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Flextube reflectometry for determination of sites of upper airway narrowing in sleeping obstructive sleep apnoea patients

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Abstract The aim of this study was to examine a new technique based on sound reflections in a flexible tube for identifying obstructive sites of the upper airway during sleep. There was no significant difference between two nights in seven obstructive sleep apnoea (OSA) patients regarding the level distribution of pharyngeal narrowings, when the pharynx was divided into two segments (retropalatal and retrolingual). We also compared the level distribution determined by magnetic resonance imaging (MRI) with the level distribution found by flextube reflectometry in seven OSA patients. There was no significant difference between flextube and MRI level distributions during obstructive events, but due to few subjects the power of the test was limited. We found a statistically significant correlation between the number of flextube narrowings per hour of sleep and the number of obstructive apnoeas and hypopnoeas per hour of sleep determined by polysomnography (PSG) in 21 subjects (Spearman's correlation coefficient $r = 0{\cdot}79$, $P < 0{\cdot}001$). In conclusion, the flextube reflectometry system seems to be useful for level diagnosis in OSA before and after treatment.

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Keywords sleep apnoea syndromes; acoustics; diagnosis; upper airway.

INTRODUCTION

Obstructive sleep apnoea (OSA) is characterized by obstructions of the upper airway resulting in oxygen desaturations and arousals from sleep. This results in daytime sleepiness and cognitive symptoms; the obstructive sleep apnoea syndrome. Treatment mainly consists of nasal continuous positive airway pressure (nCPAP) and to a lesser degree surgery and oral appliance therapy aiming to increase the dimensions of the upper airway. Uvulopalatopharyngoplasty (UPPP) is sometimes used as a treatment for OSA (1). The success rate of UPPP is generally reported to be approximately 50%. Patients with mainly retropalatal obstructions are more likely to benefit from UPPP than patients with mainly retrolingual obstructions. Patients with mainly retrolingual obstructions are candidates for oral appliance therapy (2).

Polysomnography (PSG) provides information regarding the severity of OSA, but not regarding the level of obstructions. A number of methods have been used to determine the level of obstructions during sleep: continuous pressure measurements (3–7), fibreoptic endoscopy during sleep (8), magnetic resonance imaging (MRI) (9,10) and computed tomography (CT) scanning (11). However, these methods are expensive and time consuming. Some of these methods only document a limited number of obstructions, and since the narrowing may occur at different pharyngeal levels during the night in the same patient this may lead to bias. Care should consequently be taken when the obstructive level is diagnosed in patients with few recorded narrowings (12). Fibreoptic endoscopy and pressure recording during sleep do not provide information regarding narrowings below the proximal obstruction in cases with multiple sites of upper airway obstruction (10).

The aim of this study was to examine a new acoustic reflection method based on a flexible tube inserted into the nose, pharynx and oesophagus during sleep. The study was designed to compare results from flextube reflectometry with results from PSG and MRI. We also intended to assess the reproducibility of the flextube method by double measurements on two different nights. The degree of sleep disturbance caused by the use of flextube reflectometry was also evaluated.

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METHODS

Subjects

Fourteen male patients who had been successfully treated by nCPAP for OSA for 1 year or longer were studied. Seven male controls, who reported themselves as healthy, non-snoring and with normal sleep habits, also agreed to participate. The mean (SD) score of the controls on the Epworth Sleepiness Scale was 6·1 (2·9).

Demographic characteristics are shown in Table 1.

The patients were informed about the study objectives and gave written informed consent to participate. The study was in accordance with the Declaration of Helsinki and was approved by the local Ethics Committee.

The participants (n=21) were investigated for one night (n=10) or two nights (n=11) with standard PSG and flextube reflectometry included, and one night (n=21) with PSG only. Double investigations with the flextube were performed on OSA patients who accepted to participate for two nights.

Measurements

Acoustic reflectometry

The acoustic reflectometry system (SRE2100, RhinoSleep version 2.2.0.0, RhinoMetrics, Lynge, Denmark) has been described previously (13). It consisted of a portable computer and a miniprobe; a minor and light metal rod (10 cm and 70 g), attached to a flexible tube (RhinoFlex Tube) with a wall thickness of 0·2 mm, shore 38A, PVC. The diameter of the flextube was 5·2 mm. The flextube was closed at the distal end.

The probe generated a noise signal and measured the reflected sound using a microphone. When the soft palate, the tongue, or other structures of the pharynx narrowed the flextube, its cross-sectional area decreased. This resulted in a reflection of the sound from the narrowed level. The software provided information concerning the internal cross-sectional area of the flextube and determined the number and duration of flextube narrowings (Fig. 1).

