

Forced Oscillation Technique to Evaluate Tracheostenosis in Patients With Neurologic Injury*

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Study objectives: To determine the utility of forced oscillation technique (FOT) for measuring pulmonary resistance and reactance in patients with central nervous system injuries, for detection and follow-up of posttracheostomy tracheal stenosis.

Design: Case series.

Setting: A rehabilitation hospital, Brasília, Distrito Federal, Brazil.

Patients: Ten consecutive neurologically impaired patients, who had previously undergone tracheostomies, with tracheostenosis without current tracheostomy or other tracheal lesion.

Interventions and measurements: FOT evaluations were compared to tracheal diameter before and after bronchoscopic tracheostenosis dilatation procedures. Forced spirometry examinations were also obtained and compared.

Results: Tracheal stenotic lesions were characterized by marked increase in resistance and reduction in reactance at low frequency and a marked increase in resonance frequency (Rf). Consistent reversal of this pattern with large reductions in total impedance of the respiratory system (Zresp) Rf and resistance at 5 Hz (R 5 Hz) were noted in all patients after each successful dilatation. Diameter of the stenosis was strongly correlated with Rf, Zresp, and R 5 Hz. The change in diameter before and after dilatation was similarly correlated with the changes in FOT values of Rf and Zresp. Spirometry values did not correlate well with the diameter of the tracheal stenosis.

Conclusion: The strong correlation of Rf, Zresp, and R 5 Hz to diameter of tracheostenosis suggests a previously unappreciated role for FOT in the noninvasive detection and follow-up of airway stenosis. This may be especially useful for patients with concomitant neurologic disabilities who are at risk of airway stenosis. (CHEST 2001; 120:69–73)

Key words: brain injury; forced oscillation; pulmonary function testing; quadriplegia; spirometry; tracheostenosis

Abbreviations: ANOVA = analysis of variance; FOT = forced oscillation technique; *r* = correlation coefficients; Rf = resonance frequency; R 5 Hz = Rf and resistance at 5 Hz; Zresp = total impedance of the respiratory system

The Hospital SARAH Brasília is a tertiary referral center for neurologic, orthopedic, and rehabilitation medicine and surgery. Over 600 patients are admitted each year for the rehabilitation of cervical spine, cranioencephalic traumatic, vascular, and degenerative brain lesions. Oral-tracheal intubation occurs in 30% and tracheostomy in 10% of all patients with brain injuries who are later admitted to SARAH for rehabilitation. Cervical spine injury pa-

tients receive intubation in 42% of cases and tracheostomy in 29% of cases prior to transfer to this hospital. After admission to our hospital, 28% of brain injury patients and 27.5% of spinal cord injury patients who have had prior tracheostomy require operative intervention by dilatation alone or in combination with stent or tracheoplasty for stenosis of ≤ 8 mm of the trachea.

Other authors confirm a high frequency of tracheostomy use in neurologically injured patients.¹ Obstructive airway abnormalities are higher than expected in this patient population, leading to the recommendation to perform routine bronchoscopy in all patients with long-term tracheostomy.² Noninvasive diagnoses may be limited by the inability to perform or by the unreliability of forced expiratory pulmonary function tests.^{3–5} Noncooperation and

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metallic immobilization devices may similarly limit radiologic evaluations. General anesthesia to obtain bronchoscopic and radiologic studies places the patients at additional risk.

Our present study of the usefulness of forced oscillation technique (FOT) in tracheostenosis was suggested by our experience with a previously reported patient.⁶ Other authors have suggested another technique performed at quiet breathing during bronchoscopy for preoperative assessment of tracheal stenotic lesions.⁷ Our objective was to assess FOT as a potential screening and follow-up method, with a view to reducing the dangers of stenotic tracheal lesions at the time of diagnosis, while reducing the need for costly invasive and radiologic exams.

MATERIALS AND METHODS

During the period July 1, 1998 to August 1, 2000, 43 patients were diagnosed by bronchoscopy with cicatricial tracheostenosis of $\geq 50\%$ of the diameter of the trachea. All but one had undergone tracheostomy for airway management of the complications of neurologic disease or injury. Excluded from this analysis were patients in whom we encountered multiple lesions, such as chondromalacia, granulomas, open tracheostomy fistulas, and vocal cord paralysis concomitant with the tracheostenosis. The remaining 10 patients underwent FOT examinations before and after bronchoscopic dilatation of their stenosis and subsequent episodes of restenosis. Four of these patients were dilated on more than one occasion during the evolution of their stenotic lesions.

