almost all studies referred to linear regression models for oscillometric indices, Schulz *et al*. [23] referred to a quantile regression method and Brown *et al*. [18] suggested a polynomial (quadratic) regression model for reactance (X_6). Although all studies created reference equations separately for men and women, equations developed by Shiota *et al*. [22] were established for both sexes. One study [20] considered the variable weight in resistance (R_5 and R_{20}) equations for men but not women, while another study reported weight only in equations for women.

While all included equations showed a negative trend in total airway resistance (R_5) with increasing height, Moitra *et al*. [15] demonstrated a positive trend for both sexes (*i.e.* R_5 increases with height) (figure 3). This trend was similar for central airway resistance (R_{20}) as well. For total airway reactance (X_5), all equations showed a positive trend of X_5 (*i.e.* X_5 becomes less negative) with increasing height in women; however, in men the previous equation [15] showed the opposite association (*i.e.* X_5 becomes more negative with increasing height). We found prediction equations for AX in five studies, which showed a negative association with height in all studies, except one in women [15], where it showed a positive association with increasing height (*i.e.* AX increases with increasing height). Therefore, it was evident that

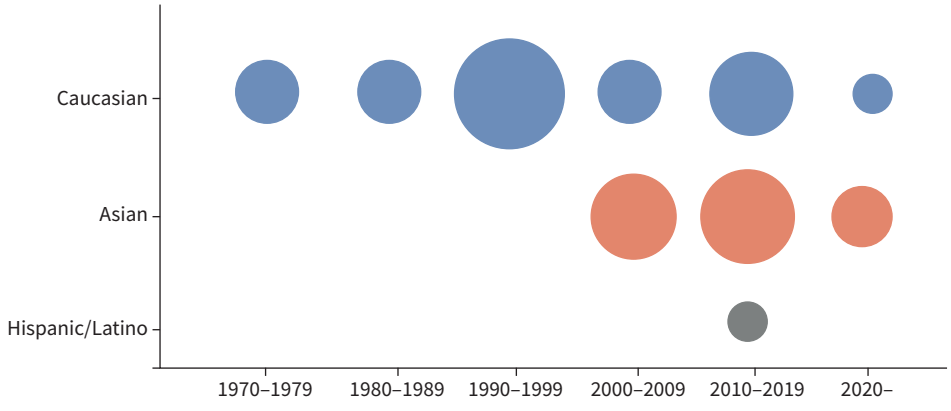

FIGURE 2 Bubble plot of the relative number of studies identified that developed oscillometric reference equations for three major ethnic groups in the past 20 years. Bubble size indicates the number of publications.

TABLE 1 Characteristics of included studies that developed reference equations for oscillometric parameters of interest

Study	Study country	Study population	Oscillometry device(s)	Signal type	Frequencies considered (Hz)	Reference parameters	Smoker inclusion
Shiota *et al.* [22]	Japan	Non-Caucasian	MasterScreen IOS	Recurrent impulses	5, 20	R_5, R_{20}, X_5	Never-smokers, active smokers, ex-smokers
Newbury *et al.* [20]	Australia	Caucasian	MasterScreen IOS	Recurrent impulses	5, 10, 15, 20, 25, 35	Z_5, R_{rs}, X_{rs}	Never-smokers, ex-smokers
Brown *et al.* [18]	Australia	Caucasian	Custom-made	Pseudorandom	6, 11, 19	R_{rs}, X_{rs}	Never-smokers, ex-smokers
Aarli *et al.* [24]	Norway	Caucasian	MasterScreen IOS	Recurrent impulses	5, 20	R_5, R_{20}, X_5, Fres, AX	Never-smokers, ex-smokers
Schulz *et al.* [23]	Germany	Caucasian	MasterScreen IOS	Recurrent impulses	5, 20	Z_5, R_5, R_{20}, $R_{5–20}$, X_5, Fres, AX	Never-smokers only
Oostveen *et al.* [16]	Belgium, the Netherlands, Hungary, Australia	Caucasian	Custom-made (C1, C3), ROS Oscilink (C2), Quark i2m (C4), MasterScreen IOS (C5)	Pseudorandom (C1–C4), recurrent impulses (C5)	4, 5, 6, 8, 10, 12, 14, 15, 16, 18, 20, 22, 24, 26	R_{rs}, R_m, X_{rs}, Fres, AX	Never-smokers, ex-smokers
Ribeiro *et al.* [21]	Brazil	Caucasian, Non-Caucasian	Custom-made	Pseudorandom	4, 6, 8, 10, 12, 14, 16, 18, 20, 22	Z_{rs}, R_{rs}, R_m, R_0, X_{rs}, Fres, Xm	Never-smokers only
De *et al.* [19]	India	Non-Caucasian	Resmon Pro	Pseudorandom, relative primes	5, 19	R_5, R_{19}, $R_{5–19}$, X_5	Never-smokers only
Moitra *et al.* [15]	India	Non-Caucasian	MasterScreen IOS	Recurrent impulses	5, 20	Z_5, R_5, R_{20}, $R_{5–20}$, X_5, Fres, AX	Never-smokers only
Berger *et al.* [17]	USA	Caucasian	MasterScreen IOS	Recurrent impulses	5, 10, 15, 20	R_5, R_{10}, R_{15}, R_{20}, $R_{5–15}$, $R_{5–20}$, X_5, X_{10}, Fres, AX	Never-smokers only

IOS: impulse oscillometry; R_5: resistance at 5 Hz; R_{20}: resistance at 20 Hz; X_5: reactance at 5 Hz; Z_5: impedance at 5 Hz; R_{rs}: respiratory resistance; X_{rs}: respiratory reactance; Fres: resonant frequency; AX: reactance area; R_m: mean respiratory resistance; R_0: resistance at 0 Hz; R_{19}: resistance at 19 Hz.

while reference equations for R_{20} showed some degree of homogeneity regarding their association with height, equations for R_5 and X_5 demonstrated greater variability in terms of their association with height.