Flextube narrowings, which resulted in a cross-sectional area reduction of the flextube of 16% or more for at least 10 sec, were scored as obstructive events. We divided the pharynx into two segments (retropalatal and retrolingual) and the average cross-sectional area reductions during obstructive events of the retropalatal and retrolingual parts of the flextube were found. The retropalatal narrowing as percentage of the total narrowing (retropalatal and retrolingual) during obstructive events provided the pharyngeal level distribution (Fig. 2).

Pauses in flextube narrowings of up to 1 sec were accepted unless this resulted in a mean duration of flextube events of more than 100 sec. In this case pauses were not accepted during narrowings in the specific examination. If kinking of the flextube was suspected during a study—due to constant sound reflections from a single point for more than 5 min—these periods were excluded of the analysis.

The narrowings were divided into two groups depending on their distribution: retropalatal narrowings (from the posterior border of the septum to 4·7 cm below) and retrolingual narrowings (from 4·7 to 9 cm below the posterior border of the septum). The distance from the nostril to the posterior border of the nasal septum was determined by endoscopy in each patient. The flextube was fixed to the nose and cheek with the aid of adhesive tape and the 0 point of the flextube was placed exactly at the posterior border of the nasal septum.

TABLE 1. Characteristics of the OSA patients and controls included in the study

	OSA patients (n=14)	Controls (n=7)	Differences
Age (years)*	52·0 (11·8)	34·6 (11·8)	17·5 (5·5)
BMI (kg m^{-2})**	32·4 (5·4)	24·2 (2·5)	8·2 (2·2)
AHI**	51·8 (24·9)	1·8 (2·7)	50·0 (6·7)
Flextube narrowings**	56·8 (27·7)	11·6 (4·7)	45·2 (7·6)

Values are means (SD). AHI: apnoea hypopnoea index found in the studies without flextube; Flextube narrowings: number of narrowings of the flextube per hour of sleep.
*Statistically significant difference (P < 0·01);
**Statistically significant difference (P < 0·001).

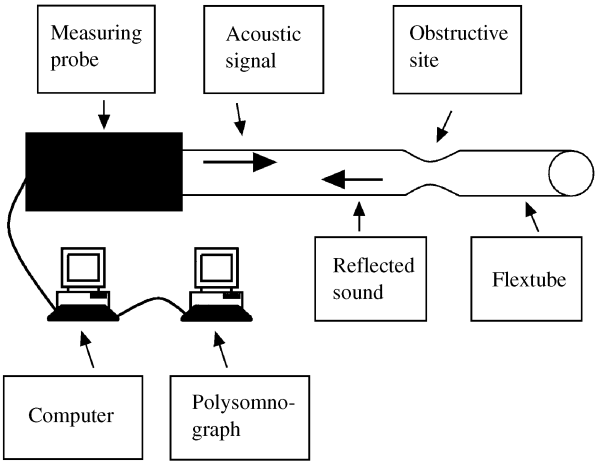

FIG. 1. The flextube reflectometry system. A continuous white band noise was generated in the probe and sent into the flextube. The flextube was inserted into the nose, pharynx and oesophagus. When the flextube was compressed during obstructions the noise was reflected. A microphone in the probe recorded the reflected sound. The distance to the obstructive site and the duration of obstructions was calculated by the measuring system and graphically illustrated by the software.

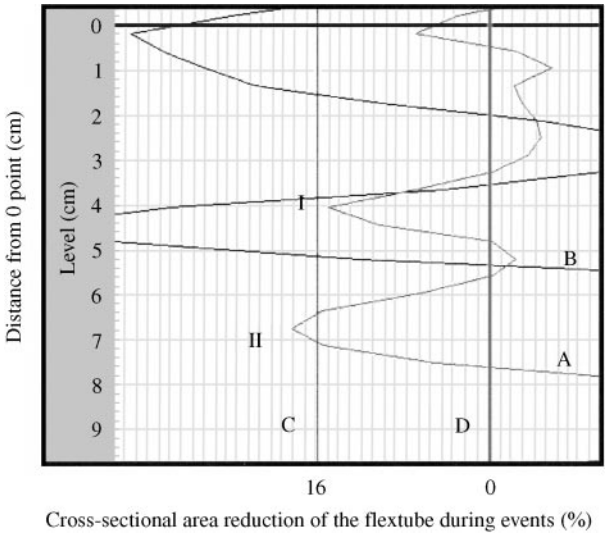

Fig. 2. Graph showing the level distribution of flextube narrowings during obstructive events determined in an OSA patient. The relationship between the distance from the 0 point of the flextube and the cross-sectional area reduction of the flextube during obstructive events is seen. The vertical straight line labelled D (——) represents 0% area reduction and the other straight vertical line, labelled C (– – –) represents a 16% cross-sectional area reduction of the flextube. Line A (- - -) indicates the mean cross-sectional area reduction of the flextube from the posterior border of the nasal septum (0 cm) to 9 cm below during obstructive events. Line B (. . .) indicates the cross-sectional area reduction of the actual sample curve. This person had a maximum of the mean flextube area reduction (15·3%) at the retropalatal level at 4 cm from the 0 point during obstructive events (I). He had a maximum flextube area reduction (17·4%) at the retrolingual level at 6·7 cm from the 0 point during obstructive events (II). Consequently, the maximum of the mean narrowing at the retropalatal level was 46·7% of the sum of the maximum of the mean narrowing at the retropalatal and retrolingual levels during events [I/(I+II)].

