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Technical note

Technical protocol for the use of esophageal manometry in the diagnosis of sleep-related breathing disorders

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Abstract

A time-tested protocol for intrathoracic pressure monitoring during sleep is described. This method of esophageal manometry uses a fluid-filled catheter to measure variations in transmitted intrathoracic pressure with respiration. Esophageal manometry is an invaluable tool for the sleep specialist in the diagnosis of sleep-related breathing disorders, especially for detecting cases of upper airway resistance syndrome and for distinguishing subtle central apneas from obstructive events. The methods for scoring esophageal pressure, the indications and contra-indications for esophageal manometry, the use of esophageal manometry as the 'gold standard' for the measurement of respiratory effort, and directions for future research are also discussed.

Keywords: Esophageal manometry; Intrathoracic pressure; Sleep-related breathing disorders

1. Introduction

As stated in a report by the American Academy of Sleep Medicine (AASM), the reference standard for the measurement of respiratory effort is the measurement of esophageal pressure with continuous overnight monitoring [1]. We describe, in outline form, one method of measuring respiratory effort by intrathoracic or trans-pulmonary pressure monitoring during sleep that we have used at Stanford University since 1991. Assessment of intrathoracic pressure relies on the changing volume of the thoracic cavity that varies with the respiratory cycle and it provides an indirect measurement of pleural surface pressure. During inspiration, contraction of the diaphragm and accessory muscles of respiration results in expansion of the thoracic cavity with a corresponding increase in negative pressure which, in turn, inflates the lungs. During expiration, there is a decrease in lung volume and diaphragmatic relaxation, which results in a relative positive pressure within the thoracic cavity. A fluid-filled catheter placed within the esophagus can detect transmitted variation in intrathoracic pressure, since the esophageal wall expands and contracts during the respiratory cycle, resulting in corresponding fluctuations in esophageal pressure [2,3]. Increased respiratory effort associated with the increased upper airway resistance of sleep-related breathing disorders can be measured by this technique.

This fluid-filled catheter system for assessing respiratory effort relies on a high-pressure low-flow valve connected to the esophageal catheter and pressure transducer. A pressure infusor (or blood pressure cuff) maintains a pressure of 300 mmHg on a saline bag, resulting in a constant drip rate of 3 cm^3 per hour. The fluid in the catheter transmits the pressure to the transducer and the continuous drip keeps the catheter patent, allowing the measurement of relative changes in esophageal pressure during sleep.

2. Methodology (Fig. 1)

2.1. Equipment

2.1.1. Hardware components

(a) Pressure transducer (e.g. Medex® Inc., Dublin, OH, USA).
(b) Pressure infusor (e.g. Clear-Cuff®, Medex® Inc., Dublin, OH, USA) or blood pressure cuff.
(c) Water manometer (e.g. Respironics® Inc., Murrysville, PA, USA).
(d) High-pressure low-flow valve with single-line standard drip administration set including drip chamber,

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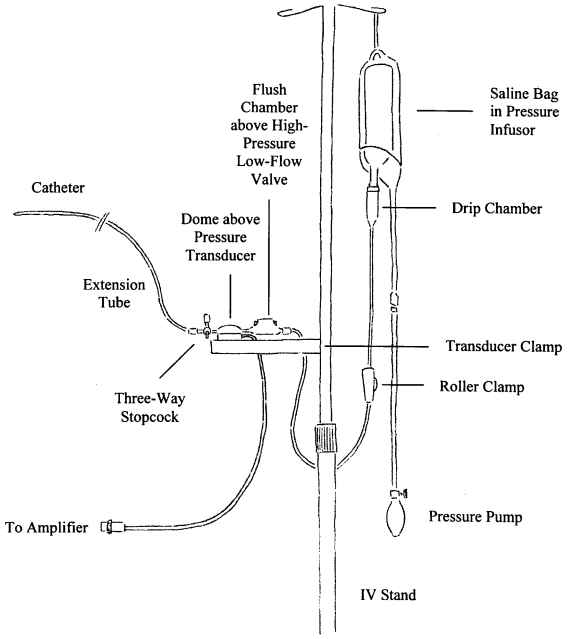

Fig. 1. Diagram illustrating fluid-filled catheter system for monitoring esophageal pressure.

dome (Novadome), 3-cm^3 flush chamber, 48-in. connector tubing, and triple stopcock (e.g. Novatrans Monitoring Kit 60 (152.4 cm) Single Line, Medex® Inc., Dublin, OH, USA). These components are single-use and preassembled; alternative kits or setups may be used if the components are comparable to those described in the following protocol and can be similarly assembled.
(e) Data acquisition and monitoring system (e.g. polygraphic system).