Homogeneity between equations

The agreement between included reference equations with the standard model [16] is presented in table 4. Using reference equations for imaginary individuals, we found that one Caucasian study [18] yielded consistently higher resistance and reactance values than all other equations included in the study. For example, mean R_5 values in men and women according to the equation of Brown *et al.* [18] were 0.92 kPa·L^{-1}·s^{-1} and 1.15 kPa·L^{-1}·s^{-1}, respectively, which were significantly higher than others (range 0.08–0.39 and 0.08–0.60 kPa·L^{-1}·s^{-1} in men and women, respectively). In the agreement analysis, the equations of Brown *et al.* [18] were remarkably different from those developed by Oostveen *et al.* [16]. While reference equations for R_5 and R_{20} of other Caucasian studies [17, 20] showed homogeneity with the standard model [16] for men, there was some degree of heterogeneity for women. Intriguingly, reference equations developed in the Latin American population [21] showed significant homogeneity with the standard reference [16]. In the case of X_5, while there was significant homogeneity between the equations of the reference study [16] and equations of other studies [17, 19–24], equations developed by Moitra *et al.* [15] and Brown *et al.* [18] were markedly different from the standard reference [16]. The equations developed for AX were significantly different from the standard reference, except for one study [24] that showed low-to-moderate agreement with the reference study.

Discussion

Summary of findings

We identified 23 adult oscillometric reference equations published in the past 20 years. The majority of equations were developed for Caucasian populations while limited or no studies were found from Asian, Latin American, African, African American or Indigenous populations; this inequity of addressing race/

TABLE 2 Subject demographics from included studies that developed reference equations for oscillometric parameters of interest

Study	Subjects (n)	Males (n)	Height (cm)	Weight (kg)	Age (years)	Smoking history (pack-years)
Shiota *et al.* [22]	166	69	162.7±8.3	58.9±11.2	38.6±17.2 (20–81)	22.2±22.1
Newbury *et al.* [20]	125	59	175.89±8.77 164.58±6.56	87.3±11.49 73.3±12.41	49.54 (25–74) 48.76 (25–74)	<5
Brown *et al.* [18]	904	341	176.7±6.7 163.5±6.5	84.2±13.1 69.3±13.5	55.6±17.5 54.7±17.7	<5
Aarli *et al.* [24]	75	40	173±6 159±6	76.4±12.7 65.5±10.8	79.4±6.9 78.8±6.3	20/4
Schulz *et al.* [23]#	397	154	173.30 (163.00–188.41) 160.07 (149.00–172.24)	80.89 (67.02–106.76) 68.37 (53.40–91.05)	64.89 (46.00–84.75) 67.26 (46.00–85.00)	0
Oostveen *et al.* [16]	368	180	171.44#	54–128 43–111	49.55# (18–84)	4.4
Ribeiro *et al.* [21]	288	144	173±1 (153–189) 160±1 (145–181)	78.78±2.07 (49–128) 65.02±1.79 (47–96)	49.04±2.88 (20–81) 49.0±2.88 (20–86)	
De *et al.* [19]	323	122	168.1±8.2 154.8±6.5	65.5±13.3	42.7±13.7 40.9±13.7	<1
Moitra *et al.* [15]	190	92			45±18 41±17	
Berger *et al.* [17]	439	223	177±7 (157–203) 164±7 (146–183)	83.1±17.1 (51.3–170.0) 63.9±12.7 (43.1–147.4)	46.7±11.2 (21–85) 44.0±11.9 (21–76)	<5

Data are presented as pooled totals (n) or according to sex (male/female) in mean±SD or mean (range), unless otherwise indicated. #: calculated from means of subgroups within study.

ethnicity has also been persistent in the construction of spirometric reference equations [11]. However, most studies had considerable limitations in terms of poorly defined inclusion/exclusion criteria and having equations for only selected oscillometric indices. Our included studies (n=10) consisted of Caucasian, Asian and Latin American populations and had all the clinically relevant oscillometric indices for comparison. Our comparative analyses of heterogeneity between a standard reference model and all other models provide a clinically important overview of similarities and dissimilarities between equations.

Critical evaluation of the reference equations

While the majority of included studies used some forms of mathematical transformation of either the oscillometric indices or physiological variables to fit them into a linear relationship, no such transformation was performed in two studies [19, 20]. It is important to note that those studies did not mention anything about the nature of distribution of oscillometric indices or physiological variables. Several studies [23, 28, 37] have reported typical non-normal distributions of oscillometric indices because of the influence of heterogeneous airway branching, even in healthy individuals. Therefore, the assumption of a "by default" linear relationship between oscillometric indices and physiological variables could be erroneous. While Schulz *et al.* [23] used a more realistic model (quantile regression) assuming a non-normal distribution of the oscillometric indices, there is substantial skewness in the oscillometric variables between the median (50th quantile) and lower and upper (5th and 95th) quantiles; in such cases, applying the most appropriate equation (quantile value) is a challenge. Therefore, it is recommended that, first, a thorough examination (nature of distribution, missingness, input errors, *etc.*) of dependent (oscillometric indices) and independent (demographics) variables should be undertaken. Second, different regression models should be applied to control for the non-normality, followed by appropriate model-fitting criteria. Third, a collinearity check between independent variables should be performed because a strong intercorrelation between independent variables may result in over-fitting of models [30]. And last, it is important to remember that reference models must not be extremely complex and should be executable in clinical practice.

Another aspect is the omission of body weight from equations in some studies [20, 22, 24]. Although these reports did not describe model-fitting criteria in detail, it can be assumed that weight was an insignificant variable in equations and was omitted to achieve a more stable model. However, several studies have shown that body weight significantly influences the physiology of the airways [38–41] and correlates with increased airway resistance [42, 43]. The same was observed for age because this was either deleted from equations [17, 24] or was discriminately used for resistance or reactance [18, 22] or a selective sex [19]. Although one previous study described that the airway resistive property remains

TABLE 3 Reference equations developed from included studies for oscillometric parameters of interest

