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Measurement of respiratory impedance by forced oscillation: comparison of the standard and head generator methods

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ABSTRACT: Physiological and clinical studies have shown that the standard method of measuring respiratory impedance by forced oscillation leads to less efficient control of the upper airway shunt effect than the head generator method.

To test the effects of these two techniques in epidemiological studies, we compared, in a sample of 73 French agricultural workers, the values obtained with each method for five forced oscillation parameters: resistance, frequency dependence of resistance, inertance, compliance and resonant frequency. For these comparisons, subjects were classified according to four respiratory status factors: smoking status, cough, expectoration and airway obstruction assessed from the maximum expiratory flow volume curve. Logistic regression models using the set of four forced oscillation parameters (excluding resonant frequency, which is derived from compliance and inertance) were then used to analyse the ability of each method to classify the subjects in each group.

Significant differences between the two methods were observed for the mean values obtained for all five parameters. However, when each parameter was considered separately, the correlations between the values for each method were significant. Each method possessed the necessary ability to separate subjects into our group classification, but the significant relationships were not always found for the same parameters. Finally, logistic regression models showed that the two methods led to almost the same classification of the subjects.

According to our results, the standard method of applying forced oscillation at the mouth seems an acceptable device for measuring respiratory impedance for epidemiological purposes.

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The forced oscillation method is a technique for measuring respiratory impedance [1–10]. It is a simple and noninvasive method requiring a minimum of active co-operation from the subject. This method has been used to evaluate airway obstruction, since respiratory impedance varies in relation to the degree of obstruction.

Estimation of respiratory impedance is affected by the upper airway shunt effect, *i.e.* vibrations of the upper airway walls (cheeks, pharyngeal walls, *etc.*). The upper airway walls may shunt a substantial part of the flow oscillations measured at the mouth, because these walls are mechanically parallel to those of the respiratory system [9, 11–13]. Several approaches have been used to minimize the errors relating to these vibrations. The standard method consists of applying the pressure oscillations at the mouth, whilst the subject firmly supports his or her cheeks with the palms [6, 14, 15]. However, supporting the cheeks has only been shown to double upper airway wall impedance (Zuaw) [11]. The alternative, used by Michaelson *et al.* [8], consists of measuring Zuaw by applying forced oscillations at the mouth during Valsalva manoeuvres, and correcting respiratory impedance data for the resulting shunt impedance. However, this method requires special training, and was abandoned because of the difficulties connected with its implementation. Recently, Peslin and co-workers [11, 16] suggested applying the pressure oscillations around the head (head generator method), to minimize the transmural pressure across the upper airway walls.

Differences between the resulting measurements were initially assessed by comparing the standard and head generator methods in healthy subjects and patients with chronic obstructive pulmonary disease (COPD) [11, 12, 14]. Recent comparisons of the two methods [14, 16, 17] showed that in healthy subjects, the differences mainly concerned the imaginary part of respiratory impedance, whereas in COPD patients, both the real and imaginary parts may be seriously underestimated with the standard method.

In occupational epidemiological studies, the workers studied do not usually suffer from severe pulmonary disease. Among such workers, as far as we know, no study has yet compared the two approaches to the forced oscillation method for the measurement of respiratory impedance. Moreover, the studies cited above focused mainly on accurate estimations of respiratory impedance parameters relating to the physical properties of the respiratory system, rather than comparing the discriminatory power of the two techniques by classifying subjects according to respiratory status; this power seems important from an epidemiological point of view.

For the present study, we took advantage of a survey being conducted in a French agricultural population to compare the performance of the standard and head generator techniques in distinguishing between subjects according to selected factors usually related to the presence of airway disease.

Subjects, materials and methods

Population

Data were collected during a study on respiratory and immunoallergic disorders in an agricultural population. Seven hundred and sixty seven volunteers participated in the survey, from a population of more than 2,300 agricultural workers who were asked to undergo preventive medicine examinations in the year 1988 [18]. The present study concerns a subgroup of 83 subjects, who took part in the survey for two consecutive weeks in October 1988, during which the forced oscillation method was applied.

Ten subjects were excluded from the initial sample of 83 (for 6 of them, the coherence value with the standard method was insufficient, and 4 subjects were not tested with the head generator method).