2.1.2. Patient supplies

(a) Enteral feeding tube with stylet, size = 6 French, length = 91 cm (Corpak® MedSystems, Wheeling, IL, USA).
(b) Oral topical viscous lidocaine hydrochloride (2%) solution and/or water-soluble lubricant (e.g. K-Y jelly).
(c) Syringe (minimum 12 cm^3).
(d) Sodium chloride (9%, 500 cm^3) bag.
(e) Tongue depressor and flashlight.
(f) Cup of water, straw, and tissues.
(g) Adhesive tape (1/2-in. width).

2.2. Amplifier calibrations

In order to use the pressure transducer, it must be connected to a low-level DC pre-amplifier. The dome and tubing should be free of saline at this time and fastened onto the pressure transducer membrane. The entire system should be open to air during the time of the baseline calibration. If solid-state signal amplification equipment is used, the pre-amplifier should be warmed up for at least 10 min. If the pre-amplifier has not warmed up sufficiently, there may be a drift in the required balance voltage and therefore the baseline may need re-calibration. Regardless of the type of pre-amplifier used, the balance controls should be adjusted to produce a zero baseline position.

2.3. Calibration of the pressure transducer and preparation of the fluid-filled system

(a) The following description applies to computerized digital polysomnographic systems. The data acquisition and monitoring system is calibrated so that a given amount of water pressure corresponds to a particular voltage (e.g. 1 V equal to 20-cm H_2O pressure) generated by the pressure transducer.
(b) The water manometer is attached to the pressure transducer by using connecting tubing between the water manometer to the triple stopcock attached directly to the end of the pressure transducer (Fig. 1). The stopcock should not be placed on the high-pressure low-flow valve side of the pressure transducer. The stopcock valve should be turned so that all three outlets on the stopcock are in the open position. With this in place, the voltage level should be at zero. The water manometer should read 0 cm H_2O.
(c) The following are the calibrations simulated by the Mueller maneuver (i.e. inspiration against an occluded nose and closed mouth). The 12-cm^3 syringe with the plunger completely depressed is placed onto the third opening of the triple stopcock. The plunger is withdrawn to generate −20 cm of water pressure on the water manometer. Based on the example above, if 1 V is equal to 20 cm H_2O, this should result in −1 V. If it does not, the sensitivity of the pre-amplifier should be adjusted so that the signal reaches the −1 V level. The syringe should be removed from the stopcock and the baseline level should return to zero. These procedures should be repeated to verify the accuracy of the baseline and correlation of a −1 V level to a −20 cm water pressure level.
(d) The following are the upward signal calibrations simulated by the Valsalva maneuver (i.e. occluded nose with the mouth closed and bearing down). The 12-cm^3 syringe is filled with at least 10 cm^3 of air and then positioned on the third opening of the triple stopcock. The plunger is depressed until 20 cm of water pressure registers on the water manometer. Based on the above example, if 1 V is equal to 20 cm H_2O, this should result in +1 V. If it does not, the sensitivity of the pre-amplifier should be adjusted so that the signal reaches the +1 V level. The syringe should be removed from the stopcock so that the transducer is opened to atmospheric pressure. The baseline should return to zero. If it does not, the sensitivity of the pre-amplifier should be re-adjusted. At this point, the calibration is complete if the signal deflections are appropriate. If