Study	Indices	Male	Female
Shiota *et al.* [22]	R_5	R_5=8.67158−3.841167·log(*h*)	R_5=8.67158−3.841167·log(*h*)
	R_{20}	R_{20}=5.841867−2.546561·log(*h*)	R_{20}=5.841867−2.546561·log(*h*)
	X_5	X_5= −2.343672−0.000097*a*+1.018597·log(*h*)	X_5= −2.343672−0.000097*a*+1.018597·log(*h*)
	AX	Not available	Not available
Newbury *et al.* [20]	R_5	R_5=1.1672−0.0017*a*−0.007*h*+0.0043*w*	R_5=0.768−0.00064*a*−0.00276*h*
	R_{20}	R_{20}=0.9216−0.0013*a*−0.0049*h*+0.0027*w*	R_{20}=0.4821+0.00034*a*−0.00125*h*
	X_5	X_5= −0.3593+0.00013*a*+0.0016*h*	X_5= −0.4689−0.00092*a*+0.00245*h*
	AX	Not available	Not available
Brown *et al.* [18]#	R_6	log(R_6)=3.18955−0.01617*h*+0.00882*w*	log(R_6)=3.88965−0.01944*h*+0.00812*w*
	R_{19}	log(R_{19})=2.89318−0.01445*h*+0.00789*w*	log(R_{19})=3.25796−0.01519*h*+0.00605*w*
	X_6	exp(X_6)= −1.23047+0.01286*a*−0.00013712a^2+0.01098*h* −0.00323*w*	exp(X_6)= −1.36295+0.00845*a*−0.0001035a^2+0.01282*h* −0.00449*w*
	AX	Not available	Not available
Aarli *et al.* [24]	R_5	ln(R_5)=3.02−0.023*h*	ln(R_5)=2.68−0.026*h*+0.012*w*
	R_{20}	ln(R_{20})=1.52−0.016*h*	ln(R_{20})=1.26−0.017*h*+0.009*w*
	X_5	ln(−X_5)=3.57−0.033*h*	ln(−X_5)=3.85−0.041*h*+0.014*w*
	AX	ln(AX)=12.0−0.074*h*	ln(AX)=10.8−0.074*h*
Schulz *et al.* [23]	R_5	5th quantile: R_5=1.0685571−0.0022403*a*−0.004312*h*	R_5=0.5012224+0.0002940*a*−0.0037866*h*+0.0045199*w*
		50th quantile: R_5=0.9861137−0.0001223*a*−0.0055278h +0.0029891*w*	R_5=0.7887960+0.0015118*a*−0.0046594h+0.0029768*w*
		95th quantile: R_5=0.6683472+0.0029051*a*−0.0026280*h*	R_5=0.1926787+0.0004133*a*+0.0016756*h*
	R_{20}	5th quantile: R_{20}=0.6342369−0.0019656*a*−0.0021069*h*	R_{20}=0.5970057−0.0006897*a*−0.0030934*h*+0.0016623*h*
		50th quantile: R_{20}=0.7722257−0.0006446*a*−0.0037120*h* +0.0013924*w*	R_{20}=0.4505645+0.0001251*a*−0.0020488*h*+0.0017939*w*
		95th quantile: R_{20}=1.1824320−0.0003590*a*−0.0048639*h*	R_{20}=0.8177947−0.0003549*a*−0.0025771*h*
	X_5	5th quantile: X_5= −0.5568254−0.0004762*a*+0.0025397*h*	X_5= −0.5446960−0.0018068*a*+0.0029323*h*
		50th quantile: X_5= −0.4670275−0.0003344*a*+0.0027755*h* −0.0010424*w*	X_5= −0.3313017−0.0007541*a*+0.0022090*h*−0.001413*w*
		95th quantile: X_5= −0.2058333+0.0006944*a*+0.0006944*h*	X_5= −0.1831886+0.0003607*a*+0.0005743*h*
	AX	5th quantile: AX=0.0430162+0.0012195*a*−0.0002327*h*	AX=1.0968758−0.0001349*a*−0.0077805*h*+0.0048793*w*
		50th quantile: AX=1.7584772+0.0027451*a*−0.0132469*h* +0.0077552*w*	AX=1.7909627+0.0110077*a*−0.0168559*h*+0.0104360*w*
		95th quantile: AX=2.2955939+0.0161916*a*−0.0139157*h*	AX=2.7124098+0.0173679*a*−0.0227368*h*+0.0152978*w*
Oostveen *et al.* [16]¶,+	R_5	ln(R_5)=5.327−0.00381*a*−3.032*h*+0.01390*w*	ln(R_5)=2.591+0.00279*a*−1.461*h*+0.0121*w*
	R_{20}	ln(R_{20})=3.540−0.0033*a*−1.824*h*+0.00888*w*	ln(R_{20})=2.482+0.00135*a*−1.122*h*+0.00695*w*
	X_5	ln(4−X_5)=2.683+0*a*−0.703*h*+0.0019*w*	ln(4−X_5)=2.373+0.0015*a*−0.607*h*+0.00312*w*
	AX_5	ln(AX_5)=9.730+0*a*−6.107*h*+0.02122*w*	ln(AX_5)=5.490+0.00960*a*−4.122*h*+0.02836*w*
Ribeiro *et al.* [21]#,¶	R_6	ln(R_6)=2.964−0.002*a*−1.545*h*+0.009*w*	R_6=8.164−0.006*a*−3.563*h*+0.014*w*
	R_{20}	ln(R_{20})=2.196−0.002*a*−0.970*h*+0.005*w*	R_{20}=9.142−0.005*a*−3.811*h*+0.003*w*
	X_6	exp(X_6)= −1.082+0*a*+0.983*h*−0.003*w*	X_6= −5.293+0*a*+2.759*h*−0.007*w*
	AX	Not available	Not available
De *et al.* [19]#	R_5	R_5=10.035+0.008*a*−0.057*h*+0.036*w*	R_5=9.697−0.046*h*+0.033*w*
	R_{19}	R_{19}=8.077−0.040*h*+0.02*w*	R_{19}=8.683−0.038*h*+0.019*w*
	X_5	X_5= −3.334−0.004*a*+0.018*h*−0.009*w*	X_5= −4.40+0.02*h*
	AX	Not available	Not available
Moitra *et al.* [15]¶	R_5	ln(R_5)= −0.30+0.003*a*−0.83*h*+0.01*w*	ln(R_5)=0.003+0.004*a*−0.66*h*+0.007*w*
	R_{20}	ln(R_{20})= −0.14−0.001*a*−0.99*h*+0.01*w*	ln(R_{20})=0.164+0.0003*a*−0.92*h*+0.007*w*
	X_5	X_5= −0.23−0.002*a*+0.15*h*−0.002*w*	X_5= −0.60−0.004*a*+0.37*h*−0.001*w*
	AX	ln(AX)= −0.20+1.24ln(*a*)−2.98*h*+0.01*w*	ln(AX)= −2.33+0.76ln(*a*)−0.004*h*+0.004*w*
Berger *et al.* [17]¶,+	R_5	ln(R_5)=2.07069−1.05124*h*+0.03337·BMI	ln(R_5)=2.22395−0.98351*h*+0.02903·BMI
	R_{20}	ln(R_{20})=1.95570−0.81148*h*+0.02042·BMI	ln(R_{20})=2.01077−0.72768*h*+0.02009·BMI
	X_5	ln(X_5+4)=0.10509+0.82626*h*−0.01775·BMI	ln(X_5+4)=0.29066+0.73387*h*−0.01984·BMI
	AX	ln(AX)=4.36142−3.47450*h*+0.08784·BMI	ln(AX)=4.67153−3.31633*h*+0.06719·BMI

