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ORIGINAL ARTICLE

Flextube reflectometry for localization of upper airway narrowing—a preliminary study in models and awake subjects

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Abstract The aim of this study was to examine an acoustic reflection method using a flexible tube for identifying the obstructive site of the upper airway in snorers and patients with obstructive sleep apnoea (OSA). As a preliminary study it was performed in models and subjects in the awake state. Flextube narrowing was produced in a model of the nose and pharynx and three blinded observers assessed the obstructive level. The correlation between pharyngeal narrowing assessed by endoscopy and by acoustic measurement during Müller manoeuvres was also examined in 10 OSA patients and 11 healthy, non-snoring, adults. Three blinded observers identified the level of 176 of 180 random cases of flextube narrowing in a polycarbonate model correctly. The level of narrowing was always correctly evaluated within 1·9 mm. Pharyngeal area decrease was measured by the flextube method during the Müller manoeuvre but it was not closely related to the findings by endoscopy. In conclusion the flextube reflectometry method was able to demonstrate narrowing in a model of the nose and pharynx in a precise way. Narrowing was also observed during Müller manoeuvres. Flextube reflectometry may be a promising method to detect upper airway narrowing but further evaluation during sleep is required.

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Keywords sleep apnoea; acoustics; diagnosis; upper airway.

INTRODUCTION

Obstructive sleep apnoea (OSA) is caused by collapse of the upper airway during sleep. The dilating force of the pharyngeal muscles is reduced during sleep (1,2), which decreases the airway size and increases the upper airway resistance (3,4). Structural narrowing has been identified in the majority of OSA patients using magnetic resonance imaging (MRI) and computed tomography (CT) scanning (5–7).

The treatment of choice for OSA is continuous positive airway pressure. However, surgery may be used to enlarge the upper airway in some patients (8). Uvulopalatopharyngoplasty (UPPP) has been performed to treat OSA. It is based on removal of the uvula and a margin of the soft palate to increase the area of the retropalatal airway. However, this surgical procedure is effective in treating OSA in less than 50% of patients (9). Serious complications are rare, but prolonged discomfort when swallowing is reported by more than 10% after UPPP (10). The site of pharyngeal collapse is a significant prognostic factor for success from surgery (9). However, a simple and effective technique for clinical use to identify the site of narrowing or collapse of the upper airway has not been described. At present, simple visual inspection, pressure measurements, fiberoptic endoscopy, cephalometry, fluoroscopy, acoustic reflections, MRI and CT scanning are all in use for investigating the upper airway. None of these methods have been validated for identifying the site of obstruction. Research has therefore recently been encouraged to obtain and validate effective techniques (11).

The purpose of this study was to describe and examine a new method for localization of upper airway narrowing based on acoustic reflections in a flexible tube. Primarily for ethical and legal reasons this first examina-

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tion of the technique was performed in models and awake subjects.

METHODS

The acoustic reflection system

The acoustic device (SRE 2000, RhinoSleep version 2.2.0.0, RhinoMetrics, Lynge, Denmark) consisted of a portable computer and a miniprobe; a small and light metal rod (10 cm and 70 g), attached to a flexible tube (RhinoFlex Tube) as shown in Fig. 1. The computer contained a 24-bit digital signal processor (DSP) and an analogue to digital (A/D) and digital to analogue (D/A) converter.

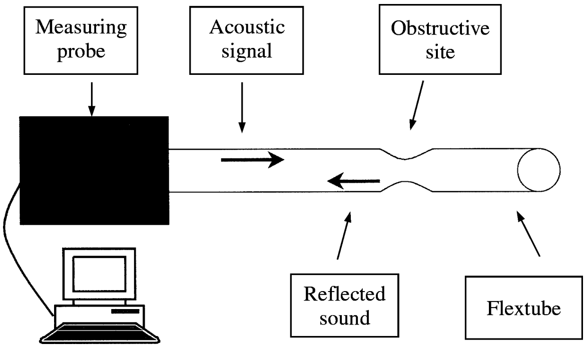

Fig. 1. The flextube reflectometry system. A continuous white band noise was generated in the probe and sent into the flextube. When the flextube was narrowed the noise was reflected. A microphone in the probe recorded the reflected sound. The distance to the flextube narrowing and the duration and degree of the narrowing were calculated by the measuring system and graphically illustrated by the software.

