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Nasal airflow resistance measurement: forced oscillation technique *versus* posterior rhinomanometry

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ABSTRACT: This study was designed to determine whether nasal airflow resistance (R_n) which is nonlinear during tidal breathing, can be assessed by the forced oscillation (FO) technique.

R_n values obtained by the FO technique and extrapolated to 0 Hz ($R_{n,FO}$) were compared to those assessed by posterior rhinomanometry at maximal tidal inspiratory flow ($R_{n,m}$), at a 0.5 L·s^{-1} flow ($R_{n,F}$), and at a 1 hPa transnasal pressure ($R_{n,P}$). All R_n estimates were derived from the same inspiratory and expiratory nasal flow and transnasal pressure signals obtained during tidal nasal breathing whilst a forced flow was applied at the nose *via* a rigid nasal mask in 23 healthy volunteers, of whom 14 had additional measurements after vasoconstrictor treatment.

In the basal state, no significant difference, and significant correlations ($p<0.0001$) were found between $R_{n,FO}$ and the other R_n estimates. Only the regression line of $R_{n,FO}$ *versus* $R_{n,m}$ was not significantly different from the identity line. After nasal decongestion, $R_{n,P}$ became significantly higher than the other R_n estimates ($p<0.005$). The regression line of $R_{n,FO}$ *versus* $R_{n,m}$ remained nonsignificantly different from the identity line. Similar results were observed regarding the percentage values of the different R_n estimates after decongestant treatment.

This study shows that, despite its nonlinearity, R_n can be assessed by the FO technique, and that $R_{n,FO}$ and $R_{n,m}$ could be indifferently used as physiological indices of nasal patency. As the FO technique is more difficult to implement than the conventional rhinomanometry, its interest in rhinology appears not to be obvious.
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Measurement of nasal airflow resistance (R_n) is of clinical importance to evaluate the degree of nasal patency objectively. Several methods are presently available for measuring R_n. The conventional methods for direct R_n measurement, active anterior rhinomanometry [1–5] and posterior rhinomanometry (PR) [1–3, 5–8], are based on transnasal pressure (P) and nasal flow (V') measurements. Since R_n is flow-dependent, it is generally related to a reference nasal V' or to a fixed transnasal P. To avoid transnasal P measurement which may be problematic, subtraction methods based on the forced oscillation (FO) technique have begun to be used for R_n measurement [1, 9–14]. With such methods, a mean R_n value is calculated as the difference between total respiratory resistances measured at the nose and at the mouth. From a theoretical point of view, the presence of nonlinearities renders the use of the FO technique debatable for R_n measurement. Indeed, nasal impedance (Z_n) measurement with this method is based on the assumption that the mechanical system considered behaves linearly. However, small V' oscillations are expected to linearize the mechanical behaviour of such nonlinear systems, and it has been observed that the nonlinear characteristics of the transnasal P-V' relationship which are pronounced at 1–2 Hz, diminish as the frequency increases [15].

Comparative studies of PR and the subtraction FO technique have shown either significant differences but no correlation between the different R_n values [1], or no significant difference but no correlation [12]. These discrepancies are likely to result from the nonlinearity of the transnasal P-V' relationship, particularly when subtraction methods are used [1, 11]. In addition, the applicability of the FO technique to R_n measurement has not been clearly established as regards both its reliability and the relevance of its results.

The present study was therefore initiated to determine whether the nonlinear R_n could be accurately assessed by the direct FO technique, *i.e.* from transnasal P and nasal V' signals. For this purpose, we compared the R_n values obtained by the FO technique ($R_{n,FO}$) to those measured by the conventional PR technique at three different nasal V' levels: R_n measured by PR at an airflow of 0.5 L·s^{-1} ($R_{n,F}$); R_n calculated by PR at a fixed transnasal pressure of 1hPa (V'_P) ($R_{n,P}$); and R_n measured by PR at the point of maximal inspiratory flow (V'_m) ($R_{n,m}$).