The flextube was advanced slowly while the patients swallowed some water.

Polysomnography

PSG was recorded overnight by the Compumedics W-series system (Sleep V2, Abbotsford, Australia). Signals included electroencephalography (EEG), right and left electrooculography (EOG), right and left electromyography (EMG), and electrocardiography (ECG) recorded by bipolar lead and oro-nasal airflow detected by a thermistor. A microphone recorded snoring sound and respiratory inductance plethysmography bands were used to measure thoracoabdominal movement. We also monitored oxyhaemoglobin saturation level (SaO_2) by pulse oximetry using a finger probe (Novametrics, model 515 C), carbon dioxide tension ($PtcCO_2$) using a transcutaneous carbon dioxide analyser (TCM3, Radiometer, Copenhagen, Denmark), body position using a mercury gauge sensor and leg movements. Techniques for sensor attachment were standardised. Impedance values were checked and EEG, EOG and EMG electrodes were replaced if impedance values exceeded 5 kohms. The same technician performed all studies.

Two trained observers (CEF and ON) reviewed all examinations. We excluded examinations if less than 5 h of good quality data were available.

Scoring of polysomnograms

The participant's sleep stages were manually scored according to the Rechtschaffen and Kales scoring criteria (14). Sleep time was defined as the total duration of staged sleep during the study. Study duration was defined as the total recording time. The Compumedics software scored the number of apnoeas and hypopnoeas. An apnoea was defined as a complete or almost complete (below 20% of baseline) cessation of airflow, as measured by the amplitude of the thermistor signal, lasting $\geq$10 sec associated with an arterial oxygen desaturation of $\geq$3%. Hypopnoeas were identified if the amplitude of airflow (detected by the thermocouple) or thorax or abdominal inductance band signals decreased (but did not meet the criteria for apnoeas) to a value below 70% of the amplitude of 'baseline' breathing for $\geq$10 sec associated with an arterial oxygen desaturation of $\geq$3%. An apnoea was scored 'obstructive' when abdominal or thoracic movements were present and 'central' when thoracic and abdominal movements were absent. Apnoeas were scored as 'mixed' when a central respiratory pause was followed by obstructed ventilatory efforts. The apnoea hypopnoea index (AHI) was calculated by dividing the total number of apnoeas and hypopnoeas by the total sleep time.

Comparison between flextube reflectometry and PSG

The longest period of continuous sleep (1–4 h) of each subject was analysed. The number of flextube narrowings per hour of sleep was compared with the number of obstructive apnoeas and hypopnoeas per hour of sleep detected by the PSG system. Data collection by the flextube system was time-synchronised with the PSG system by connecting the PSG computer and the flextube computer and transmitting time signals between the systems. The set up for simultaneous PSG and flextube reflectometry is illustrated by Fig. 3.

MRI

MRI examinations were performed on a 1·5T scanner [Signa Horizon (Echo Speed), General Electrics, Milwaukee, WI, U.S.A.]. A commercially available head coil was used. Subjects were placed supine with a neutral head

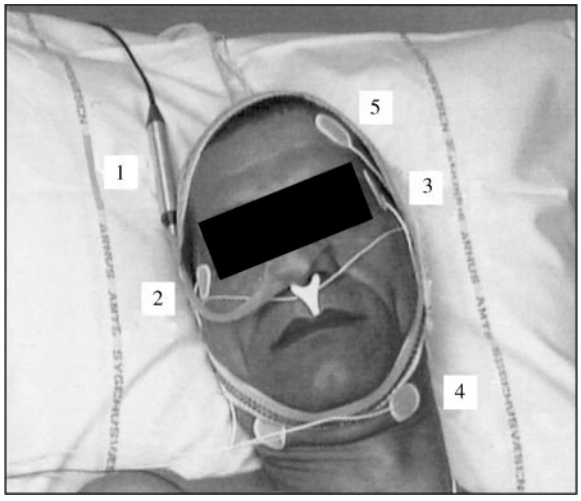

Fig. 3. The set up for simultaneous PSG and flextube reflectometry. (1) Miniprobe; (2) flextube; (3) EOG electrode; (4) EMG electrode; (5) EEG electrode. A thermistor was placed under the nose for measurement of airflow.

position. A flextube filled with a cupric sulphate solution was inserted during the scannings. Studies during wakefulness were initiated with a sagittal localizing scan to confirm the correct position (FSPGR, TR=18 ms, TE=2 ms fractional, FOV=30 × 30 cm, thickness 10 mm, matrix=256 × 196/2 NEX, variable bandwidth).