The proximal part of the flextube, placed in the nose, was relatively thick walled (0·7 mm, shore 64A, PVC). The distal part of the flextube (55 cm), which was placed in the pharynx and esophagus, was thin-walled (wall thickness 0·2 mm). It was made of soft PVC (shore 38A). 'Shore' specifies a method for the determination of the indentation hardness of plastics and ebonite by means of durometers of two types: type A is used for softer materials and type D for harder materials. The diameter of the flextube was 5·2 mm. The flextube was closed at the distal end. The probe generated a continuous white band noise signal characterized by a bandwidth from 125 to 20 000 Hz, which was measured by a microphone.

The software performed a statistical comparison of the generated noise and the measured noise providing information concerning the internal diameter of the flextube when narrowing of the upper airway occurred (Fig. 1).

The user interface depicted the actual state of the flextube by presenting graphs five times per second (Fig. 2). These graphs were saved in the computer allowing studies of the duration, degree and localization of flextube narrowing. The flextube was also studied after importing the raw data into a spreadsheet. We used graphs from the user interface for the *in-vitro* experi-

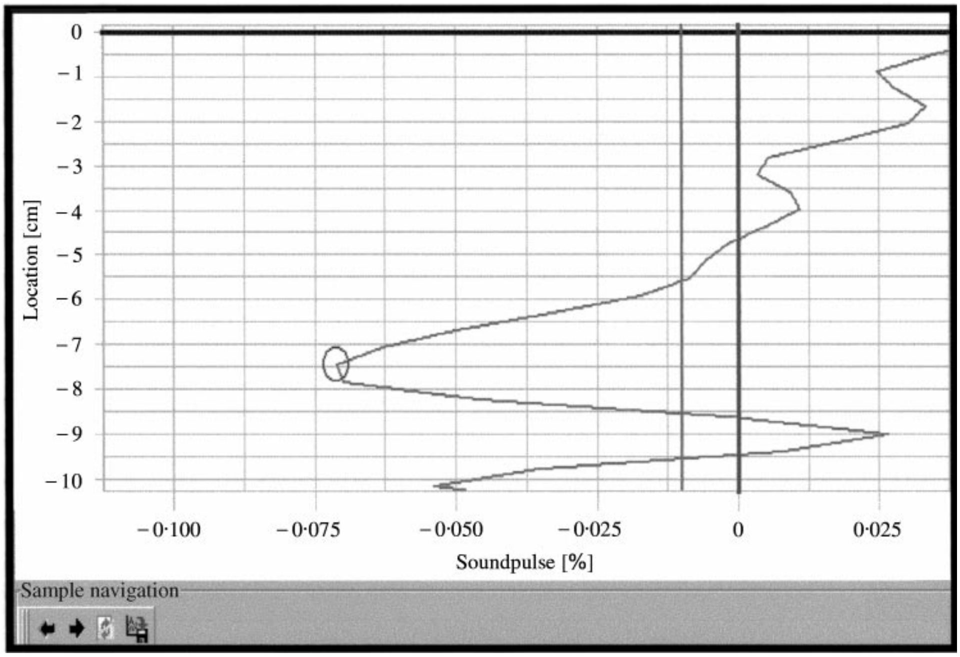

Fig. 2. Graphs were produced by the user interface of the acoustic device five times $\sec^{-1}$. The degree of flextube narrowing was plotted for every 3·8 mm of the flextube on the graph. Narrowing resulted in a deflection to the left. The degree of narrowing was illustrated by the size of the deflection. The maximum narrowing (marked with a circle) at this instant was located 7·5 cm from the zero-point (the posterior border of the nasal septum). By pointing on the arrow button, it was possible to scroll between graphs.

ments. The subjects were studied during wakefulness by analysis of the raw data imported into a spreadsheet.