Materials and methods

Subjects

R_n measurements were performed in a group of 23 asymptomatic healthy subjects (13 males and 10 females), aged

18–45 yrs, with no upper or lower respiratory complaints. In the first nine subjects (group 1), *R*n was only measured in the basal state. In the 14 other subjects (group 2), *R*n was also measured 10 min after inhalation of two puffs of an α-adrenergic agonist consisting of a 0.05% solution of tymazoline hydrochlorate (Pemazène®; Synthelabo, le PlessisRobinson, France). In that way, it was possible to compare not only the different *R*n estimates, but also their respective sensitivities in evaluating the efficacy of a topical nasal decongestant.

Data acquisition

All *R*n values were calculated from the same nasal *V'* and transnasal *P* signals. The subjects were studied during spontaneous nasal breathing, with the mouth occluded by a closed mouth-piece in which a 5 cm length and 3 mm inside diameter catheter was inserted, whilst a pseudorandom forced flow was applied at the nose *via* a rigid nasal mask. The pseudorandom forced flow used in this study was composed of 29 harmonics (4–32 Hz), with enhanced amplitudes at the lower frequencies, to limit the influence of spontaneous breathing. The forced signal generated by a digital-to-analogue converter, excited, through a power amplifier, two 60 W loudspeakers attached to a 12 L rigid chamber. The peak-to-peak amplitude of the resulting flow was about 0.2 $L \cdot s^{-1}$.

Transnasal *P* was measured by a differential pressure transducer (Sensym SCX 01 D, ±70 hPa; Sensym, Sunnyvale, CA, USA), one port of which was connected to the nasal mask, and the other to the mouth-piece catheter. Nasal *V'* was sensed by a screen pneumotachograph (Jaeger Lilly, internal resistance: 0.35 $hPa \cdot L^{-1} \cdot s$, Jaeger, Würzburg, Germany) connected to a similar pressure transducer. This experimental set-up allowed reliable measurements up to 32 Hz. Transnasal *P* and nasal *V'* signals were low-pass filtered and sampled at 128 Hz for 16 s. Three consecutive sequences of data acquisition were performed and analysed as described below.

R*n,FO assessment*

Transnasal *P* and *V'* data were high-pass filtered to eliminate the low harmonics of the breathing noise. A Fast Fourier Transform algorithm was applied to adjacent 4 s periods. Zn was calculated from the mean auto- and cross-spectra obtained over three consecutive 16s manoeuvres, and retained for analysis when the coherence value was higher than 0.9 [16]. The real part of Zn (Re (Zn)) was subjected to linear regression analysis *versus* frequency, and *R*n,FO was taken as Re(Zn) extrapolated at 0 Hz. The efficacy of the decongestant was assessed by the percentage ratio of *R*n,FO to its basal value (%*R*n,FO).

R*n,m,* R*n,F, and* R*n,P assessment*

Transnasal *P* and *V'* data were low-pass filtered to eliminate the high harmonics resulting from the pseudorandom noise. Transnasal *P* and nasal *V'* data were analysed cycle by cycle, by multiple linear regression analysis of transnasal *P* over nasal *V'* and flow × absolute value of flow ($V'|V'|$), to determine the Rohrer coefficient K_1 and K_2 characterizing the nonlinear *R*n, according to the following equation adapted from [17] to account for bidirectional flows:

$$P = K_1 V' + K_2 V' |V'| + P_0 \qquad (1)$$

where P_0 is a constant. Only cycles where r^2 was higher than 99% were retained for *R*n calculation. *R*n,m was calculated as *R*n at the point of *V'*m, *viz* as $K_1 + K_2 V'_m$. *R*n was also calculated at a fixed 0.5 $L \cdot s^{-1}$ airflow as $R_{n,F} = K_1 + 0.5 K_2$, and at the flow (V'_P) corresponding to a fixed 1 hPa transnasal pressure as $R_{n,P} = K_1 + K_2 V'_P$. For each calculation mode, *R*n was taken as the average of its different estimates. The efficacy of the decongestant was assessed by the percentage ratio of *R*n,m, *R*n,F and *R*n,P to their respective basal values (%*R*n,m, %*R*n,F and %*R*n,P).

Statistical analysis

Values are means±SD, except where otherwise indicated. Nasal mechanical characteristics and *R*n values were compared by one factor analysis of variance for repeated measures, completed as necessary by Student's paired t-test, and by linear regression analysis. A p-value of less than 0.05 was considered to be statistically significant. The agreement between methods was evaluated by the method of BLAND and ALTMAN [18].