Midsagittal dynamic images (one slice) were then obtained (FGR, TR=8·7 ms, TE=1·9 ms fractional, FOV=35 × 17, thickness=7 mm, matrix=256 × 128/1 NEX, variable bandwidth, multi-phase, sequential).

The dynamic sequence was then used during sleep and manually initiated during apnoeas.

Monitoring during MRI included pulse oximetry (Nonin 8600-FO pulse oximeter, Plymouth, MN, U.S.A.), nasal airflow by measuring end-tidal CO_2 (Datex CD-200 Normocap 200) and MRI-linked plethysmography to detect thoracic respiratory movements. The signals were video-recorded.

Comparison between flextube reflectometry and MRI

MRI was performed on a randomly selected subset of seven OSA patients after these subjects had completed flextube measurements. It was determined that the patients had an obstructive apnoea during the MRI scannings when oro-nasal airflow was absent for $\geq$10 sec and thoracic movements were present associated with an arterial oxygen desaturation of $\geq$3%. Two observers independently studied the MRI scannings afterwards and determined the obstructive levels during apnoeas. They agreed on the obstructive level in all cases. The MRI scannings were examined without knowledge of the results of the flextube measurements. The percentage of retropalatal narrowings of the total number of narrowings (retropalatal and retrolingual) determined by MRI was compared to the level distribution of narrowings during obstructive events determined by flextube reflectometry (Fig. 2).

Comparison between repeated flextube measurements

The longest period of continuous sleep (1–4 h) of each subject on two different nights was analysed. Three double examinations with less than 15 narrowings per study were not included in this comparison due to the risk of bias when to few narrowings were compared. One of the double investigations was technically failed. Consequently we studied the relationship between the level distribution of flextube narrowings on two different nights on seven OSA patients.

Effects of the flextube on sleep architecture

Each of the 21 subjects had one night of PSG without a flextube inserted. We asked all OSA patients (n=14) to have two nights of flextube investigation, but three OSA patients preferred one night only. One of the double investigations was technically failed. As a result 10 OSA patients had double PSG and flextube measurements and the remaining subjects (n = 11) had only one successful study with the flextube included. The possible effect on sleep architecture caused by the flextube was determined by comparing sleep parameters between nights with the flextube inserted and nights without the flextube. For those examined for two nights (n=10) with the flextube inserted we calculated the mean value from these two nights of each sleep parameter.

Statistical analysis

Means and standard deviations (SD) were used for descriptive purposes. To compare means we used paired t-tests. The correlation between the number of flextube narrowings per hour of sleep and the number of obstructive apnoeas and hypopnoeas per hour of sleep determined by the PSG system was determined with the Spearman's rank test. To study the extent of agreement we used 95% limits of agreement (mean difference $\pm$ 2 SD). The differences will be within these limits for 95% of observations. Statistical analyses were carried out using SPSS for windows, version 9.0.0. Significance was accepted at $P < 0{\cdot}05$.

RESULTS

The flextube reflectometry procedures were accompanied by only minimal discomfort. None of the examinations had to be stopped due to inconvenience from the

flextube. There were no complications, including nasal bleeding or mucosal tears. The subjects did not have to abstain from drinking or eating when the flextube was inserted.

Comparison between flextube reflectometry and psg

We did not observe any flextube cross-sectional area reductions greater than 25% during obstructive events. During kinking of the flextube, however, area reductions greater than 25% did occur. Periods with kinking of the flextube were not included in the comparison. There was a statistically significant correlation between the number of flextube narrowings per hour of sleep and the number of obstructive apnoeas and hypopnoeas per hour of sleep determined by PSG for the 21 subjects investigated simultaneously by both methods (Spearman's correlation coefficient r=0·79, $P < 0·001$, Fig. 4). The mean number of flextube narrowings per hour sleep was 4·0 above the mean number of obstructive apnoeas and hypopnoeas per hour of sleep determined by PSG (95% CI of the mean difference: $-13·7, +5·6$). The mean difference between the number of flextube narrowings per hour of sleep and the number of obstructive apnoeas and hypopnoeas per hour of sleep determined by PSG was not statistically significantly different from 0 (P = 0·4, t-test).

The 95% limits of agreement (mean difference $\pm$ 2 SD) between the number of flextube narrowings per hour of sleep and the number of obstructive apnoeas and hypopnoeas per hour of sleep determined by PSG were 38·3 and $-46·4$ per hour of sleep (Fig. 5). This means that the number of flextube narrowings per hour of sleep would be between 46·4 above and 38·3 below the number of obstructive apnoeas and hypopnoeas per hour of sleep determined by PSG for 95% of subjects.