Reference equations developed by included studies for R_6, R_{19} and X_6 instead of R_5, R_{19} and X_5, respectively were considered. Respiratory resistance (R_{rs}) and respiratory reactance (X_{rs}) measured in kPa·L^{-1}·s^{-1} and AX measured in kPa·L^{-1} unless otherwise indicated. Age (a), height (h), weight (w) and body mass index (BMI) measured in years, cm, kg and kg·m^{-2}, respectively, unless otherwise indicated. Shiota *et al.* [22] developed unisex reference equations. Schulz *et al.* [23] developed reference equations for the 5th, 50th and 95th quantiles. For Oostveen *et al.* [16] the equations for AX_5 are included. R_5: resistance at 5 Hz; R_{20}: resistance at 20 Hz; X_5: reactance at 5 Hz; AX: reactance area; R_6: resistance at 6 Hz; R_{19}: resistance at 19 Hz; X_6: reactance at 6 Hz. #: R_{rs} and X_{rs} measured in cmH_2O·L^{-1}·s^{-1} and AX measured in cmH_2O·L^{-1}; ¶: height measured in metres (m); +: R_{rs} and X_{rs} measured in hPa·L^{-1}·s^{-1} and AX measured in hPa·L^{-1}.

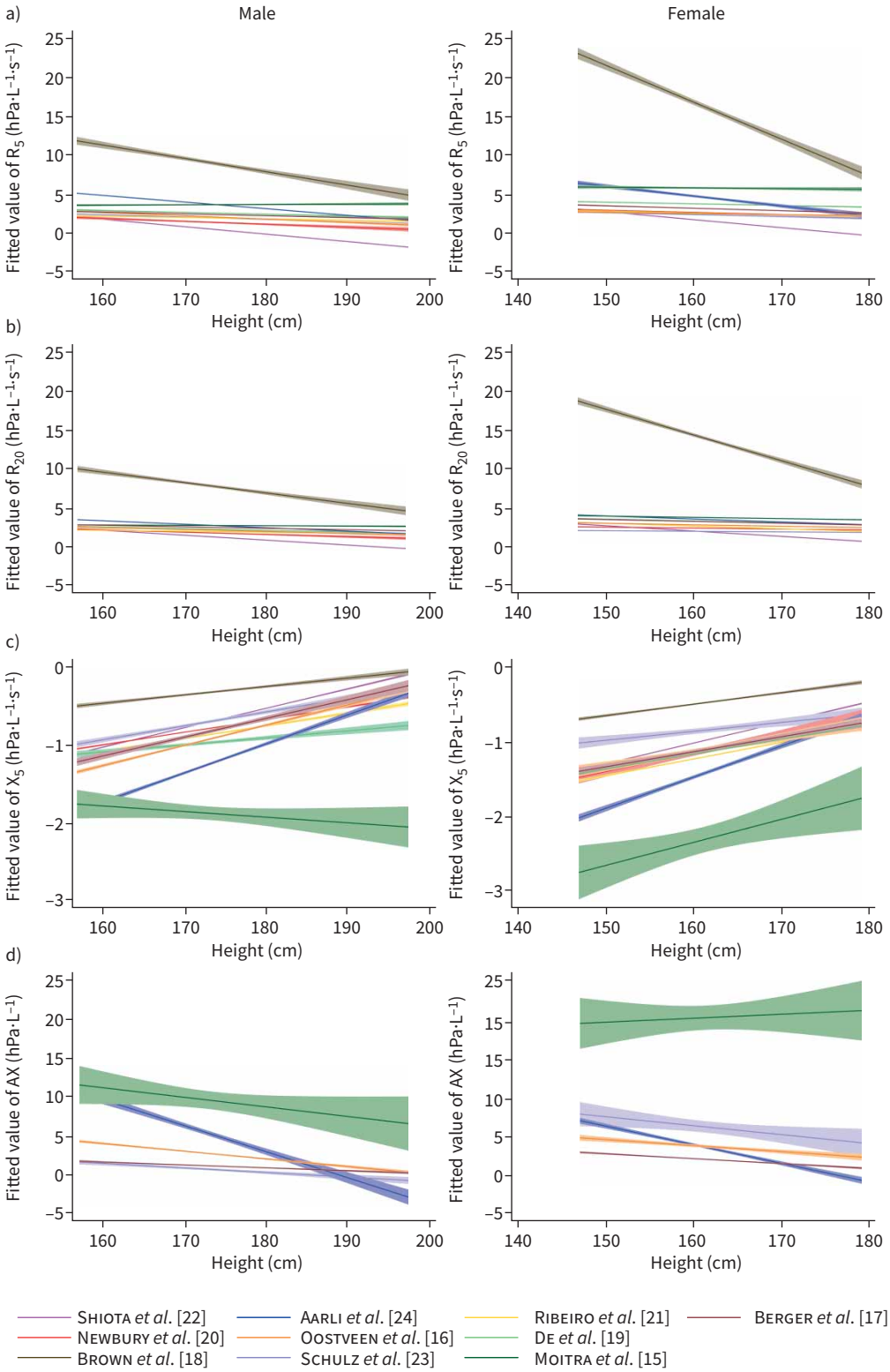

FIGURE 3 Differences in predicted values for oscillometric indices of interest from reference equations of included studies as functions of height for men and women. Predicted values for resistance and reactance at 6 Hz and 19 Hz are considered for some equations, please see the text and footnote of table 3 for details. R_5: resistance at 5 Hz; R_{20}: resistance at 20 Hz; X_5: reactance at 5 Hz; AX: reactance area.