Results

Re(Zn) was little or not dependent on frequency (fig. 1), and nasal reactance reduced to a single inertance.

The number of cycles where r^2 was lower than 99% and which were consequently discarded for *R*n calculation, was lower than 8% in all subjects.

Basal state

The nasal mechanical characteristics obtained in the basal state in our 23 subjects (group 1 + group 2) are given in table 1. The differences between *R*n,FO on the one hand and *R*n,m, *R*n,F and *R*n,P on the other, are presented in figure 2. No significant difference was observed between the different Rn estimates. Highly significant correlations were observed between *R*n,FO and the *R*n estimates derived from PR (fig. 3), and the best correlation was found between *R*n,FO and *R*n,m. Furthermore, the regression line of *R*n,FO *versus* *R*n,m was not significantly different from the identity line, whereas the regression lines of *R*n,FO *versus* *R*n,F and *R*n,P were significantly different from this line ($p < 0.001$ and 0.02, respectively).

Decongestant

Decongestant treatment affected most of the nasal mechanical characteristics in our subjects (group 2, table 1).

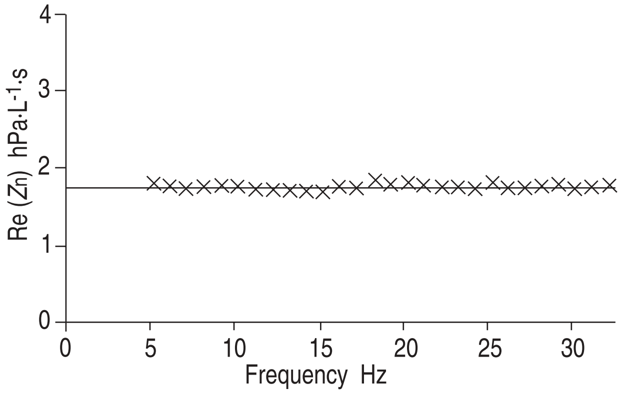

Fig. 1. – Typical data of the real part of nasal impedance (Re (Zn)), plotted as a function of frequency. ×: measured values;—— : fit of the model Re (Zn) = nasal airflow resistance measured by forced oscillation (*R*n,FO)+S*f*, where S represents the frequency (*f*) dependence of Re (Zn).

The K_1 and K_2 values characterizing *R*n significantly decreased. *V*'P significantly increased, whereas *V*'m remained unchanged (table 1). As illustrated in figure 4, *V*'P was higher than *V*'m in all subjects, which shows that *V*'P was never reached during tidal breathing. A significant decrease was observed in all the different *R*n estimates (table 1).

*R*n,FO, *R*n,m, and *R*n,F, were found significantly lower than *R*n,P (table 1). The mean differences between *R*n,FO on the one hand and *R*n,m, *R*n,F and *R*n,P on the other were: 0.01±0.12; 0.02±0.20; and 0.3±0.23 hPa·L^{-1}·s, respectively. *R*n,FO remained significantly correlated with *R*n,m (r=0.96, $p<0.0001$), *R*n,F (r=0.89, $p<0.0001$), and *R*n,P (r=0.86, $p<0.0001$), and the regression line of *R*n,FO *versus* *R*n,m remained nonsignificantly different from the identity line.

Table 1. – Nasal mechanical characteristics and airflow resistances, in the basal state and after treatment with Tymazoline, a topical decongestant spray

	Basal state		Tymazoline
	Group 1 + Group 2 (n=23)	Group 2 (n=14)	Group 2 (n=14)
K_1 hPa·L^{-1}·s	0.90±0.42	0.82±0.39	0.39±0.27‡
K_2 hPa·L^{-2}·s^{2}	2.53±1.99	2.13±1.12	0.99±0.39‡
V'm L·s^{-1}	0.54±0.17	0.57±0.17	0.53±0.16
*R*n,m hPa·L^{-1}·s	2.12±0.87	1.94±0.74	0.91±0.39$^{§\#}$
*R*n,FO hPa·L^{-1}·s	2.15±0.89	1.99±0.74	0.91±0.44$^{§\#}$
*R*n,F hPa·L^{-1}·s	2.16±1.22	1.89±0.77	0.90±0.41$^{§\#}$
*R*n,P hPa·L^{-1}·s	2.02±0.62	1.88±0.47	1.21±0.32§
V'P L·s^{-1}	0.53±0.15	0.56±0.15	0.89±0.19^{++}