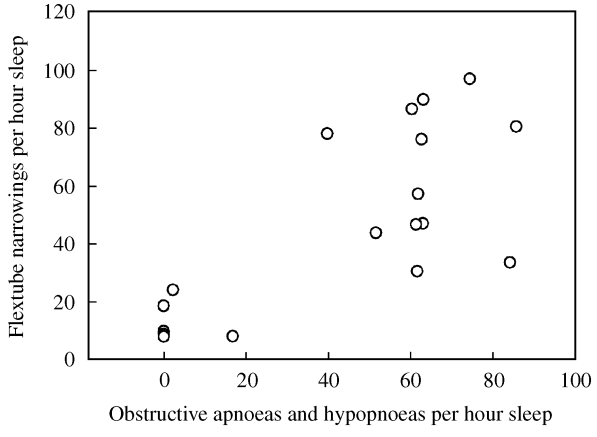

Fig. 4. Scatter plot of the relationship between the number of flextube narrowings per hour of sleep and the number of obstructive apnoeas and hypopnoeas per hour of sleep determined by PSG.

Reproducibility of flextube measurements

The retropalatal narrowing as percentage of the total narrowing (retropalatal and retrolingual) during obstructive events provided the pharyngeal level distribution. The mean (SD) difference between the level distribution on two different nights was 6% (27%) for the seven OSA patients with more than 15 events per study (Fig. 6). The mean difference in level distribution between the two nights was not statistically significantly different from 0 (P=0·59, t-test).

In all subjects flextube narrowing was observed both at the retropalatal and the retrolingual level during both study nights.

Comparison between flextube reflectometry and MRI

The level distribution of flextube narrowings during obstructive events was 14·6% below the percentage of retropalatal narrowings of the total number of narrowings (retropalatal and retrolingual) measured by MRI (SD of the mean difference = 29·9%). The mean difference between the level distribution determined by flextube reflectometry and MRI on two different nights was not statistically significantly different from 0 (P = 0·24, t-test) (Fig. 7).

Effects of flextube measurement on sleep architecture

The flextube did not interfere with sleep efficiency, central apnoeas per hour of sleep, mixed apnoeas per hour of sleep, hypopnoeas per hour of sleep, EEG arousals per hour of sleep, REM latency, percentage stage 2 non-REM sleep, percentage stages 3 and 4 non-REM sleep or minimum SaO_2 (Table 2).

Flextube measurement was associated with a minor but statistically significant decrease in the total sleep time and percentage REM sleep and a minor but statistically significant increase in percentage stage 1 non-REM sleep, the number of obstructive apnoeas per hour of sleep and the AHI (Table 2).

DISCUSSION

This study presents the first series of flextube reflectometry measurements on sleeping subjects. The flextube method allows measurement of the patency of the entire pharynx dynamically throughout the night. The method may improve the understanding of nocturnal pharyngeal dynamics and could be helpful before and after intervention for OSA but the limitations of the device and of the present study should be considered.

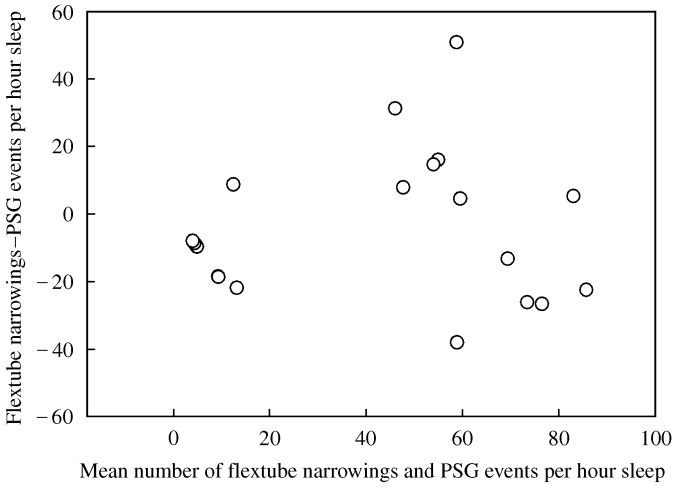

Fig. 5. Difference versus mean plot of the relationship between the number of flextube narrowings per hour of sleep and PSG events per hour sleep (PSG events=the number of obstructive apnoeas and hypopnoeas per hour of sleep determined by PSG).