Flextube narrowing *in vitro*

Measurement of duration and localization of flextube narrowing

The flextube was pinched off 5 cm from the zero point. This way we produced 20 total occlusions of 12–57 sec duration. The maximum difference between actual and acoustically measured duration of the occlusions was determined. The 95% limits of agreement were calculated (12). These limits represent the mean difference ±2 standard deviations (SD) of the differences.

Similarly, we produced 48 total occlusions 0–9 cm from the zero point and the distances were determined. The zero point of the flextube was defined as the crossing between the thick walled and thin walled part of the flextube (Fig. 3).

We also narrowed the flextube increasingly by a slide gauge 10 cm from this zero point. This made it possible to study the size of the resulting acoustic graphs.

Flextube narrowing in a polycarbonate model

The flextube was placed in a polycarbonate model, as shown in Fig. 3, of the nose and pharynx, made by a technique previously described (13). Digital narrowing was performed 60 times in random order while acoustic measurement was made. The narrowing was partial, and it was attempted to perform narrowing in a consistent way. Four categories of digital narrowing were applied: no narrowing, narrowing at the retropalatal level only, narrowing at the retrolingual level only, and finally narrowing at both levels simultaneously. We performed 21 cases of double narrowing. Three blinded observers scored the acoustically produced graphs. The assessments of the graphs by the three observers (180 assessments) were compared to the actual type of narrowing. The number of incorrect assessments was determined.

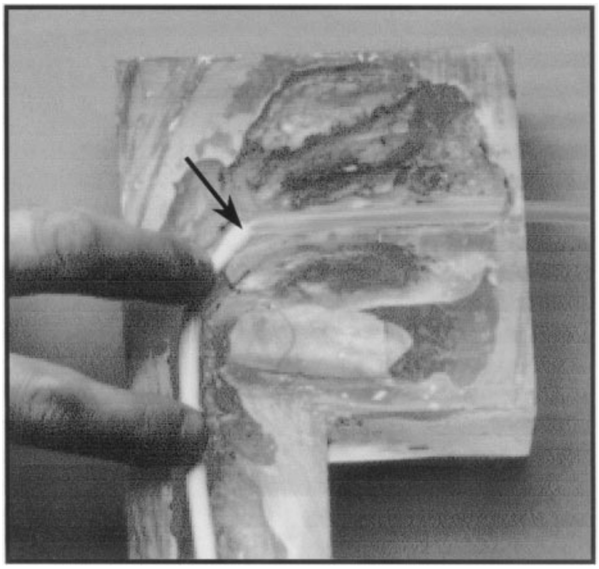

FIG. 3. Polycarbonate model of the nose and pharynx. Digital narrowing was performed 60 times in random order while acoustic measurements were made. Afterwards, three blinded observers assessed the resulting graphs. The agreement between the actual and the assessed level of the narrowing was studied. The arrow is pointing at the crossing between the thick walled and thin walled part of the flextube—the zero-point. This was located at the posterior border of the nasal septum.

Flextube narrowing *in vivo*—before and during the müller manoeuvre

Subjects

We performed flextube measurements during wakefulness on 10 severe OSA patients (diagnosed by Compumedics W-series, Sleep V2, Abbotsford, Australia or AutoSet, version 3.03, ResMed Ltd., North Ryde, Australia) currently treated with continuous positive airway pressure. A control group, consisting of 11 healthy, non-snoring adults was also investigated. All subjects were interviewed concerning their general health and sleep habits and they had a full medical examination. The participants gave their informed consent prior to the study, which was approved by the local Ethics Committee. The study was performed in accordance with the Declaration of Helsinki.