Values are presented as mean±SD. Group 1: subjects in whom *R*n was measured in the basal state only. Group 2: subjects in whom *R*n was measured both in the basal state and after decongestant treatment; K_1 and K_2: Rohrer's constants for the nasal passages; *V*'m: maximal inspiratory flow; *R*n,m: nasal resistance measured by posterior rhinomanometry (PR) at the given *V*'m flow; *R*n,FO: nasal resistance measured by the forced oscillation technique; *R*n,F: nasal resistance measured by PR at an airflow of 0.5 L·s^{-1}; *R*n,P: nasal resistance calculated by PR at a transnasal pressure of 1 hPa; *V*'P: flow value corresponding to a 1hPa transnasal pressure. ‡, §: $p<0.001$, $p<0.0001$, compared to the basal value in the same group. $^{\#}$: $p<0.05$, compared to *R*n,P under the same condition. $^{++}$: $p<0.0001$, compared to *V*'P basal values.

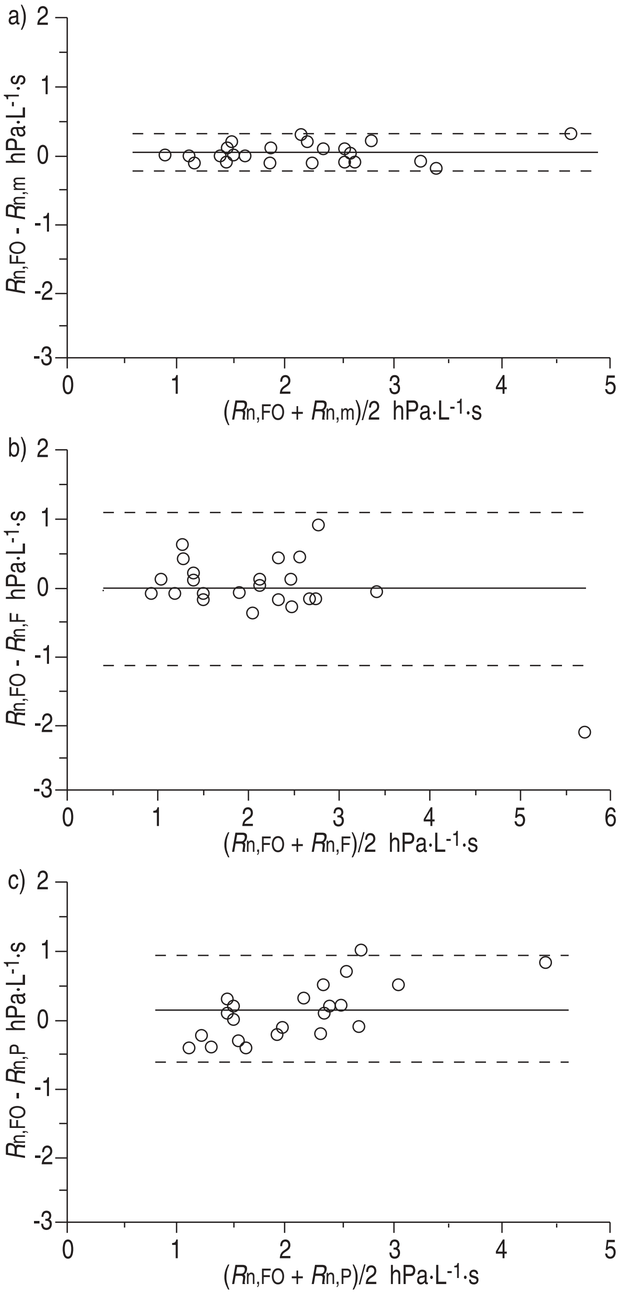

Fig. 2. – Representation of the differences between nasal resistance measured by the forced oscillation technique (*R*n,FO) and nasal resistance measured by posterior rhinomanometry at a) the point of maximal inspiratory flow (*R*n,m), at b) the 0.5 L·s^{-1} flow (*R*n,F) and at c) the 1 hPa transnasal pressure (*R*n,P). ——: mean difference; - - -: mean±2SD.