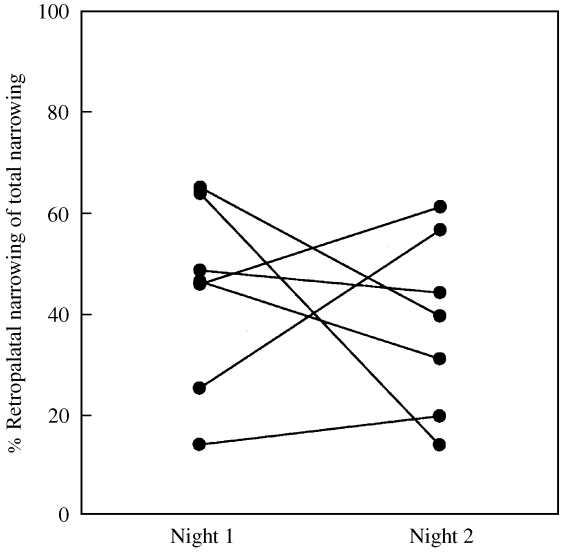

Fig. 6. We divided the pharynx into two segments (retropalatal and retrolingual) and found the retropalatal narrowing as percentage of the total narrowing (retropalatal and retrolingual) during obstructive events. This level distribution of pharyngeal narrowings was compared between two different nights in seven patients with OSA.

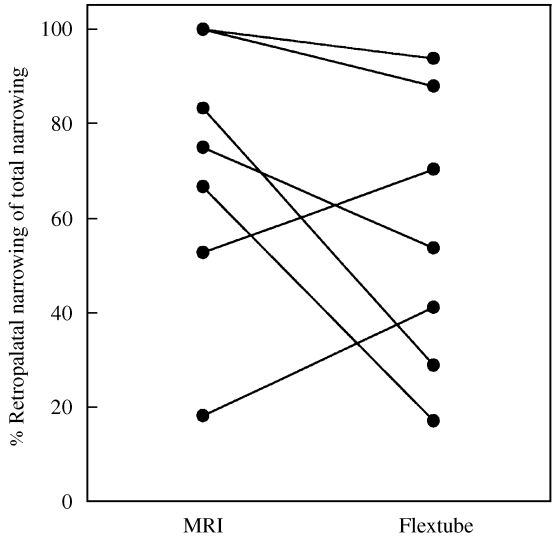

Fig. 7. Level distribution determined by the flextube reflectometry method compared with the level distribution of MRI narrowings in seven patients with OSA. The retropalatal narrowing as percentage of the total narrowing (retropalatal and retrolingual) during obstructive events provided the level distribution by the flextube method.

Acoustic reflections have previously been used to evaluate the cross-sectional area of the upper airways and upper parts of the lower airways. A high correlation has been demonstrated between acoustic and roentgenographic areas (15–18). The acoustic method has also been used as an objective method to assess the geometry of the nasal cavity—acoustic rhinometry (19). Acoustic rhinometry provides an estimate of the cross-sectional area of the nasal cavity as a function of the distance to the nostril. The nasal cross-sectional areas obtained by acoustic reflections have been compared with those obtained by other means: CT scanning, a specially developed water displacement method, anterior rhinomanometry (19) and MRI (20). Hilberg *et al.* (19) found a coefficient of variation of $<2\%$ using the acoustic method. Acoustic areas correlated highly to similar areas obtained by CT scanning ($r=0{\cdot}94$) and by water displacement ($r=0{\cdot}96$) (19).

Djupesland *et al*. validated the same miniprobe as used by us in their model study using metallic discs with circular holes ranging from 0·02 cm^2 to 0·6 cm^2. By rearranging these discs cavities with different minimum cross-

Table 2. Sleep parameters in 21 subjects examined for one or two nights with a flextube inserted and one night without a flextube. In both situations standard PSG was also performed. For those participants examined for two nights with the flextube inserted the mean of two nights for each sleep parameter was used

	Flextube inserted	Flextube not inserted	Difference
TST*	283·9 (50·9)	310·0 (55·9)	−26·1 (53·5)
Sleep efficiency	73·4 (11·8)	78·8 (11·9)	−5·4 (14·7)
CAI	0·6 (1·0)	1·5 (5·6)	−0·9 (4·8)
OAI*	22·2 (20·6)	16·8 (19·0)	5·4 (11·6)
MAI	1·7 (2·2)	1·1 (1·7)	0·6 (2·1)
HYI	18·0 (16·1)	15·7 (15·0)	2·3 (6·7)
AHI*	43·1 (34·1)	35·2 (31·5)	7·9 (15·4)
EEG arousals	41·3 (25·1)	39·7 (24·0)	1·6 (19·3)
REM latency	131·0 (75·8)	104·9 (56·4)	26·1 (76·3)
% Stage 1**	27·8 (20·1)	16·8 (15·1)	10·9 (14·0)
% Stage 2	43·6 (13·7)	48·5 (11·5)	−5·0 (13·6)
% Stages 3 and 4	18·0 (16·2)	20·9 (15·5)	−2·9 (7·0)
% REM sleep*	10·7 (6·5)	13·7 (6·6)	−3·1 (5·0)
Min O_2	59·0 (33·5)	65·8 (32·4)	−6·8 (32·4)