Placing of the flextube and measurements during the Müller manoeuvre

The zero point of the flextube was defined as the crossing between the two parts. The crossing was placed exactly at the posterior end of the nasal septum (Fig. 3). This point was located by fiberoptic endoscopy and also the distance to the epiglottis was measured. After Xylocain spray (10 mg dose^{-1}) was applied to the pharynx and the flextube was lubricated by lidocain gel (2%) it was inserted with the aid of an internal guide wire and fixed to the external nose.

The supine patients were asked to perform the Müller manoeuvre. This manoeuvre consisted of a forced inspiratory effort against a closed mouth and nose. To avoid narrowing of the flextube in the nose during the Müller manoeuvres we used a rubber ring (diameter 1·9 cm, length 2·2 cm) with a hole (diameter 5·2 mm) in the centre enclosing the flextube where it passed the nasal vestibule.

The maximum difference between the oropharyngeal pressure (Po) and the atmosphere pressure (Patm) was measured during three Müller manoeuvres. For this pur-

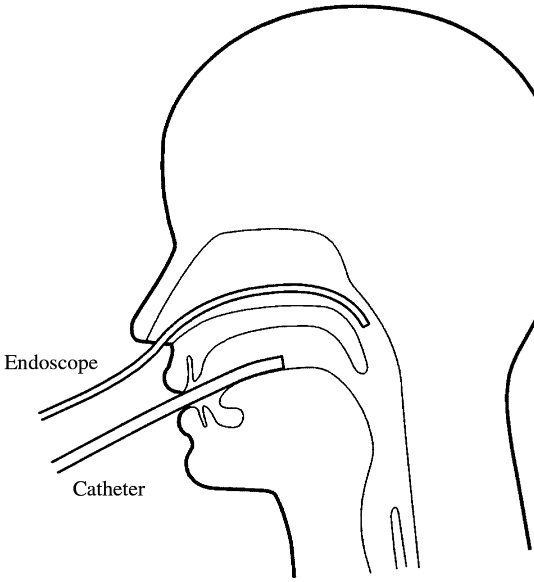

Fig. 4. The participants in the study underwent fibreoptic nasopharyngoscopy with the Müller manoeuvre. At first, the retrolingual pharynx was visualized by placing the endoscope behind the tongue and the patients were asked to perform the Müller manoeuvre three times. After that the endoscope was withdrawn to the level above the soft palate to visualize the velopharynx during three Müller manoeuvres. A catheter connected to a water column measured the pressure in the oropharynx. The maximum difference between the oropharyngeal pressure (*P*o) and the atmosphere pressure (*P*atm) during the Müller manoeuvres was measured.

pose we placed a thick-walled catheter connected to a water column (Fig. 4) in the mouth of the subject measuring the *P*o. To standardize the manoeuvres we decided that the median pressure difference (*P*o — *P*atm) during three Müller manoeuvres had to be of a comparable size for each participant before and after the introduction of the endoscope or flextube.

The mean difference between narrowing of the flextube for 6 sec before and during the Müller manoeuvre was calculated for the retropalatal and retrolingual pharynx respectively (Fig. 5).

Fibreoptic nasopharyngoscopy (using an Olympus ENF type P2 endoscope) was performed during the Müller manoeuvres by the same two 'blinded' experienced investigators. The endoscope was inserted through one of the nostrils, while the patients were supine and in the awake state. Both nostrils were occluded.

At first, the retrolingual pharynx was visualized by placing the endoscope behind the tongue and the patients were asked to perform the Müller manoeuvre three times. After that the endoscope was withdrawn to the level above the soft palate to visualize the velopharynx during three Müller manoeuvres. The pressure in the oropharynx was measured as described above (Fig. 4).