The percentage *R*n values after decongestant inhalation were: %*R*n,FO=46.1±3.8%, %*R*n,m=48.2±3.8%, %*R*n,F=49.8±4.4%, and %*R*n,P=66.1±3.7%. The mean differences between %*R*n,FO on the one hand and %*R*n,m, *R*n,F and %*R*n,P on the other were -2.1±7.1, -3.7±11.7 and -20±10.8%, respectively. %*R*n,FO, %*R*n,m and %*R*n,F were not significantly different, but all three indices were found to be significantly lower than %*R*n,P. %*R*n,FO was significantly correlated with %*R*n,m, %*R*n,F, and %*R*n,P (fig. 5), and the regression line of %*R*n,FO *versus* %*R*n,m was not significantly different from the identity line.

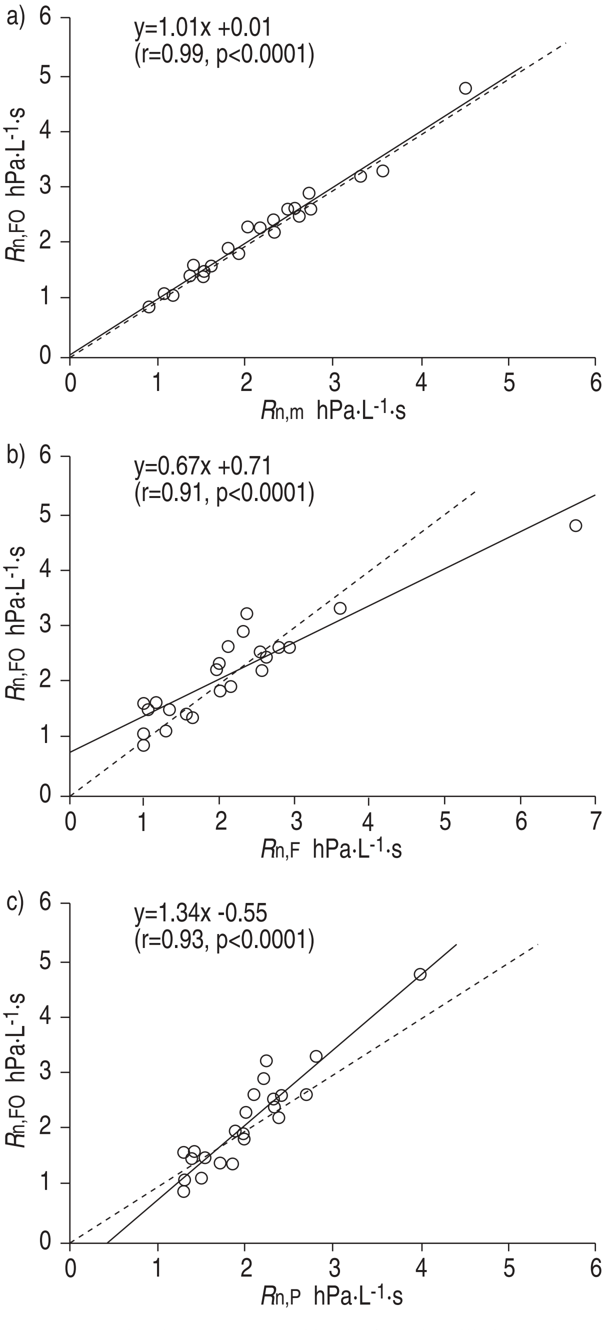

Fig. 3. – Nasal resistance measured by the forced oscillation technique (Rn,FO), plotted in relation to nasal resistance measured by posterior rhinomanometry at a) the point of maximal inspiratory flow (Rn,m), at b) the 0.51 L·s^{-1} flow (Rn,F), and at c) the 1 hPa transnasal pressure (Rn,P). ○: data from individual subjects in the basal state; —— : regression lines; - - - - : identity lines.