Values are means (SD). TST: total sleep time in min; sleep efficiency: (total sleep time/time in bed) × 100%; REM sleep: (rapid eye movement sleep/total sleep time) × 100; CAI: central apnoea index: (central apnoeas per sleeping hour); OAI: obstructive apnoea index (per sleeping hour); MAI: mixed apnoea index (per sleeping hour); HYI: hypopnoea index (per sleeping hour); AHI: apnoea hypopnoea index (apnoeas and hypopnoeas per sleeping hour); EEG arousals: EEG arousal index (per sleeping hour); REM latency: latency to REM sleep in min; Min O_2: minimum oxygen saturation.
*Statistically significant difference ($P < 0.05$);
**statistically significant difference ($P < 0.01$).

sectional areas could be modelled. The reproducibility was high (the coefficient of variation as percentage of the mean $<4\%$) when individual measurements were carried out under changing conditions such as time, temperature, pressure, calibration sequence and probe. The agreement between the results of the measured acoustic curves and true values of the model—the accuracy—was generally high (the maximum error percentage $<12\%$) for minimum cross-sectional areas of 0·05 cm^2 and larger (21).

We found a statistically significant correlation between the number of flextube narrowings per hour of sleep and the number of obstructive apnoeas and hypopnoeas per hour of sleep determined by PSG (Spearman's correlation coefficient $r=0.79$, $P<0.001$). Discrepancies were expected because different qualities of an apneic event were measured by the two methods. Oximetry was not included in the detection of events by the flextube system because we were interested in a direct comparison between flextube narrowings versus obstructive apnoeas and hypopnoeas measured by PSG. Further adjustments of the detection criteria of the flextube system are possible and this is expected to increase the correlation between PSG and flextube measurements and the reproducibility of measurements. Oximetry is possible with the most recent version of the flextube system.

Definitions of apnoeas and hypopnoeas

There is a general agreement on the definition of apnoeas as a cessation of airflow lasting $\geq$10 sec associated with varying magnitudes of arterial oxygen desaturation, but no 'gold standard' exists for defining and measuring hypopnoeas. Controversies exist regarding which sensors best detect and distinguish apnoeas and hypopnoeas and which definitions should be used. To study the impact of changes in the PSG scoring criteria we scored a randomly selected subset of five PSG examinations with different approaches for scoring hypopnoeas. Criteria included varying degrees of amplitude reduction in airflow (detected by a thermistor) and thoracoabdominal inductance band signals and varying degrees of arterial oxygen desaturation: (1) hypopnoeas identified on the basis of 30% amplitude reduction and $\geq$3% desaturation; (2) hypopnoeas identified on the basis of 50% amplitude reduction and $\geq$3% desaturation; (3) hypopnoeas identified on the basis of 30% amplitude reduction and $\geq$4% desaturation.

Changing the scoring criteria for hypopnoeas, as defined by a decrease in amplitude of 'baseline' breathing from 30% to 50%, was associated with a decrease in the mean (SD) AHI from 51·1 (17·7) to 46·3 (20·9). The mean difference in AHI between the two different amplitude criteria was 4·9 (95% CI of the mean difference; −1·2,

10·9), which was not statistically significantly different from 0 (P =0·09, t-test).

Changing the required arterial oxygen desaturation from ≥3% to ≥4% was associated with a decrease in the mean (SD) AHI from 51·1 (17·7) to 47·6 (18·3). The mean difference between the AHIs with a required desaturation of ≥3% and ≥4% was 3·5 per hour of sleep (95% CI of the mean difference: 0·3, 6·7), which was statistically significantly different from 0 (P=0·04, t-test).

We decided to include both pulse oximetry and airflow and respiratory inductance plethysmography in our definitions of apnoeas and hypopnoeas when we interpreted the PSG data. We used computerized scoring of events, which is a potential limitation of our study. Computerized scoring has, however, a strong event-by-event agreement with manual scoring by experienced polysomnographers (22).

Reproducibility of flextube measurements

We divided the pharynx into two segments (retropalatal and retrolingual) and found the retropalatal narrowing as percentage of the total narrowing (retropalatal and retrolingual) during obstructive events. The level distribution of flextube narrowings remained relatively constant between two nights in seven OSA patients.

The reproducibility of flextube measurements has not been assessed previously but our results can be compared to the results of Rollheim *et al*. who performed repeated pressure measurements during sleep on 11 men referred for suspected OSA (12). In that study one monitoring night was performed in hospital and the other was performed in the patient's home. The mean difference (SD) in the percentage upper obstructive events between the two recordings was 18% (9%).