Endoscopic dilatation was performed with progressive insertion of pediatric and adult rigid bronchoscopes. The length, and the anterior, posterior, and transverse dimensions of the stenosis were measured directly by inserting a foreign body forceps during bronchoscopy both before and after dilatation. The forceps were locked, and the opening was measured against a scale in millimeters. The average of the measured transverse and anterior posterior values was used for the value of the diameter. The visualized point of minimal diameter was chosen as the measurement point for diameter. The length of the stenosis could not always be accurately visualized prior to dilatation, especially in the tighter stenoses. Thus, length was determined after dilatation. Two authors (T.H. and L.A.) jointly performed and confirmed each bronchoscopic measurement in all 10 cases.

The diameter of the immediate postdilatation stenosis was assumed to be the diameter of the stenosis at the time of the postdilatation FOT examination. Because of the possible effect of tissue elasticity and edema following dilatation, the measurement of FOT occurred as soon as possible within the first 24 hours subsequent to the procedure. One patient had an endotracheal metallic expandable stent placed at the time of dilatation. In this case, the internal diameter of the stent was used as the postdilatation diameter of the stenosis. This diameter measurement was verified as unchanged at a subsequent unrelated follow-up bronchoscopy examination.

FOT and pulmonary function tests were conducted using combined spirometry and FOT equipment (IOS; Erich Jaeger GmbH; Hoechberg, Germany). A standardized examination was conducted in all patients. No premedication prior to the FOT examinations was used. No patient reported a prior history of asthma or other chronic pulmonary disease. No patient had used tobacco products subsequent to their injury. The FOT examina-

tions were obtained with the patient breathing quietly while seated in a chair or hospital bed. Nasal clips and manual compression of the cheeks were used to reduce the confounding factors of cheek vibration and escape of air via the nostrils. Spirometry examinations were conducted immediately following the FOT examination, but on eight occasions, the patients were not able to follow the instructions for the forced maneuvers.

The FOT parameters were compared with the known tracheal diameters documented by bronchoscopy. Analyses were performed to obtain analysis of variance (ANOVA) values, linear regression models, *p* values, and correlation coefficients (*r*) using StatView software (SAS Institute; version 5.0.1; Cary, NC). Initially, the measurements from the first dilatation episode of each patient were analyzed. To test reliability of the technique during repeated episodes of stenosis, all measurements from all patients were included for analysis. The analysis was adjusted to avoid disproportionate influence from the four patients having multiple dilatations. This was done by determining the range of correlation of the values of FOT and tracheal diameter for all possible combinations containing only a single episode from each patient. Analyses of these 71 scenarios were conducted in exactly the same way as the first. The values obtained were then tested for equality.

RESULTS

The 10 patients (Table 1), 7 men and 3 women, ranged in age from 13 to 55 years, with a mean of 26.3 years. The diameters of the tracheal stenosis ranged from a minimum of 2 mm before and a maximum of 13 mm after dilatation. Length of the stenosis varied from 3 mm to 3 cm. Principal admission diagnosis was tetraplegia in four patients and brain injury in five patients. One patient suffered combined cervical spine and brain injury.

Tracheal diameter was strongly correlated with resonance frequency (*R_f*) of the FOT examinations ranging from $r = -0.91$ to $r = -0.80$ (Fig 1). The values for total impedance of the respiratory system (*Z_{resp}*; $r = -0.87$ to $r = -0.69$) and *R*/5 Hz ($r = -0.87$ to $r = -0.69$) were just slightly less discriminating than *R_f*. Reactance at 5 Hz was not consistently correlated with tracheostenotic diameter ($r = -0.48$ to $r = -0.08$). The FVC, when obtainable, was not correlated to tracheostenotic diameter ($r = 0.47$ to $r = 0.40$). FEV₁ bore a weak correlation to tracheostenotic diameter ($r = 0.58$ to $r = 0.54$). Length of the stenosis bore no significant relationship to any of the FOT values. The significant results are summarized in Table 2.