Discussion

The FO technique was originally introduced in rhinology to facilitate Rn assessment by avoiding transnasal P measurement. It was indeed anticipated that this technique, sequentially applied at the nose and mouth, might allow Rn measurement by simple subtraction. However, discrepancies were observed between the substraction FO technique and PR. Our results show that, when a direct FO technique is used, FO and PR can provide similar Rn assessments, both at the basal state and after decongestant inhalation.

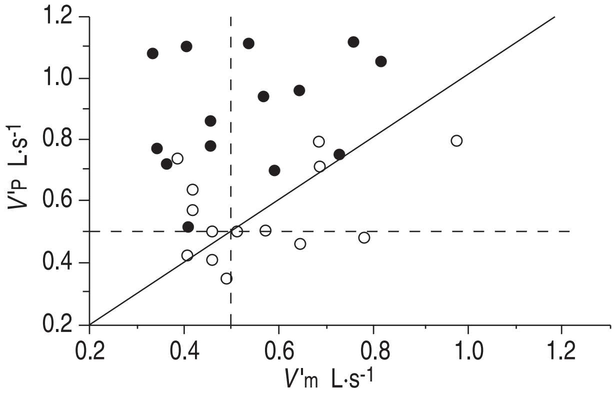

Fig. 4. – Nasal airflow corresponding to a 1 hPa transnasal pressure resistance (V'P) plotted in relation to maximal nasal inspiratory flow (V'm), in the basal state (○), and after topical vasoconstrictor treatment (●). —— : identity line; - - - - : 0.5 L·s^{-1} flow levels.

The nasal mask we used had a low internal volume and was rigid enough not to influence Rn,FO measurement. Indeed, we previously checked in subjects breathing *via* the mouth with a noseclip, that there was no significant difference between the respiratory resistance values measured at the mouth, whether the measurements were made through a mouth-piece or through the nasal mask applied over the oral cavity. Oral pressure was assumed to reflect lateral nasopharyngeal pressure. This assessment could be considered to be satisfactory since we observed no inconsistency between the Zn data at the lowest and the highest frequencies.

With rhinomanometry, nasal resistances are estimated either over the ventilatory cycle [2, 5–7, 12, 14], or separately over inspiration and/or expiration [8, 19, 20], even though the influence on Rn of the ventilatory phase remains controversial [1, 19]. As Rn,FO is determined over both ventilatory phases, it appeared sensible in this study to determine K_1 and K_2 over the entire ventilatory cycle. To minimize intrasubject variability, Rn,FO, Rn,m, Rn,F, and Rn,P were derived from the same P-V' samples. Furthermore, all the data presented in this study correspond to an r^2 and a coherence values ensuring: 1) a good quality of the fit of transnasal P by the analytical function of equation 1; 2) a relative stability of Rn throughout the entire 16 s period taken into account for Zn measurement.

In the present study, Rn was evaluated at V'm, which represents the maximal tidal flow, and at 0.5 L·s^{-1} and V'P, which are flows more commonly used in rhinomanometry. It is worth noting that, although these different flows were not always significantly different in average in group 2 (table 1), they could be in a ratio of about two in some individuals (fig. 4), thereby leading to very different values of the corresponding Rn estimates.

Basal state

Our K_1 and K_2 values were in the range of those previously reported [8, 19], and our Rn,F values were comparable to those calculated at a comparable reference flow [5, 8, 21]. The fact that no significant difference was observed between Rn,m, Rn,F, and Rn,P may be explained by the com-parable mean levels of the three flows, V'm, 0.5 L·s^{-1}, and V'P, used for Rn calculation. However, figure 4, shows that in some subjects, either the 0.5 L·s^{-1} or the V'P