There may be different explanations of differences in the level distribution between nights: a single night's recording does not always reflect a person's usual sleep stage distribution or the usual number of apnoeas and hypopnoeas. Penzel *et al*. have demonstrated that the collapsibility of the upper airways is strongly influenced by body position (23). Differences in sleep position may occur because it may be difficult to sleep in certain positions due to the attached equipment. The unfamiliar surroundings may also affect sleep variables. In another study using pressure sensors it was found that obstructions at lower levels of the upper airway were more often observed during REM sleep than during non-REM sleep (24). A similar observation was made by Okada *et al*. who investigated four patients with OSA by MRI and polysomnography. When the subjects sleep stage was stable for at least 3 min the investigators switched from the polysomnograph to using MRI because both recordings could not be conducted simultaneously due to magnetic interference. The MRI was conducted for the next 5–10 episodes of apnoea in order to identify the sites of upper airway obstruction corresponding to sleep stage. In two subjects the upper airway narrowing was exclusively retropalatal during non-REM sleep but became combined—retropalatal and retrolingual—during REM sleep. In one person upper airway narrowing was exclusively retropalatal during stage 1 non-REM sleep but became combined during stage 2 non-REM sleep. In one subject combined narrowings were observed during stage 1 and 2 non-REM sleep but no MRI recordings were obtained during REM sleep (10).

In a study by Suto *et al.* using MRI during sleep in 33 OSA patients combined narrowings were most frequently seen in patients with a high apnoea index (AI) and with low SaO_2 values and during mixed apnoeas (25). In conclusion, there are a number of reasons why a complete reproducibility of flextube measurements cannot be expected. The reasons may mainly be the dynamic character of apnoeas with combined and moving sites of obstruction and different sites of obstructions during different periods of sleep. These problems may partly be solved through software changes of the flextube system allowing a full report of all narrowings.

Other studies using MRI have confirmed that combined obstructed sites are a common finding in patients with OSA (26). These combined obstructive events may be misinterpreted by the fibreoptic method and by the pressure recording method because these techniques only document the proximal obstruction in cases with multiple sites of upper airway obstruction (10).

Comparison between flextube measurements and MRI

We compared the level distribution of narrowings during sleep determined by the flextube method versus MRI in seven patients who were investigated by both methods on two different nights. The mean difference in level distribution was not statistically significantly different from 0, but the power of the test was weak due to the limited number of subjects. Differences in sleep stages and sleep position may explain the discrepancies in relative distribution of narrowings.

One problem connected with MRI during sleep is the loud noise during imaging and the unfamiliar and uncomfortable surroundings. The MRI method is furthermore restricted by its ability to document only a limited number of events, in contrast to pressure recordings and flextube reflectometry measurements.

Effects of flextube measurement on sleep architecture

The minor effects of flextube measurements on sleep architecture and respiratory events have not been evalu-

ated previously but the effects of pressure catheter monitoring have been assessed. In a study by Skatvedt *et al*. the only significant difference between PSG results with and without pressure recordings was in the duration of non-REM sleep with SaO_2 below 90% (27).

In another study Chervin *et al*. found minor, but statistically significant, differences between PSG results with and without oesophageal pressure monitoring with respect to sleep stage distribution (28).

Technical concerns

A narrowing of the flextube was scored when the flextube area was reduced by 16% or more. This definition was applied after a preliminary analysis of a single OSA patient because an area reduction of the flextube of 16% or more was typically observed during obstructive apnoeas and hypopnoeas detected by the polysomnograph. We did not observe flextube area reductions greater than 25% in any of the subjects during apnoeas and hypoponeas. During kinking of the flextube, however, area reductions greater than 25% did occur. A pause of 1 sec or less was accepted during flextube narrowings *in vivo* because we noticed from the MRI scannings that such pauses often occurred during apnoeas. Using pressure recordings it has also been demonstrated that during apnoeas swallowing and vigorous inspiratory efforts occur, interrupting the apnoeas (29). We decided not to accept pauses during flextube narrowings in investigations where the mean duration of flextube events exceeded 100 sec.

Further studies are required to analyse the treatment outcomes of patients diagnosed using the flextube reflectometry system. The system may be useful for level diagnosis in snoring and OSA before and after treatment, but further comparisons with other methods for determination of the obstructive levels are required.

In summary the number of narrowings detected by the flextube reflectometry system correlated in a statistically significant way with the number of apnoeas and hypopnoeas registered by the PSG system. The mean difference between the level distributions of flextube narrowings on two different nights was not statistically significantly different from 0. The mean difference between the level distributions of flextube narrowings and obstructions detected by MRI was not statistically significantly different from 0 either.

The flextube investigations were associated with only minimal discomfort. Sleep during flextube measurements was disturbed to a minor extent compared to sleep without a flextube.

Our results suggest that this new application of the acoustic technique allows dynamic detection of the level of obstructive predominance in the pharynx during sleep. This may provide new insights into the pharyngeal pathophysiology during sleep and may prove to be a useful tool before and after any surgery or oral appliance therapy.

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