The analysis of the slope of the regression analysis of all scenarios showed statistical equality. Figure 1, containing all measured points of *R_f*, shows the narrow band within which the slopes of the regression curves all reside, from the best to the poorest. The intercepts of all regressions occurred between 49.2 and 53.9 Hz. The slopes of all 72 regression curves (-3.33 to -3.50) were statistically equal. The analyses of *Z_{resp}* and *R_f* and resistance at 5 Hz (*R* 5

Table 1—Patients*

Patient No.	Age, yr/sex	No. Dilatations	Diagnosis	No. of Days of Intubation and Tracheostomy†	Before/After First Dilatation			
					Diameter (mm)	Rf (Hz)	FVC (L)	FEV ₁ (L)
1	13/F	4	ABI	5‡	2.0/12.0	44/8	1.7/2.8	0.5/2.2
2	28/F	2	TBI	20	3.5/11.0	41/22	NA	NA
3	48/M	1	TBI	90	5.0/11.0	37/13	NA	NA
4	55/M	1	C4	165	6.0/10.5	22/11	2.3/2.7	1.4/1.6
5	20/M	3	C2 + TBI	30	4.5/11.0	39/24	1.5/1.6	0.7/1.0
6	15/M	3	C6	42	4.0/12.0	37/5	1.9/2.1	0.8/1.0
7	26/M	1	C4	89	10.0/12.0	11/9	3.8/3.4	3.4/2.9
8	17/M	1	C4	344	5.0/11.0	28/7	1.3/1.5	0.9/1.5
9	26/M	1	TBI	201	5.0/10.0	44/14	NA	NA
10	15/F	1	TBI	43	5.0/10.0	36/27	NA	NA

*M = male; F = female; ABI = anoxic brain injury; TBI = traumatic brain injury; C2, C4, C6 = the level of cervical spinal trauma; NA = not applicable.

†Length of time with oral tracheal intubation plus tracheostomy is measured in days.

‡This patient had only oral tracheal intubation.

Hz) were also found to be statistically equal for all of the 72 possible combinations (Table 2). Thus, the marked correlation noted above held true for all combinations of data.

For every increase of 1 mm in the diameter, resulting from dilatation of the stenosis, there was an average decrease in Rf of 2.8 Hz and a reduction of Zresp of 0.11 kPa/L/s. The change in Rf and Zresp correlated strongly to the changes in diameter ($r = 0.82$, $p < 0.0001$ and $r = 0.53$, $p = 0.03$, respectively).

DISCUSSION

The FOT described by Dubois et al⁸ in 1956 has been used for pulmonary function studies in children,⁹ veterinary medicine,¹⁰ and epidemiologic studies.¹¹ Wassermann et al⁷ have presented another technique, using local pressure and flow measurements during bronchoscopy to discriminate between stenoses requiring surgery and those not requiring surgery. We are not aware of any prior studies demonstrating the use of FOT for the noninvasive diagnosis or follow-up of tracheal stenosis. This is likely due to the long experience gathered with spirometry, peak expiratory flow volumes, and flow volume loops.¹² These tests obviate any need for FOT in most clinical situations. However, when patients cannot cooperate nor perform the forced respiratory maneuvers, some other method of evaluation is necessary. This may mean diagnostic bronchoscopy or tomographic evaluation of the upper airway, frequently requiring general anesthesia and exposing these patients to additional risks.

FOT, on the other hand, consists of breathing quietly into a system within which a loudspeaker creates superimposed oscillations. Data collection is

rapid and noninvasive and can be obtained easily at the bedside. The driving oscillatory pressure results in flow oscillations whose magnitude and phase are determined by the resistive, elastic, and inertial properties of the respiratory system. Pressure and flow are then measured at the mouth with a differential pressure transducer and pneumotachograph. Resistance is calculated from the ratio of pressure changes at the mouthpiece to the changes in flow generated by the oscillating loudspeaker diaphragm. Measurement is done over a range of frequencies between 5 and 35 Hz.