TABLE 4 Assessments of agreement between predicted values for oscillometric parameters of interest from reference equations of included studies and a standard reference for men and women

Oostveen *et al.* [16] *versus*	Sex		R_5	R_{20}	X_5	AX
Shiota *et al.* [22]	Male	Bias (LoA)	0.15 (0.06, 0.25)	0.08 (0.01, 0.15)	−0.02 (−0.03, −0.01)	NA
		ρ_c	0.19	0.22	0.65	NA
	Female	Bias (LoA)	0.09 (−0.05, 0.23)	0.09 (0.006, 0.17)	−0.01 (−0.04, 0.01)	NA
		ρ_c	0.14	0.15	0.67	NA
Newbury *et al.* [20]	Male	Bias (LoA)	0.07 (0.04, 0.10)	0.03 (0.02, 0.05)	−0.01 (−0.03, 0.005)	NA
		ρ_c	0.41	0.57	0.68	NA
	Female	Bias (LoA)	−0.01 (−0.07, 0.04)	0.04 (0.01, 0.07)	0.001 (−0.02, 0.02)	NA
		ρ_c	0.27	0.11	0.93	NA
Brown *et al.* [18]#	Male	Bias (LoA)	−0.69 (−0.94, −0.43)	−0.57 (−0.78, −0.36)	−0.06 (−0.08, −0.03)	NA
		ρ_c	0.03	0.02	0.10	NA
	Female	Bias (LoA)	−1.35 (−2.09, −0.61)	−1.09 (−1.59, −0.60)	−0.06 (−0.09, −0.04)	NA
		ρ_c	0.006	0.007	0.09	NA
Aarli *et al.* [24]	Male	Bias (LoA)	−0.16 (−0.24, −0.08)	−0.06 (−0.11, −0.02)	0.03 (0.01, 0.06)	−0.26 (−0.69, 0.18)
		ρ_c	0.16	0.28	0.55	0.31
	Female	Bias (LoA)	−0.21 (−0.41, −0.01)	−0.07 (−0.11, −0.04)	0.03 (−0.01, 0.07)	0.01 (−0.30, 0.32)
		ρ_c	0.05	0.17	0.44	0.49
Schulz *et al.* [23]	Male	Bias (LoA)	0.01 (−0.02, 0.04)	0.04 (0.006, 0.07)	−0.02 (−0.04, −0.006)	0.20 (0.09, 0.31)
		ρ_c	0.84	0.55	0.55	0.18
	Female	Bias (LoA)	0.01 (−0.01, 0.04)	0.06 (0.03, 0.08)	−0.03 (−0.04, −0.01)	−0.25 (−0.66, 0.15)
		ρ_c	0.79	0.10	0.46	0.28
Ribeiro *et al.* [21]#	Male	Bias (LoA)	0.02 (−0.03, 0.06)	0.02 (−0.006, 0.04)	−0.006 (−0.02, 0.01)	NA
		ρ_c	0.66	0.55	0.86	NA
	Female	Bias (LoA)	−0.01 (−0.05, 0.04)	0.02 (−0.02, 0.06)	0.01 (−0.01, 0.03)	NA
		ρ_c	0.43	0.51	0.72	NA
De *et al.* [19]¶	Male	Bias (LoA)	−0.05 (−0.11, 0.01)	−0.01 (−0.03, 0.01)	0.004 (−0.03, 0.04)	NA
		ρ_c	0.34	0.78	0.59	NA
	Female	Bias (LoA)	−0.12 (−0.15, −0.10)	−0.05 (−0.06, −0.03)	0.003 (−0.02, 0.03)	NA
		ρ_c	0.05	0.22	0.73	NA
Moitra *et al.* [15]	Male	Bias (LoA)	−0.15 (−0.25, −0.06)	−0.06 (−0.10, −0.02)	0.09 (0.01, 0.17)	−0.68 (−1.46, 0.10)
		ρ_c	−0.01	0.11	−0.02	0.03
	Female	Bias (LoA)	−0.33 (−0.38, −0.28)	−0.09 (−0.11, −0.08)	0.12 (0.02, 0.21)	−1.68 (−2.68, −0.69)
		ρ_c	0.01	0.06	0.12	0.02
Berger *et al.* [17]	Male	Bias (LoA)	−0.03 (−0.07, 0.01)	−0.04 (−0.06, −0.01)	−0.01 (−0.02, −0.0001)	0.16 (0.05, 0.26)
		ρ_c	0.59	0.37	0.89	0.18
	Female	Bias (LoA)	−0.07 (−0.10, −0.03)	−0.04 (−0.06, −0.03)	−0.0001 (−0.02, 0.02)	0.17 (0.06, 0.28)
		ρ_c	0.18	0.28	0.82	0.20

Data presented as bias (lower and upper LoA) and Lin's concordance correlation coefficient (ρ_c). Reference values developed by Oostveen *et al.* [16] were considered as the standard model and these were compared with other reference values for R_5, R_{20} and X_5. Bias and LoA should be read as a percentage (*e.g.* a bias of 0.15 should be read as 15%). #: resistance and reactance values measured at 6 Hz (R_6, X_6) and 19 Hz (R_{19}) were considered in the comparison; ¶: resistance value at 19 Hz (R_{19}) was considered in the comparison. R_5: resistance at 5 Hz; R_{20}: resistance at 20 Hz; X_5: reactance at 5 Hz; AX: reactance area; LoA: limit of agreement; NA: not applicable.

unchanged after 5 years of age [44], this concept has not been confirmed by follow-up reports. Interestingly, Oostveen *et al.* [16] and Ribeiro *et al.* [21] did not eliminate age from their equations despite achieving negligible coefficient values (which were very small). Although there could be a debate on which variables are to be considered in prediction equations, a more inclusive approach (considering all relevant anthropometric variables) followed by statistical criteria for model stability could be considered when constructing reference models for oscillometric indices.

Similarly, the inclusion of participants with a smoking history is inappropriate in any lung function reference framework given the significant impact of smoking on airway physiology. Paradoxically, almost half of the studies included in this analysis recruited smokers (current or former). Although it was unclear from these studies [16, 18, 20, 22, 24] whether the presence of current or former smokers influenced measurements of oscillometric indices, it was evident that the forced expiratory volume in 1 s/forced vital capacity ratio of participants in one study [24] was lower than in other reports. It is well known that smokers tend to develop subtle yet significant changes in their small airways even before they can be

detected by spirometry [45]. A recent report has also described an accelerated decline of lung function in former smokers compared to never-smokers [46], suggesting that the decline of airway function is not restricted to current smokers. One study [24] included participants who were ⩾70 years of age. Such an advanced age group would be expected to exhibit naturally reduced lung function and thus would generate potential bias in measurements.