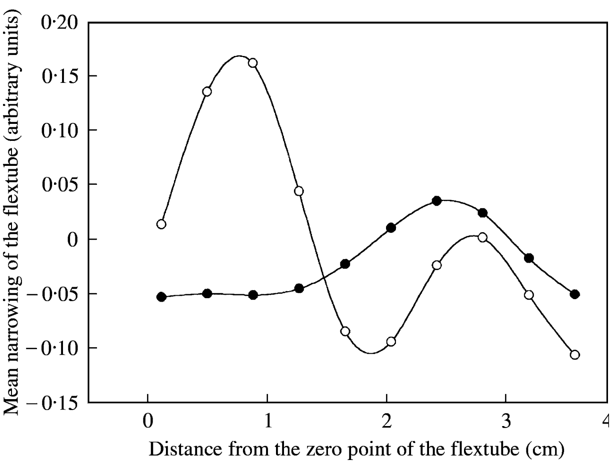

Fig. 5. Flextube reflectometry on a normal subject during wakefulness. Narrowing of the flextube from the zero-point (the posterior border of the nasal septum at 0 cm) to the inferior border of the soft palate (at 3·6 cm). Mean narrowing for 6 sec before (●) and for 6 sec during (○) three Müller manoeuvres. The difference between maximum of the mean narrowing before and during the Müller manoeuvres was 0·13 arbitrary units.

The two observers assessed the approximate percentage decrease in cross-sectional area at both levels of the pharynx during three video-recorded Müller manoeuvres. The percentage decrease in cross-sectional area was used to classify the video-recorded endoscopies in a similar way to Sher: 0=no area decrease; 1=1–49% decrease; 2=50–74% decrease; 3=75–99% decrease; 4=100% obliteration of the airway (14).

Inconvenience by the noise during flextube reflectometry

To measure the sensation level of the noise during flextube reflectometry we used a silent chamber and an audiometer (Orbiter 922, Version 2, Clinical Audiometer; Madsen Electronics, Denmark). The audiometer was connected to a calibrated loudspeaker system placed 1·5 m in front of a normal hearing person (CEF). The audiometer provided the loudspeakers with white noise. The test person compared the noise from the loudspeakers with the noise from the flextube and probe by adjusting the noise from the loudspeakers to the same level. Meanwhile he was breathing quietly with his mouth closed or open or he made swallowing movements.

Data analysis

Medians and inter-quartile ranges were used for descriptive purposes. Ninety-five per cent limits of agreement were calculated to describe the ability of the flextube method to measure duration and localization of obstructions (12). Paired *t*-tests were used to examine variations in the median pressure difference (*P*o − *P*atm) during the Müller manoeuvres before and after the introduction of the flextube or the endoscope. We used Cohen's Kappa statistics to describe the agreement between two observers who assessed the area decrease during Müller manoeuvres by endoscopy.

The correlation between the endoscopic assessment of the pharynx cross-sectional area and the acoustic measurement of flextube narrowing during Müller manoeuvres was tested using Spearman's rank correlation coefficient.

The correlation between the median pressure difference (*P*o − *P*atm) and the acoustic measurement of flextube narrowing during Müller manoeuvres was tested using Spearman's rank correlation coefficient. Statistical analyses were carried out with the aid of SPSS for windows, version 8·0. Significance was accepted at $P < 0{\cdot}05$.

RESULTS

Flextube narrowing *in vitro*

The maximum difference between actual and acoustically measured duration of manual occlusions of the flextube was 0·6 sec. The 95% limits of agreement between actual and acoustically measured duration were −2% and 1%. This means that the acoustically measured duration would be between 2% below and 1% above the actual duration for 95% of observations.

The maximum difference between the actual and the acoustically measured distance to a flextube occlusion was 1·9 mm. The 95% limits of agreement between actual and acoustically measured distance were −2·1 mm and 2·7 mm.