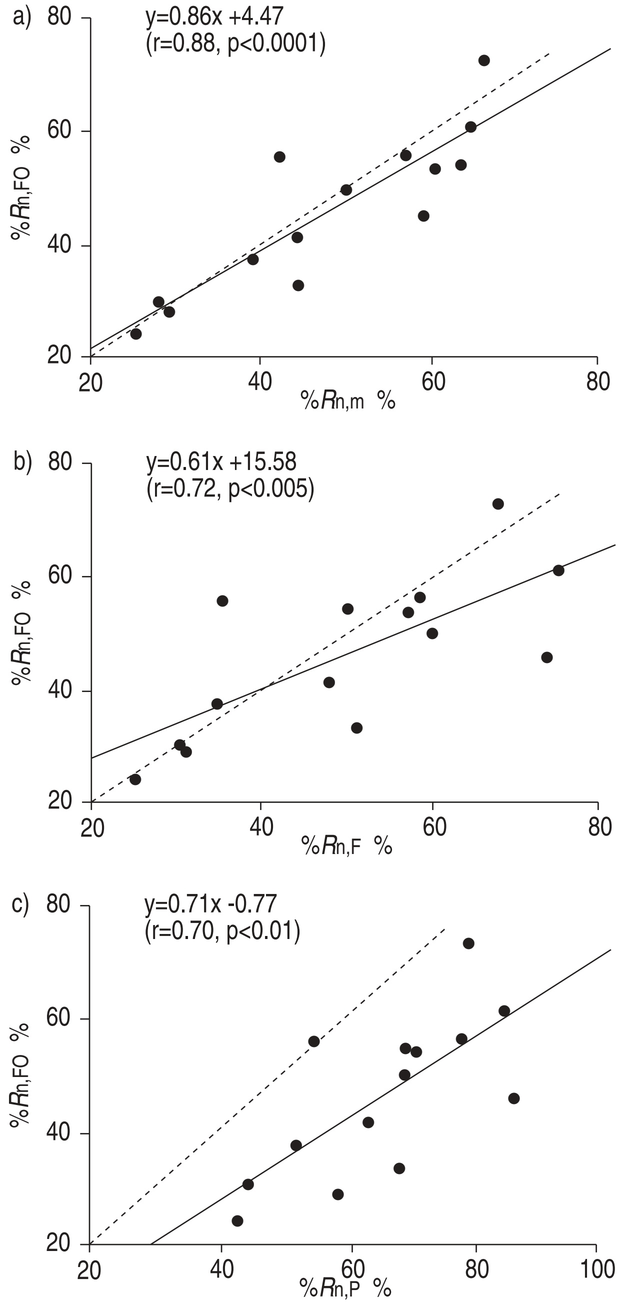

Fig. 5. – Decongestant-induced changes in nasal resistance measured by the forced oscillation technique (%*R*n,FO) plotted in relation to changes in nasal resistance measured by posterior rhinomanometry at a) the point of maximal inspiratory flow (%*R*n,m), at b) the 0.5 $L \cdot s^{-1}$ flow (%*R*n,F), and at c) the 1 hPa transnasal pressure (%*R*n,P). %*R*n,FO, %*R*n,m, %*R*n,F and %*R*n,P are expressed as a percentage of their corresponding basal values. ●: data from individual subjects; —— : regression lines; - - - - : identity lines.

flows were higher than *V*'m, and consequently were never reached dur-ing tidal nasal breathing. This shows that, in those subjects, *R*n,F and *R*n,P did not reflect a physiological value of nasal resistance. NAITO *et al.* [6] already observed that the 1 hPa transnasal P level was not reached in 24% of their patients, and suggested that *R*n,m might be an appropriate index of nasal patency.

Our *R*n,FO values were in the range of the *R*n values previously obtained with other FO techniques [1, 9, 11–14]. As previously observed in normal subjects [9, 11, 12], there was little or no frequency dependence of Re(*Z*n) in our subjects, which suggests that flows of small amplitude and high frequency tend to linearize the *P*-*V*' relationship of flow-dependent resistances [11, 15, 17].

The similitude and the correlations found here between *R*n,FO and the conventional *R*n estimates prove that *R*n can be assessed by the FO technique. Moreover, the small differences between *R*n,FO and *R*n,m, associated with a regression line of *R*n,FO *versus* *R*n,m nonsignificantly different from the identity line, show that *R*n,FO reflects nasal *R*n at *V*'m, *i.e.* maximal nasal resistance. This result, for which we have no direct explanation, is in accordance with the study by NAITO *et al.* [6] who showed that *R*n obtained by the time averaging method was similar to *R*n calculated at the point of *V*'m. Indeed, *R*n,FO represents a mean estimate of *R*n over several consecutive cycles of nasal tidal breathing. It should be possible to extrapolate this similarity between *R*n,FO and *R*n,m to respiratory resistance measured at the mouth, which might be physiologically interpreted as maximal respiratory resistance when nonlinearities occur.