Another key feature missing in the included studies is the description of the use of short-acting bronchodilator response and its effect on oscillometry [47]. Previous studies have shown that airway impedance can be significantly altered upon short-acting bronchodilator administration in healthy individuals [48–50]. However, only one study [16] included in our analyses explicitly described the use of short-acting bronchodilators while performing oscillometry. While there is inconsistency in the recommendation of whether pre- or post-bronchodilation values should be used for oscillometric reference equations, it is an important issue because it is essential to report the use of short-acting bronchodilators for the development of appropriate oscillometric reference equations.

While Caucasian models were expected to be similar or have less heterogeneity, we observed that one Caucasian study [18] generated very high impedance values and was significantly different from standard reference values. Therefore, it is important to understand potential sources of heterogeneity and to be vigilant while considering reference models. Last, it is very important to report sample size and power calculations so that the robustness of the constructed models can be determined; these were unfortunately lacking in several studies considered in this review. Therefore, the generalisability of those models cannot be confirmed.

Implications for clinical practice and future research

Considering the increasing popularity of oscillometry as a sensitive and user-friendly approach for the detection of small airway changes in a wide variety of lung diseases, eliminating the potential risk of over- and under-diagnosing respiratory abnormalities is a priority. Because oscillometry has relatively high within-subject variability compared with other conventional lung function tests, it is important to consider such variations while developing reference equations. This also applies when assessing patients in clinical settings, particularly if patients are at early stages of respiratory disease or if they are elderly. The importance of our study is that it will help inform clinicians on the use of proper reference equations appropriate to their patient populations.

Notably, there are some fundamental differences among different oscillometry devices in terms of their engineering and functionality, as previous reports have demonstrated [8, 51–53]. These differences may lead to measurement bias for certain indices, particularly X_{rs} values [53]. Therefore, it is important to consider the measurement technique and device when choosing a suitable reference equation [28, 52]. It is also important to remember that, apart from differences between devices, model developers should also consider posture, sequence of testing before or after spirometry, physical exertion, exposure to first- or second-hand smoke and consumption of caffeine or menthol products as potential influencers [54–56]. Therefore, it is important that desired models are validated in larger samples before their use in clinical settings, even though these models could have been developed from similar populations [28, 57]. Additionally, large sample sizes, inclusion of only non-smoking individuals, generalised random sampling and broad intra-population demographic ranges are encouraged for better model efficacy, translatability and specificity of testing [12, 28, 57]. Our study advocates for the importance of a globally accepted reference standard for oscillometry, particularly considering African, African American, Hispanic, North American, Asian, Indigenous and other populations. Meanwhile, ongoing standardisation of oscillometric testing, as has been implemented for spirometry, will be of great benefit in increasing testing quality and repeatability [5, 28, 52].

Strengths and limitations

To date, the most important question remains of which oscillometric reference equations should one adopt for a specific population, and this has been cited as a limiting factor in the widespread adoption of oscillometry in PFTs. This review provides the first quantitative evaluation of the heterogeneity of equations obtained from different populations, and a comprehensive overview of their features and shortcomings. Our study also demonstrates that there are population-specific and country-specific variations in reference equations, and that no equations should be adapted indiscriminately, even though populations are apparently the same.

There are, however, some limitations regarding our review. First, our inclusion of studies with patients' age ⩾18 years might have excluded other studies on adults where the lower limit of age was 16 years. Second, we only considered studies that showed a linear relationship between oscillometric indices and

demographic variables. Therefore, we may have excluded studies with some robust yet statistically complex results. Third, although frequency dependence ($R_{5–20}$) is a sensitive parameter for small airway disease and is of particular interest in COPD, we could not include this index in our study because of the non-availability of its reference equations in some studies [16]. Moreover, because the included studies used two different types of devices (devices that produce impulse and non-impulse signals), the different wave function of these devices could have possible artefacts in reference equations even though both devices generate nearly the same frequency of sound waves. Additionally, we excluded some studies owing to the unavailability of full-text versions or for being reported in a language besides English, and these studies could have had important observations. Finally, the nature of this scoping review with selected outcomes did not allow us to assess any potential bias for study selection.

Conclusions

In this comprehensive review, we, for the first time, systematically evaluated different adult oscillometric reference equations. We found considerable heterogeneity between equations that warrants focused attention while using oscillometric reference values. We also propose that a large-scale, multinational study for developing a global reference model for oscillometry is urgently required because a population-adjusted oscillometric reference model could be beneficial in the diagnosis and clinical care of respiratory diseases.

Provenance: Submitted article, peer reviewed.

Acknowledgements: The research team would like to thank the University of Alberta librarians for their efforts in assisting the authors to retrieve the full texts of studies needed for their full-text review and Alberta Innovates for granting a studentship to help fund these research efforts.

Author contributions: A. Deprato: Methodology, investigation, validation, resources, data curation, writing – original draft preparation, funding acquisition; G. Ferrara: Visualisation, writing – revision; M. Bhutani: Visualisation, writing – revision; L. Melenka: Visualisation, writing – revision; N. Murgia: Visualisation, writing – revision; O.S. Usmani: Visualisation, writing – revision; P. Lacy: Project administration, resources, funding acquisition, supervision, writing – revision; S. Moitra: Conceptualisation, methodology, validation, formal analysis, resources, visualisation, supervision, project administration, writing – revision. All authors have reviewed and agreed to the published version of this manuscript.