Questionnaire

The study was conducted with the co-operation of the Preventive Medicine Department of the French Agricultural Social Security Organization. Subjects were given detailed explanations of the protocol by the study team and occupational physicians, and were then asked to come to the Medical Department at Bar le Duc in North-Eastern France for examination. Subjects answered questions concerning bronchitis and emphysema in a standardized questionnaire elaborated by the European Community for Coal and Steel, and other questions about allergic symptoms and occupational conditions [18]. Their answers were reviewed by an occupational physician and missing data were completed.

Respiratory function test

Forced oscillation method. a) Principle and practical application. The standard and head generator methods of measuring respiratory impedance by forced oscillation are both based on the same principle of applying pressure oscillations to the respiratory system whilst the subject is quietly breathing room air. To measure impedance by the standard technique (Method A) [6, 8, 14, 15], the subject was comfortably seated with his elbows on the table, and was asked to hold his cheeks firmly whilst pressure oscillations were applied at the mouth. For measurements using the head generator technique (Method B) proposed by PESLIN and co-workers [3, 11, 14], the oscillations were applied around the head in order to minimize the upper airway artefact. In both cases, flow and pressure were measured at the mouth, which allowed determination of input respiratory impedance.

Using the standard technique, developed by LORINO and co-workers [1, 7], a pressure input was applied at the mouth with an external generator including two loudspeakers. The excitation was a random noise with a frequency content ranging 3–25 Hz. Flow was sensed by a pneumotachograph (Jaeger Lily; resistance=0.35 $hPa \cdot s \cdot l^{-1}$) connected to a differential pressure transducer (Sensym SCX O1D, ±70 hPa), and pressure was sensed by a similar transducer. Both signals were low-pass filtered at 30 Hz and then sampled at 128 Hz for periods of 12 s. Auto- and cross-spectra of flow and pressure were estimated every 0.25 Hz for adjacent 4 s blocks submitted to Hamming windowing. These spectra were averaged over each 12 s period to yield an estimate of the impedance and the coherence function (γ^2). Spectra were then averaged again over three 12 s periods, in which more than 80% of the coherence values observed between 3 and 30 Hz were higher than 0.8. A single estimate of the real components of impedance (Zr), of its imaginary components (Zi), and of the coherence function was, thus, obtained as a function of frequency (f).

Using the head generator technique, developed by PESLIN and co-workers [16], the pressure input was applied both at the mouth and around the head with a specially devised generator consisting of a Plexiglass cylinder covered with a 100 W loudspeaker [3, 16]. The cylinder was supported by a wooden frame and mounted on hinges, so that it could easily be lowered around the head at the time of measurement. A good seal at the neck, without compression of the upper airway, was obtained using a collar fitted with small glass beads and evacuated by a vacuum line. The signal sent to the loudspeaker was a pseudorandom noise including all the harmonics of 2 Hz from 4 to 30 Hz. Airway flow was measured with a Fleisch No. 2 pneumotachograph connected to a Validyne differential transducer (type MP45 ±2 hPa); the pressure applied was measured with a similar transducer matched to the first within 1% of amplitude and 2° of phase up to 30 Hz. The signals were sampled for periods of 16 s and digitized with a sampling rate of 128 Hz by an Apple 2e computer system. They were processed by Fourier analysis as with the standard technique, except that a Hanning window with a 50% overlap was applied to flow and pressure, and the γ^2 threshold was 0.9. The impedance data were then averaged for three successive 16 s periods.

b) Lumped parameter model. A series resistance-inertance-compliance model [7, 10] was fitted between the frequency bounds, *f*min (3 Hz in Method A, 4 Hz in Method B), and *f*max (25 Hz in Method A, 30 Hz in method B), to impedance data corresponding to a coherence value higher than a preset threshold (0.8 in Method A, 0.9 in Method B):

$$Z = R_\phi + P \cdot f + j(I \cdot \omega - 1/(C \cdot \omega)),$$
$$\text{with } j^2 = -1 \text{ and } \omega = 2 \cdot \pi \cdot f$$

In this model, respiratory resistance was described by a linear function of frequency in which the P slope accounts for frequency dependence of resistance, R_ϕ is the intercept of the regression line, I is total respiratory inertance, and C is total respiratory compliance. The resonant frequency (F), *i.e.* the frequency at which the imaginary part of impedance is zero, was also used to describe the data ($F=1/2\pi\ (IC)^{1/2}$)