The acoustic measurement of a gradually increasing narrowing by a slide gauge, placed 10 cm from the zero point is shown in Fig. 6. The influence of a proximal narrowing on the acoustic measurement of a total distal occlusion is seen in Fig. 7. This experiment was also performed with a partial narrowing (39% of maximum narrowing) distally and the resulting graph had a similar shape.

It was possible to recognize a double narrowing whenever there was a minimum of 0·6–1 cm between the two points.

Three blinded observers assessed the level of narrowing in a polycarbonate model correctly in 176 of 180 cases. Four of 63 assessments of double narrowings were incorrect. In these four cases the observers were able to identify the narrowing at the retropalatal level but not at the retrolingual level.

Flextube narrowing *in vivo*—before and during the Müller manoeuvre

The 11 normal persons (eight males and three females) reported themselves as healthy, non-snoring and with normal sleep habits. They had a median score on the Epworth Sleepiness Scale of 4 (interquartile range: 1·5–5·75). The 10 OSA patients (nine males and one female) had a median apnoea/hypopnea index (AHI) of 40·5 (interquartile range 37–56·3). Age and body mass index (BMI) of the normal persons and the patients are shown in Table 1.

The median pressure difference (*P*o − *P*atm) between the oropharyngeal pressure (*P*o) and the atmosphere pressure (*P*atm) during the Müller manoeuvres was not affected by the flextube or endoscope (Table 2).

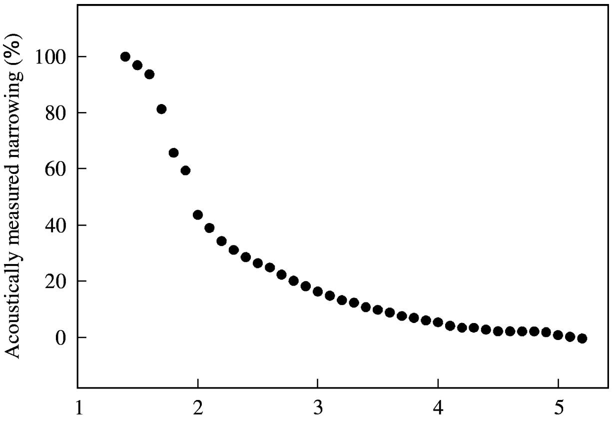

FIG. 6. Flextube reflectometry. Acoustically measured narrowing (percentage of maximum narrowing) 10 cm from the zero point when the diameter of the slide gauge was gradually increased. When the diameter of the slide gauge reached 5·2 mm, the acoustically measured narrowing fell to zero.

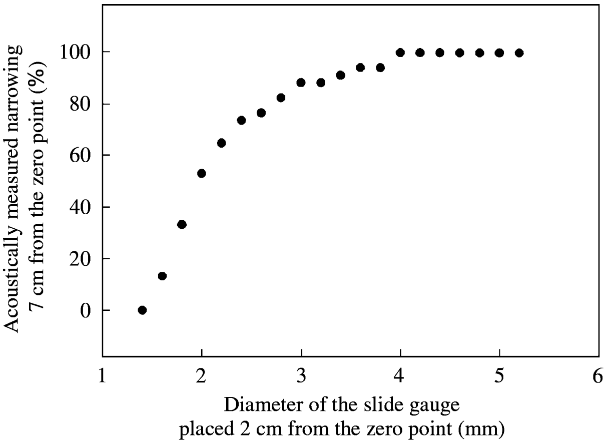

FIG. 7. Flextube reflectometry. The flextube was constantly occluded 7 cm from the zero point. The diameter of the slide gauge at 2 cm was gradually increased while the occlusion 7 cm from the zero point was measured acoustically (percentage of maximum narrowing).

TABLE 1. Characteristics of the OSA patients and normal subjects

	OSA patients (n=10)	Normal people (n=11)
Age (years)	50·9 (41·7–61·6)	32·9 (31·1–35·2)
BMI (kg m^{-2})	32·5 (28·8–38·1)	23·8 (21·6–25·6)

Values are medians (interquartile range).
BMI: body mass index=weight. height^{-2} (kg m^{-2}); OSA: obstructive sleep apnoea.