Conflict of interest: A. Deprato has received support for the present manuscript from Alberta Innovates Summer Studentship. G. Ferrara has received payment for lectures, presentations, speakers' bureaus, manuscript writing or educational events from Roche, Boehringer Ingelheim and AstraZeneca, outside the submitted work. G. Ferrara has received payment for participation on a Data Safety Monitoring Board or Advisory Board from Boehringer Ingelheim, outside the submitted work. M. Bhutani has received grants or contracts from AstraZeneca, Boehringer Ingelheim, Canadian Institute of Health Research, GlaxoSmithKline and Novartis; consulting fees from AstraZeneca, Boehringer Ingelheim, GlaxoSmithKline, Covis Pharmaceuticals, Sanofi Genzyme and Grifols; and payment for lectures, presentations, speakers' bureaus, manuscript writing or educational events from AstraZeneca and GlaxoSmithKline, outside the submitted work. L. Melenka has received grants or contracts from Wellness of Workers (WoW) Program, Local 110 Heat & Frost Insulators & Allied Workers, outside the submitted work. N. Murgia has received payment for lectures, presentations, speakers' bureaus, manuscript writing or educational events from Chiesi, Menarini and AstraZeneca; and other financial or non-financial interests from GlaxoSmithKline, Chiesi, Menarini, AstraZeneca and Alk-Abelo, outside the submitted work. No further information was provided with respect to these interests. P. Lacy has received support for the present manuscript from Synergy Respiratory and Cardiac Care, Sherwood Park, AB, Canada (research grant, paid to institution); grants from Natural Science and Engineering Research Council of Canada and AstraZeneca; honorarium for presentations, speakers' bureaus, manuscript writing or educational events from GlaxoSmithKline Canada and AstraZeneca Canada; support for attending meetings and/or travel from Synergy Respiratory and Cardiac Care, Sherwood Park, AB, Canada; and receipt of equipment, materials, drugs, medical writing, gifts or other services from Synergy Respiratory and Cardiac Care, outside the submitted work. S. Moitra has received payment for lectures, presentations, speakers' bureaus, manuscript writing or educational events from Synergy Respiratory & Cardiac Care, Permanyer Inc., Elsevier and Apollo Gleneagles Hospital (Kolkata), outside the submitted work.

Support statement: The study was partially supported by a grant from Synergy Respiratory & Cardiac Care, Sherwood Park, Canada (awarded to P. Lacy). A. Deprato received a summer studentship from Alberta Innovates, Edmonton, Canada. However, none of the funders were involved in the conceptualisation or the outcome of this study. Funding information for this article has been deposited with the Crossref Funder Registry.

References

1 Bateman ED, Hurd SS, Barnes PJ, *et al.* Global strategy for asthma management and prevention: GINA executive summary. *Eur Respir J* 2008; 31: 143–178.
2 Vestbo J, Hurd SS, Agusti AG, *et al.* Global strategy for the diagnosis, management, and prevention of chronic obstructive pulmonary disease: GOLD executive summary. *Am J Respir Crit Care Med* 2013; 187: 347–365.
3 Raghu G, Remy-Jardin M, Myers JL, *et al.* Diagnosis of idiopathic pulmonary fibrosis. An official ATS/ERS/JRS/ALAT clinical practice guideline. *Am J Respir Crit Care Med* 2018; 198: e44–e68.
4 Oostveen E, MacLeod D, Lorino H, *et al.* The forced oscillation technique in clinical practice: methodology, recommendations and future developments. *Eur Respir J* 2003; 22: 1026–1041.
5 Graham BL, Steenbruggen I, Miller MR, *et al.* An official American Thoracic Society and European Respiratory Society technical statement. *Am J Respir Crit Care Med* 2019; 200: e70–e88.
6 Dubois AB, Brody AW, Lewis DH, *et al.* Oscillation mechanics of lungs and chest in man. *J Appl Physiol* 1956; 8: 587–594.
7 Makan G, Dandurand RJ, Gingl Z, *et al.* Intra-breath changes in respiratory mechanics assessed from multi-frequency oscillometry measurements. *Physiol Meas* 2022; 43: 045004.
8 Hantos Z. Intra-breath oscillometry for assessing respiratory outcomes. *Curr Opin Physiol* 2021; 22: 100441.
9 Usmani OS. Calling time on spirometry: unlocking the silent zone in acute rejection after lung transplantation. *Am J Respir Crit Care Med* 2020; 201: 1468–1470.
10 Kaminsky DA, Simpson SJ, Berger KI, *et al.* Clinical significance and applications of oscillometry. *Eur Respir Rev* 2022; 31: 210208.
11 Kouri A, Dandurand RJ, Usmani OS, *et al.* Exploring the 175-year history of spirometry and the vital lessons it can teach us today. *Eur Respir Rev* 2021; 30: 210081.
12 Quanjer PH, Stanojevic S, Cole TJ, *et al.* Multi-ethnic reference values for spirometry for the 3–95-yr age range: the global lung function 2012 equations. *Eur Respir J* 2012; 40: 1324–1343.
13 Landser FJ, Clement J, Van de Woestijne KP. Normal values of total respiratory resistance and reactance determined by forced oscillations: influence of smoking. *Chest* 1982; 81: 586–591.
14 Guo YF, Herrmann F, Michel JP, *et al.* Normal values for respiratory resistance using forced oscillation in subjects >65 years old. *Eur Respir J* 2005; 26: 602–608.
15 Moitra S, Moitra S, Ghosh AK, *et al.* Reference values of impulse oscillometry (IOS) for healthy Indian adults. *Int J Tuberc Lung Dis* 2020; 24: 536–539.
16 Oostveen E, Boda K, van der Grinten CP, *et al.* Respiratory impedance in healthy subjects: baseline values and bronchodilator response. *Eur Respir J* 2013; 42: 1513–1523.
17 Berger KI, Wohlleber M, Goldring RM, *et al.* Respiratory impedance measured using impulse oscillometry in a healthy urban population. *ERJ Open Res* 2021; 7: 00560-2020.
18 Brown NJ, Xuan W, Salome CM, *et al.* Reference equations for respiratory system resistance and reactance in adults. *Respir Physiol Neurobiol* 2010; 172: 162–168.
19 De S, Banerjee N, Kushwah GDS, *et al.* Regression equations of respiratory impedance of Indian adults measured by forced oscillation technique. *Lung India* 2020; 37: 30–36.
20 Newbury W, Crockett A, Newbury J. A pilot study to evaluate Australian predictive equations for the impulse oscillometry system. *Respirology* 2008; 13: 1070–1075.
21 Ribeiro FCV, Lopes AJ, Melo PL. Reference values for respiratory impedance measured by the forced oscillation technique in adult men and women. *Clin Respir J* 2018; 12: 2126–2135.
22 Shiota S, Katoh M, Fujii M, *et al.* Predictive equations and the reliability of the impulse oscillatory system in Japanese adult subjects. *Respirology* 2005; 10: 310–315.
23 Schulz H, Flexeder C, Behr J, *et al.* Reference values of impulse oscillometric lung function indices in adults of advanced age. *PLoS One* 2013; 8: e63366.
24 Aarli BB, Eagan TM, Ellingsen I, *et al.* Reference values for within-breath pulmonary impedance parameters in asymptomatic elderly. *Clin Respir J* 2013; 7: 245–252.
25 Bickel S, Popler J, Lesnick B, *et al.* Impulse oscillometry: interpretation and practical applications. *Chest* 2014; 146: 841–847.
26 Kaczka DW, Dellaca RL. Oscillation mechanics of the respiratory system: applications to lung disease. *Crit Rev Biomed Eng* 2011; 39: 337–359.
27 Kalchiem-Dekel O, Hines SE. Forty years of reference values for respiratory system impedance in adults: 1977–2017. *Respir Med* 2018; 136: 37–47.
28 King GG, Bates J, Berger KI, *et al.* Technical standards for respiratory oscillometry. *Eur Respir J* 2020; 55: 1900753.
29 Wu JK, DeHaas E, Nadj R, *et al.* Development of quality assurance and quality control guidelines for respiratory oscillometry in clinic studies. *Respir Care* 2020; 65: 1687–1693.
30 Narchi H, AlBlooshi A. Prediction equations of forced oscillation technique: the insidious role of collinearity. *Respir Res* 2018; 19: 48.