Maximal expiratory flow-volume curves. Maximal expiratory flow-volume curves (MEFV) were obtained by measuring flow with a Fleisch No. 3 pneumotachograph connected to a microprocessor with a visual display unit (Spiromatic®; MSR, France). To construct an MEFV envelope, at least three curves were required, the forced vital capacity (FVC) to which differed by less than 5%. All three were displayed and checked on the screen. The curve components measured included FVC, forced expiratory volume in one second (FEV_1), maximal mid-expiratory flow (FEF_{25-75}), and maximal expiratory flow when 75, 50 and 25% of the FVC remained to be expired ($\dot{V}max_{75}$, $\dot{V}max_{50}$ and $\dot{V}max_{25}$), respectively. For all these parameters, the reference values of the European Community for Coal and Steel [19] were used to calculate the ratios of measured to reference values.

Respiratory status parameters

We considered four variables generally assumed to be indicators of the presence of airway disease: 1) smoking status; 2) the presence of cough; 3) the presence of expectoration; and 4) observed maximal mid-expiratory flow (FEF_{25-75}) lower than 70% of the predicted value.

Smoking status and the presence of respiratory complaints were evaluated from subjects' answers to the standardized questionnaire. Current and past smokers were considered as those who had ever smoked, and nonsmokers were those who had never smoked. The presence of cough or expectoration concerned regular seasonal complaints. The decrease in FEF_{25-75} was defined by the ratio of observed to reference values. These variables are referred to as "respiratory status factors".

Statistical analysis

The relationships between forced oscillation techniques, Methods A and B, were examined using the Pearson correlation coefficients computed for each of the five parameters R_ϕ, P, I, C and F, and the mean values obtained for each parameter by the two methods were compared by the paired t-test in the whole sample.

To compare the ability of Method A and method B to distinguish between subjects according to respiratory status factors, two types of analysis were successively undertaken. In the first, the distributions obtained for each of the above five forced oscillation parameters by Methods A and B were compared according to the presence or absence of each respiratory status factor. For this purpose, individual forced oscillation parameter values were adjusted for potential confounding factors, *i.e.* sex, age, height and weight, using standard linear regression with forward selection of the independent variables. Finally, the distributions of the adjusted values (difference between observed and predicted values plus the mean of the whole sample) were compared using the Wilcoxon's nonparametric test, because the samples were small and some of the forced oscillation parameters did not seem to be normally distributed.

In the second analysis, the abilities of each method to predict the presence of each respiratory status factor were compared by logistic regression, as follows: for each method, several logistic regression analyses were performed, each corresponding to one of the four respiratory status factors, taken as the dependent binary variable [20]. The independent variables were the impedance-related variables R_ϕ, P, C and I. F was discarded from the logistic regression models, as it was determined directly from I and C. The forced oscillation parameters were adjusted for sex, age, height and weight as described above. From each of the resulting estimated regression equations, subjects could be classified as exhibiting, or not exhibiting, the given factor. The proportions of subjects misclassified by either method were compared using McNemar's test.

The number of subjects measured was not identical for all parameters, because resonant frequency could not be determined by Method A for two subjects.

All statistical analyses were made with the BMDP package (Statistical software, Los Angeles, CA, USA).

Results

Description of the sample

The total sample of 73 subjects comprised 45 men and 28 women. As stated in the Methods section, the number of subjects measured was not identical for all parameters because resonant frequency could not be determined by Method A for two subjects. The mean±SD age was 47±13 yrs for the men and 49±11 yrs for the women. Sixty seven percent of the men and 7% of the women had ever smoked. In the whole sample, 23% of the subjects complained of regular seasonal cough and 16% of expectoration. Twelve percent of the subjects (8 men and 1 women) had chronic bronchitis. However this parameter was not taken into account in the analysis because of the small number of subjects concerned.

Table 1. – Values for the forced oscillation method parameters and correlation coefficients

		Method A	Method B	p-value[#]	Correlation coefficient	p-value[##]
R_ϕ	hPa·l^{-1}·s (n=73)	3.0±1.1	3.8±1.5	***	0.80	***
P	10^{-3}·hPa·l^{-1}·s^2 (n=73)	7.2±32.2	-24.7±24.9	***	0.53	***
I	10^{-3}·hPa·l^{-1}·s^2 (n=73)	8.8±4.4	15.4±3.2	***	0.68	***
C	ml·hPa^{-1} (n=73)	32.2±12.8	37.5±17.1	*	0.34	**
F	Hz (n=71)	11.8±8.7	7.1±2.7	***	0.54	***

Data are presented as mean±SD. #: paired t-test; n: number of subjects; R_ϕ: resistance; P: frequency dependence of resistance; I: inertance; C: compliance; F: resonant frequency; *: $p<0.05$; **: $p<0.01$; ***: $p<0.001$. ##: correlation test.