The basic parameters of FOT are total respiratory impedance, which is the sum of resistance and reactance. Resistance represents the total resistance of all the airways, pulmonary parenchyma, and chest wall to the oscillatory flow generated by the loud-

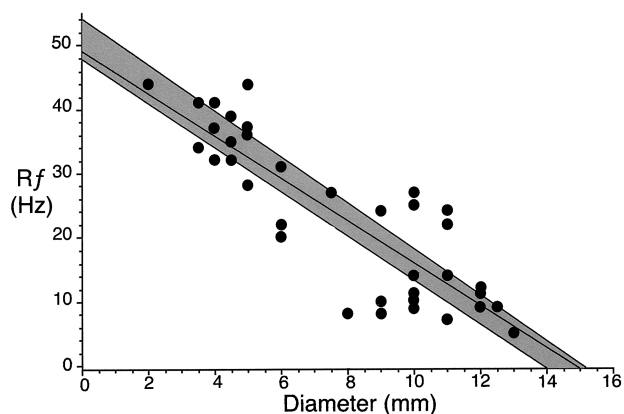


FIGURE 1. Tracheal diameter correlated with Rf. Diameter = diameter of stenosis in millimeters (mm); gray band is the area within which all regression curves of Rf reside vs diameter; black line is the overall regression curve of Rf (all episodes of each patient taken together).

Table 2—Correlation of FOT and Spirometry With Diameter of Stenosis*

		Rf	Zresp	R 5 Hz	X 5 Hz	FVC	FEV ₁
First dilatation	<i>r</i>	−0.89	−0.87	−0.87	0.15	0.48	0.58
	CI 95%	−0.96 to −0.73	−0.95 to −0.70	−0.95 to −0.70	−0.32 to 0.50	−0.13 to 0.83	0.01 to 0.87
	<i>p</i>	<0.0001	<0.0001	<0.0001	0.05	0.11	0.05
Best scenario	<i>r</i>	−0.91	−0.87	−0.87	0.48	0.48	0.48
	CI 95%	−0.97 to −0.79	−0.95 to −0.70	−0.94 to −0.69	−0.14 to 0.68	−0.15 to 0.82	0.01 to 0.87
	<i>p</i>	<0.0001	<0.0001	<0.0001	0.05	0.12	0.05
Poorest scenario	<i>r</i>	−0.80	−0.69	−0.69	0.08	0.40	0.54
	CI 95%	−0.92 to −0.56	−0.87 to −0.36	−0.87 to −0.36	−0.37 to 0.50	−0.28 to 0.80	−0.09 to 0.86
	<i>p</i>	<0.0001	0.0007	0.0007	0.72	0.24	0.09
Overall	<i>r</i>	−0.86	−0.80	−0.80	0.41	0.32	0.50
	CI 95%	−0.92 to −0.73	−0.89 to −0.64	−0.89 to −0.64	0.09 to 0.64	−0.11 to −0.65	0.10 to 0.75
	<i>p</i>	<0.0001	<0.0001	<0.0001	0.02	0.14	0.02

*X = reactance at 5 Hertz; CI 95% = 95% confidence interval.

speaker at a given frequency. Reactance expresses the capacitance of the respiratory system in its bronchopulmonary elasticity and the inertia of the bronchial air column.¹³ The Rf is the frequency at which point reactance is zero, which is the frequency at which inertial, and compliance effects cancel one another out. A review of the current understanding of methodology and the potential benefits and drawbacks of FOT compared with other methods of pulmonary function was previously presented in *CHEST*.¹⁴

Other authors have demonstrated dramatic physiologic compromise developing when tracheal diameter was between 6 and 8 mm.^{15,16} Therefore, a diameter of tracheal stenosis of ≤ 8 mm was chosen to define severe stenosis. We found Rf to be the FOT measurement best correlated with the diameter of tracheal stenosis (Fig 1). Rf was also found to discriminate well between diameter of stenosis above and below 8 mm. No case of severe stenosis (tracheal diameter < 8 mm) was encountered at levels of Rf < 20 Hz. Above an Rf value of 20 Hz, 17 of the 22 measurement values were associated with severe stenotic lesions. Our data suggest that, in patients encountered with initial values of Rf in excess of 20 Hz, we must view those values with suspicion and must give the benefit of further careful investigation to exclude upper airway obstruction. The sensitivity of Rf measurement to modest differences in tracheal diameter, as demonstrated, may be useful for the follow-up of changes in diameter of known stenotic lesions. This capability was demonstrated in our index case reported earlier.⁶