31 Pham MT, Rajic A, Greig JD, *et al.* A scoping review of scoping reviews: advancing the approach and enhancing the consistency. *Res Synth Methods* 2014; 5: 371–385.
32 Tricco AC, Lillie E, Zarin W, *et al.* PRISMA Extension for scoping reviews (PRISMA-ScR): checklist and explanation. *Ann Intern Med* 2018; 169: 467–473.
33 Deprato A, Lacy P, Moitra S. Reference equations for impulse oscillometry and their differences between populations: a scoping review and analysis. *Open Science Framework* 2021. https://doi.org/10.17605/OSF.IO/YW62A
34 McNulty W, Usmani OS. Techniques of assessing small airways dysfunction. *Eur Clin Respir J* 2014; 1: 25898.
35 Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986; 1: 307–310.
36 Lin LI. A concordance correlation coefficient to evaluate reproducibility. *Biometrics* 1989; 45: 255–268.
37 de Assumpcao MS, Goncalves RM, Martins R, *et al.* Reference equations for impulse oscillometry system parameters in healthy Brazilian children and adolescents. *Respir Care* 2016; 61: 1090–1099.
38 Salome CM, King GG, Berend N. Physiology of obesity and effects on lung function. *J Appl Physiol (1985)* 2010; 108: 206–211.
39 Bates JHT, Peters U, Daphtary N, *et al.* Altered airway mechanics in the context of obesity and asthma. *J Appl Physiol (1985)* 2021; 130: 36–47.
40 Peters U, Subramanian M, Chapman DG, *et al.* BMI but not central obesity predisposes to airway closure during bronchoconstriction. *Respirology* 2019; 24: 543–550.
41 Munoz-Cofre R, Lizana PA, Cabello ME, *et al.* Association between air flow limitation and body composition in young adults. *J Physiol Anthropol* 2021; 40: 2.
42 Parraguez Arevalo A, Rojas Navarro F, Ruz Cespedes M, *et al.* The impact of obesity on specific airway resistance and conductance among schoolchildren. *Arch Argent Pediatr* 2018; 116: e227–e233.
43 Dattani RS, Swerner CB, Stradling JR, *et al.* Exploratory study into the effect of abdominal mass loading on airways resistance and ventilatory failure. *BMJ Open Respir Res* 2016; 3: e000138.
44 Tramont CV, Faria AC, Lopes AJ, *et al.* Influence of the ageing process on the resistive and reactive properties of the respiratory system. *Clinics (Sao Paulo)* 2009; 64: 1065–1073.
45 Usmani OS, Dhand R, Lavorini F, *et al.* Why we should target small airways disease in our management of chronic obstructive pulmonary disease. *Mayo Clin Proc* 2021; 96: 2448–2463.
46 Oelsner EC, Balte PP, Bhatt SP, *et al.* Lung function decline in former smokers and low-intensity current smokers: a secondary data analysis of the NHLBI Pooled Cohorts study. *Lancet Respir Med* 2020; 8: 34–44.
47 Almeshari MA, Alobaidi NY, Sapey E, *et al.* Small airways response to bronchodilators in adults with asthma or COPD: a systematic review. *Int J Chron Obstruct Pulmon Dis* 2021; 16: 3065–3082.
48 Nair A, Ward J, Lipworth BJ. Comparison of bronchodilator response in patients with asthma and healthy subjects using spirometry and oscillometry. *Ann Allergy Asthma Immunol* 2011; 107: 317–322.
49 Cavalcanti JV, Lopes AJ, Jansen JM, *et al.* Using the forced oscillation technique to evaluate bronchodilator response in healthy volunteers and in asthma patients presenting a verified positive response. *J Bras Pneumol* 2006; 32: 91–98.
50 Jetmalani K, Brown NJ, Boustany C, *et al.* Normal limits for oscillometric bronchodilator responses and relationships with clinical factors. *ERJ Open Res* 2021; 7: 00439-2021.
51 Brusasco V. Partitioning of pulmonary impedance. *Curr Opin Anesthesiol* 1994; 7: 527.
52 Dandurand RJ, Lavoie JP, Lands LC, *et al.* Comparison of oscillometry devices using active mechanical test loads. *ERJ Open Res* 2019; 5: 00160-2019.
53 Bates JHT, Irvin CG, Farré R, *et al.* Oscillation mechanics of the respiratory system. *Comprehensive Physiology* 2011; 39: 337–359.
54 Chapman RF, Mickleborough TD. The effects of caffeine on ventilation and pulmonary function during exercise: an often-overlooked response. *Phys Sportsmed* 2009; 37: 97–103.
55 Eccles R. Menthol: effects on nasal sensation of airflow and the drive to breathe. *Curr Allergy Asthma Rep* 2003; 3: 210–214.
56 Brashier B, Salvi S. Measuring lung function using sound waves: role of the forced oscillation technique and impulse oscillometry system. *Breathe (Sheff)* 2015; 11: 57–65.
57 Quanjer PH, Stocks J, Cole TJ, *et al.* Influence of secular trends and sample size on reference equations for lung function tests. *Eur Respir J* 2011; 37: 658–664.