Respiratory function evaluation by means of maximal expiratory flow-volume curves showed that the average ratios of observed to predicted values were 104±16 for FEV_1, 100±9 for FEV_1/FVC, and 89±30 for FEF_{25-75}, suggesting that, on the whole, the sample comprised fairly healthy subjects.

As regards the medians of MEFV curve parameters, they exhibited significantly lower values for smokers than nonsmokers for FEV_1 (106 *vs* 111%) and for FEV_1/FVC (99 *vs* 104%). For the subjects complaining of cough, the values for FEV_1 and the FEV_1/FVC ratio were lower than for subjects without cough (FEV_1 100 *vs* 109%; p=0.07) (FEV_1/FVC 97 *vs* 103%; p<0.01). For expectoration, similar results were found (FEV_1 89% among those with expectoration and 109% among those without; p=0.08); (FEV_1/FVC 95 *vs* 103%; p<0.01).

Comparison of Methods A and B

The mean values for the five forced oscillation parameters were significantly different when measured by the standard and head generator methods (table 1). For all five parameters, coefficients of correlation were highly significant. The mean value of R_ϕ was lower with Method A ($R_{\phi A}$ = 3.0 *vs* $R_{\phi B}$ = 3.8 hPa·l^{-1}·s), whereas the mean value of P was slightly positive with Method A and was markedly negative with Method B (P_A=7.2, P_B=-24.7 10^{-3}hPa·l^{-1}·s^2). I and C were lower, and F was higher, with Method A.

The medians of the adjusted values for the forced oscillation parameters according to the respiratory status factors examined were calculated separately for methods A and B. As regards smoking status, P and I were significantly lower among those who had ever smoked than nonsmokers, with Method A. The median value for resonant frequency was higher among those who had ever smoked (p=0.07). With Method B, a statistically significant difference was found only for resistance. Depending on the presence or absence of cough, a statistically significant difference was observed only for resistance, with both methods. With Method A, subjects with cough had lower inertance (p=0.08) and higher resonant frequency (p=0.10) than those without. With Method B, inertance was also lower (p=0.09). With respect to expectoration, the only parameter displaying differences was resistance, for which the median value was higher when expectoration was present than when it was absent. The difference was significant for Method B (p=0.05), and to a lesser degree for Method A (p=0.08). With Method A, the values measured for all five oscillation parameters in the presence of airway obstruction (evaluated from MEFV curves) differed significantly from those measured in its absence, and the same applied to Method B for all parameters except compliance, as subjects with airway obstruction had higher R_ϕ and F, and lower P, C and I than normal subjects. Therefore, for each of the two methods of forced oscillation, at least one parameter was able to distinguish subjects according to the factors of respiratory status considered.

The ability to discriminate between subjects according to the respiratory status factors considered was then assessed for each method using the logistic regression models, with the four forced oscillation parameters as the independent variables (R_ϕ, P, C and I). Thus, in table 2, the percentages of subjects misclassified by each model were compared for Methods A and B. When smoking

Table 2. – Ability of the standard and head generator methods of forced oscillation measurement to discriminate between subjects according to respiratory status[#]

Respiratory status factors	Forced oscillation method	% incorrectly classified subjects
Smoking status	Method A	37%
	Method B	40%
Cough	Method A	34%
	Method B	30%
Expectoration	Method A	33%
	Method B	25%
Obstruction*	Method A	21%
	Method B	26%

#: logistic regression models with only four parameters; R_ϕ, P, C and I as independent variables (see Methods section); *: assessed from % of predicted FEF_{25-75}; FEF_{25-75}: maximal mid-expiratory flow.

status was the dependent variable, the percentages of incorrectly classified subjects for the two methods were similar: 37 for Method A and 40% for Method B. Similar results were obtained for the three other variables. For all four factors of respiratory status considered, no significant difference between Methods A and B was found in the percentages of subjects misclassified. Note that this percentage was lowest when obstruction was evaluated from the MEFV curve obtained for Method A.