In comparative studies of the subtraction FO method and the PR technique, no correlation was found between *R*n at 6 Hz on the one hand, and *R*n at 0.75 hPa and time-averaged *R*n on the other [1, 12]. The discrepancy between these results and ours, which cannot be attributed to the frequency retained for *R*n estimation, might be explained by the fact that these authors did not apply the FO and PR techniques simultaneously, and more likely, by the fact that they used a subtraction technique. Such a technique is based on the assumption that all parts of the respiratory tract are linear [11], and becomes unreliable when resistance is *V*'-dependent at the pharyngeal and/or laryngeal levels. We personally observed in some subjects that the subtraction and direct FO methods yielded conflicting results, probably due to changes in the tidal flow profile from nasal to mouth breathing. SHELTON *et al.* [1] and AKSAMIT *et al.* [12] suggested that their intermethod discrepancy might be due to the shunt impedance of the upper airway which differs when breathing *via* the nose and mouth. This seems improbable since BERDEL and KOCH [13] reported correlations between *R*n assessed by PR and by a variant of the subtraction FO technique [22] in subjects who breath-ed through a reference impedance, which probably lowered their tidal flow and thereby the influence of flow dependence on *R*n.

Decongestant

As previously observed [4, 8, 20, 23], decongestant treatment significantly decreased nasal K_1 and K_2 and the different *R*n estimates. These decreases were associated with a significant increase in *V*'P, as already reported for the nasal airflow corresponding to a 1.5 hPa transnasal pressure [4]. Equation 1 indeed shows that, for a given transnasal P value, any decrease in K_1 and K_2 results in an increase in the corresponding *V*' value. Consequently, *R*n,P reflects a *R*n in which the decrease in K_2 is partly counterbalanced by the increase in *V*'P, contrarily to *R*n,F, which is calculated for a fixed flow, and to *R*n,m, which is calculated for a *V*'m unaffected by nasal decongestion. This probably explains why after decongestant treatment, *R*n,P became higher than *R*n,F and *R*n,m. Interestingly, *R*n,FO and *R*n,m remained similar estimates of *R*n after nasal decongestion.

$\%R_{\mathrm{n,FO}}$, $\%R_{\mathrm{n,m}}$ and $\%R_{\mathrm{n,F}}$ were significantly lower than $\%R_{\mathrm{n,P}}$, thereby demonstrating a lower sensitivity of this latter index. This result is in accordance with the study by SHELTON *et al.* [1] who reported, following a vasoconstrictor treatment, $\%R_{\mathrm{n,FO}}$ values similar to our $\%R_{\mathrm{n,FO}}$, and $\%R_{\mathrm{n}}$ at a 0.75 hPa transnasal P, comparable to our $\%R_{\mathrm{n,P}}$. $\%R_{\mathrm{n,FO}}$ and $\%R_{\mathrm{n,m}}$ provided similar assessments of decongestant efficacy, which proves that $R_{\mathrm{n,FO}}$ and $R_{\mathrm{n,m}}$ are equivalent indices for the assessment of both nasal patency, either in the basal state or after topical decongestion, and vasoconstrictor efficacy. Thus, $R_{\mathrm{n,FO}}$ and $R_{\mathrm{n,m}}$, which both correspond to R_{n} actually measured during spontaneous nasal breathing, might be indifferently proposed as physiological indices of nasal patency.

In conclusion, our study shows that: 1) despite its flow dependence, nasal airflow resistance can be assessed by the forced oscillation technique provided a direct method is used; and 2) forced oscillation and posterior rhinomanometry then provide similar assessments of nasal resistance, both in the basal state and after decongestant inhalation. While both techniques require transnasal pressure measurement, the forced oscillation technique requires more sophisticated material and signal processing, and is much more sensitive to any air leak that may occur at the nasal mask or mouth-piece level. Therefore, all things considered, no specific advantage should be presently expected from the application of the forced oscillation technique to rhinology.

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