The relationship of respiratory resistance to tracheal stenotic diameter is most marked at low frequencies. As frequency rises, the measured resistance falls. The tighter the stenosis the wider the range of frequencies with elevated resistance. As reactance is a reflection of pulmonary elastic capac-

itance and inertia, the reduction in reactance is probably based solely on the expression of the low capacitance of the cartilaginous upper airway. The pulmonary components, presumably unexpressed prior to dilatation, are unmasked after the dilatation of the stenosis. These changes are manifest in the characteristic graphical representation shown in Fig 2. (The crossed curves associated with upper airway obstruction call attention to the diagnostic possibilities. Subsequent to successful dilatation of a stenotic lesion, these changes are reversed and the curves of the graph open, as the reactance at low frequency rises toward normal as the pulmonary components are manifest; simultaneously, resistance falls toward

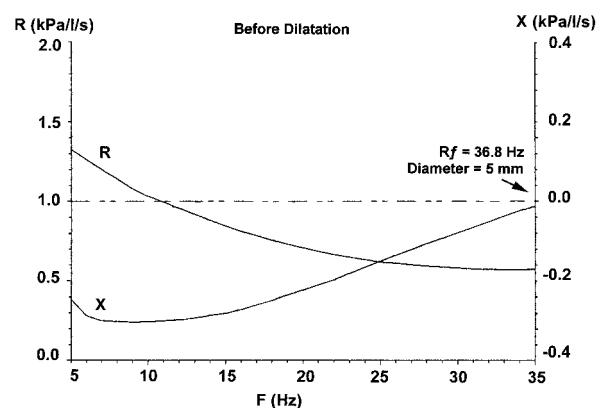


FIGURE 2. Diagram of the values before the first dilatation of case 3 of Table 1. In patients with severe stenosis, the graphs of FOT prior to dilatation show elevation of resistance (R) and reduction of reactance (X) at low frequencies. The curves change toward normal as frequency rises. The point at which the graph of X crosses the zero reference line, indicated by the arrow, is the measurement of Rf. In severe stenosis, this was consistently > 20 Hz. Recurrence of this pattern was consistently associated with recurrence of the stenosis in our patients. R(kPa/L/s) = scale of resistance in kilo Pascals per liter per second; X (kPa/L/s) = scale of reactance in kilo Pascals per liter per second; F = frequency; R = curve of resistance; X = curve of reactance.

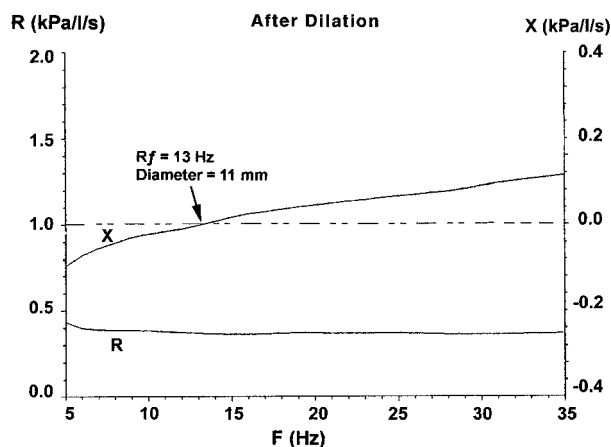


FIGURE 3. Diagram of the values after the first dilatation of case 3 of Table 1. Following dilatation of the stenosis, the curves for reactance (X) and resistance (R) assume a normal configuration as shown. As the curve of reactance crosses the zero reactance reference line at a lower frequency (arrow), the value of R_f falls within normal. See Figure 2 for abbreviations.

normal (Fig 3). In this series of cases, each time a pattern similar to the one in Fig 2 recurred after an interval following a prior dilatation, it was associated with restenosis confirmed at the subsequent bronchoscopy. This supports the findings demonstrated in our previously reported case.⁶

CONCLUSION

The demonstrated sensitivity of the FOT values of R_f , Zresp, and $R/5$ Hz may allow a role in predicting the presence of an upper airway stenosis in patients with prior airway intubation and tracheostomy. Once an airway lesion has been confirmed as a cicatricial stenosis, FOT values, especially R_f , may be used as a follow-up device. It may allow the timing of intervention to be based on deterioration in R_f . FOT may be especially useful in evaluating and following up tracheal stenosis for patients whose disabilities hamper the usefulness of other methods of evaluation.

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