TABLE 2. Median pressure difference (Po − Patm) between the oropharyngeal pressure (Po) and the atmosphere pressure (Patm) during three Müller manoeuvres performed by 10 OSA patients and 11 normal subjects (n=21)

	Median	25%/75% range
Po − Patm (cm H_2O) without flextube or endoscope	−60	−55/−73
Po − Patm (cm H_2O) with endoscope	−62	−52/−72
Po − Patm (cm H_2O) with flextube	−68	−53/−73

TABLE 3. Agreement between two observers assessing the approximate percentage decrease in cross-sectional area from video-recorded fiberoptic endoscopies of 21 subjects. The area decrease was assessed at two levels of the pharynx, giving 42 video-recorded endoscopies

	Observer A					
Observer B	0	1	2	2	4	Total
0	2	2				4
1	1	7	2	1		11
2		1	4	3		8
3		1	1	4	2	8
4				1	10	11
Total	3	11	7	9	12	42

0=no cross-sectional area decrease; 1=1–49% decrease; 2=decrease of the cross-sectional area by 50–74%; 3=decrease by 75–99%; 4=complete obliteration of the airway.

The two observers agreed on the extent of narrowing in 27 of 42 video-recorded endoscopies and disagreed in 15 endoscopies (Table 3). The agreement was good at the retropalatal level where the observers agreed on 16 of 21 video-recorded endoscopies (κ=0·63). The agreement was fair at the retrolingual level where the observers agreed on 11 of 21 video-recorded endoscopies (κ=0·3).

The correlation between flextube narrowing and cross-sectional area decrease assessed by endoscopy during the Müller manoeuvre was not statistically significant (Spearman's r=0·28, P=0·07 and Spearman's r=0·24, P=0·12, respectively). The correlation between flextube narrowing and the magnitude of the median pressure difference (Po–Patm) during the Müller manoeuvres was also statistically non-significant (Spearman's r=−0·04, P=0·85 and Spearman's r=−0·06, P=0·79 respectively).

The flextube tended to maintain a circular or slightly oval profile when it was placed in the upper airway during normal breathing evaluated by endoscopy.

Some patients reported discomfort during the introduction of the flextube especially in the nose, but they all accepted the presence of flextube and none of the flextube measurements had to be discontinued. No cases of epistaxis or mucosal tears were observed.

The calibrated sensation level of the noise from the flextube and measuring probe was 10 dB SL read from the audiometer when the normal hearing person was breathing quietly with his mouth closed. The perception of the noise was unchanged when he opened his mouth and during swallowing movements. The noise from the flextube and measurement probe did not disturb his sleep.

DISCUSSION

This study describes a new investigative method, flextube relectometry, to identify the localization, degree and duration of upper airway narrowing.

We performed *in vitro* studies and examinations in awake subjects for ethical and legal reasons to examine the flextube method in a highly controlled setting. We intend to examine sleeping patients in future studies to investigate the influence of the flextube on sleep architecture.

The acoustic reflection method has been used to make *in-vivo* cross-sectional area measurements of the nasal cavity (13), the trachea (15), the pharynx (16–21) and the vocal tract (22). It has not previously been possible to use acoustic reflections to investigate the pharynx during sleep.

The acoustic reflection method using a nosepiece—acoustic rhinometry—has been used to investigate the nose and nasopharynx during wakefulness in OSA patients and snorers. It has been shown that nasal areas and volumes are similar in female snorers and non-snorers (23). In a study of patients without nasal symptoms, nasal patency, as measured by acoustic rhinometry, did not correlate with the severity of OSA. The severity of OSA was determined by the number of apnoeas and hypopneas per hour sleep and the effective nasal continuous positive air pressure (24).