Discussion

Our results show that in the whole sample of 73 subjects, the two methods of forced oscillation gave significantly different values for all the indices measured. However, a significant correlation was observed between the results for the two methods when each parameter was considered separately. These differences cannot be imputed to the slightly different pressure input [21], and are consistent with the presence of an upper airway wall artefact, as stated below. As regards the relevance of each forced oscillation parameter, the present work showed that for the head generator method, resistance was systematically discriminant with all the respiratory status factors considered, but that this was not the case for the standard method. Nevertheless, P, I and F were also discriminant with the standard method for smoking status. Thus, when the four oscillation parameters R_ϕ, P, C and I were used, the two methods displayed similar abilities to classify subjects according to each respiratory factor. However, in interpreting the results, one should take into account the small sample size, which might have entailed insufficient statistical power. Despite this restriction, a large difference between the discriminant abilities of the two methods seems unlikely.

In the present study, the forced oscillation methods were compared according to their relationship to four variables designed to evaluate the severity of subjects' airway disorders. The variations observed in forced oscillation parameter values, estimated according to the four respiratory status factors (*i.e.* the increases in R_ϕ and F, and decreases in P and I among subjects displaying moderate airway obstruction) were in agreement with the results of other studies, in which healthy subjects were compared with COPD patients [2, 12, 14, 16]. In particular, smoking status was examined here because smoking may be associated with small airway abnormalities, even in the early stages of obstructive disorders, and significant differences were found between those who had ever smoked and nonsmokers for several forced oscillation parameters.

A review of the studies comparing the standard and head generator methods indicates that supporting the cheeks does not completely eliminate the shunt effect of the upper airways present with the standard method. However, comparison of our results with those reported in these studies is rather difficult, because of methodological variations. Thus, most previous investigations focused on the difference between the results for the two methods in healthy subjects on the one hand and COPD patients on the other. In particular, the discriminant power of each method in classifying subjects according to respiratory status was poorly documented.

PESLIN and co-workers [16] observed that among healthy subjects, lower R_ϕ, higher frequency dependence of resistance, lower inertance and larger resonant frequency were obtained by the standard method than by the head generator method. In COPD patients, these authors found no significant difference between the two methods for R_ϕ, but observed that the negative frequency dependence of resistance was much more marked with the standard method. For the reactance indices C and I, the differences between the two methods ran in the same direction in patients with COPD and normal subjects.

PESLIN and co-workers [12], who measured the flow shunted by upper airway walls, also suggested that the negative frequency dependence of resistance observed in COPD patients with the standard method may be due to the presence of an upper airway artefact. However, in the study by CAUBERGHS and VAN DE WOESTIJNE [14], the negative frequency dependence of resistance was still present with the head generator method among patients with severe COPD, although its amplitude was less pronounced that with the standard method.

The more recent study by PESLIN and co-workers [16] was one of the few in which both the standard and head generator techniques were compared among smokers and nonsmokers, as here. The only significant differences between the results for the two methods were that with the standard method, resonant frequency was larger for smokers, whereas with the head generator method, resistance at 10, 20 and 30 Hz was higher for smokers. These results have much in common with those found in the present study, in which, in addition, significant differences between the values for smokers and nonsmokers were observed for the frequency dependence of resistance and for inertance with the standard method.

For diagnostic purposes, the main consequence of the presence of residual upper airway artefact with the standard method might be to reduce the distinction between COPD patients and healthy subjects based on impedance measurements. However, even though the correction for the upper airway artefact is smaller than with the head generator method, the studies by CLEMENT *et al.* [2], and the investigation by CAUBERGHS and VAN DE WOESTIJNE [14], showed that the standard method does allow the separation of healthy subjects and those with COPD. The results of our study were similar in this respect.

In conclusion, in a population with no severe respiratory disorders, the two forced oscillation methods differentiated between the subjects in the same manner, at least for the dependent variables considered here. However, different conclusions might have been drawn with other classification criteria and different descriptive models of total respiratory impedance. The main advantage of the standard method is that it is very simple to apply. The next step in the comparison of the standard and head generator methods in occupational populations should consist of studying the ability of the different forced oscillation parameters to detect the changes induced by pharmacodynamic substances.

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