Due to noise during snoring and practical problems with a mouth piece the formerly described acoustic reflection technique is not applicable during sleep. Introducing a flexible tube into the nose, pharynx and esophagus may make the acoustic method useful in assessing upper airway narrowing during sleep.

The *in-vitro* examinations of the flextube method in the present study showed highly reproducible and accurate results. Furthermore, the flextube was well tolerated *in vivo* and we did not notice any discomfort or problems from eating or drinking with the flextube inserted. Patients do not have to abstain from these activities.

We used the Müller manoeuvre to study the new acoustic method. We did not find a significant correlation between narrowing of the pharynx assessed by endoscopy and acoustic measurement during the manoeuvre. The Müller manoeuvre is controversial due to its limited predictive value. Former studies have shown that the predictive value of the manoeuvre with respect to UPPP success is approximately 50% (14).

The degree of narrowing of the upper airway necessary to compress the flextube to a measurable degree remains to be established. In some persons, the uvula only touched the posterior wall of the pharynx gently during Müller manoeuvres. This did not produce enough narrowing of the flextube to be detected. Similarly, the manoeuvre may not necessarily reflect obstructions during sleep and this may explain the limited predictive value of the Müller manoeuvre.

The median pressure differences ($Po - Patm$) during Müller manoeuvres in our study ($-60 - -68\,\text{cmH}_2\text{O}$) were measured in the oropharynx referenced to atmosphere. These pressure differences can be compared to pressure measurements in sleeping subjects with OSA. Others have shown that the mean inspiratory pressure gradients during obstructions across the palate are between 0 and 23·6 cmH_2O and across the hypopharynx between 0·1 and 68·8 cmH_2O (25).

Dynamic imaging of the upper airway has been performed by other methods. CT and MRI scannings have been made during wakefulness ad sleep (5–7). These methods have drawbacks such as high cost, radiation exposure and noise. MRI during sleep makes full polysomnography difficult because of the strong magnetic field. Fibreoptic imaging during sleep is also a potential clinical tool to determine sites of obstruction (26,27). It is, however, often necessary to sedate patients to use this method. This makes comparison with natural sleep difficult. Area comparisons are only valid when the distance from the tip of the fibreoptic scope to the measured plane is constant. This restricts accurate area comparisons to short periods, when movements of the tip have not occurred (28).

Some authors have reported pressure recordings during sleep for determination of the obstructive site (25). It is possible to study obstructions in more than one pharyngeal segment by using a probe with several pressure transducers (29) or by using an oesophageal catheter and catheters located at the supralaryngeal airway, the oropharynx and nasopharynx (25). However, this method causes some discomfort and pressure transducers are expensive and have a limited life. The flextube method described in this paper may be a valuable alternative to these methods.

We used a fibreoptic endoscope for placing the flextube correctly, but suggest that it can be placed without endoscopy. We have measured the distance from the nostril to the posterior border of the nasal septum with a fibreoptic endoscope on 75 adult patients. The median distance was 8 cm. The first quartile was 7·7 cm and the third quartile was 8·35 cm. The distance was slightly related to the person's height. The Spearman's r was 0·27 (P=0·02). This correlation seems to be clinically unimportant, and we suggest that the zero point of the flextube should be placed 8 cm from the nostril in all patients. By inspection of the flextube in the oral cavity it will be possible to read the distance from the zero point to the lower border of the soft palate.

In summary the flextube reflectometry method was able to demonstrate narrowing in a model of the nose and pharynx in a precise way. Narrowing was also observed during Müller manoeuvres. The correlation between flextube narrowing and cross-sectional area decrease assessed by endoscopy during the Müller manoeuvre was not statistically significant.

In future studies a comparison should be made between the results of flextube measurements and the number of apnoeas and hypopneas per hour sleep measured by polysomnography. A comparison should also be made between the obstructive levels determined by flextube reflectometry and by pressure recording or MRI scanning.

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