not, and the baseline excessively fluctuates, the zero baseline is re-calibrated by following the above procedures outlined in (b)–(d).
(e) The stopcock is closed and the water manometer is disconnected from the pressure transducer.
(f) At this point, the transducer should not be disconnected from the cable connected to the data acquisition and monitoring system. The transducer should be placed on a transducer platform that is attached to an intravenous (IV) stand at the bedside. The saline bag should also be attached to the IV stand. A macro-drip IV line should be placed into the appropriate insertion spot on the saline bag. Saline should be flushed through the system so that saline will flow whenever the valve is in the open position on the IV line. The IV line should be attached to the high-pressure low-flow valve. The triple stopcock should be adjusted so that the opening that was previously connected to the syringe during the calibration process, is now in the 'off' position. The saline bag should be inserted into a pressure infusor bag. The pressure infusor should be pumped up to and maintained at a pressure of 300 mmHg. An extension tube should be placed at the end of the triple stopcock that will be later attached to the esophageal catheter. The sides of the 3-cm^3 flush chamber above the high-pressure low-flow valve should be squeezed in order to let saline flush through the dome above the pressure transducer. Any air bubbles will rise to the top of the dome and will be flushed out of the system through the extension tube. At this point, the transducer dome and tubing should be completely filled with saline and free of any air bubbles. After flushing the system, it is important to verify that the pressure on the infusor reads 300 mmHg; otherwise, it should be re-inflated. The IV roller clamp is then set to the closed (off) position until the catheter is placed in the patient.

2.4. Catheter preparation

A new catheter is removed from its sterile packaging. Using sterile surgical gloves to handle the catheter, a few (e.g. two to three) extra holes are added to the catheter with a sterile scissors or scalpel in a plane different from that of the commercial holes. For all patients (children and adults), the following formula is used for prediction of the optimal insertion of the feeding tube catheter. Multiply the patient's standing height in cm (or length in cm for infants) by 0.228 to equal the length of the catheter to be inserted and mark this point with the adhesive tape.

2.5. Catheter insertion

(a) The technologist should undergo a rigorous training program prior to inserting esophageal catheters. A physician or nurse should supervise the first few catheter insertions by the technologist.
(b) The patient is fully educated about the procedure by explaining the purpose and method of insertion. Successful insertion is often the result of taking the time necessary to appropriately educate the patient regarding the procedure.
(c) The patient should be seated with his or her body erect.
(d) The technologist should wear sterile surgical gloves while handling the catheter during the following procedures. The reasons for sterile handling of the catheter are to minimize infection in the slight chance that nasal mucosa is bruised during catheter insertion and to reduce exposure of the technologist to the patient's secretions. The technologist should carefully examine the nasal passage, by having the patient pinch off each nostril to determine the optimal side for insertion. The nostril which appears to have unobstructed airflow is selected for catheter insertion. After establishing that the patient is not allergic to lidocaine (if an allergic reaction is known, water-soluble lubricant should be substituted), between 2 and 4 cm^3 of topical viscous lidocaine is administered via syringe into the appropriate nostril. The technologist should explain to the patient that the lidocaine will cause a numbing effect and will also have a bitter taste. Any excess lidocaine should be allowed to drip down the back of the patient's throat and can be swallowed. The patient should feel numbness in the nostril in approximately 3–5 min. The patient may sneeze at this point, and should have access to tissues to wipe away any excess lidocaine dripping from the nose.
(e) The first few inches of the catheter should be generously lubricated with either topical viscous lidocaine or water-soluble lubricant. The patient is instructed to flex his or her head (i.e. the patient should bend his or her head down, with chin toward chest) prior to and during the procedure. This ensures that the catheter will be more likely to enter the esophagus as opposed to the trachea. The catheter should be slowly inserted into the nostril and advanced along the floor of the nostril. The technologist will be able to feel the catheter meet some resistance at the roof/posterior portion of the nasal cavity. The catheter will be able to suddenly glide more readily inward once the catheter passes this point. At this time, the patient should be given the cup of water (via the straw) and asked to swallow, in order to further advance the catheter. This procedure also helps to ensure that the catheter is inserted into the esophagus and not the trachea. The catheter is slowly advanced down the esophagus until placement is achieved at the pre-determined taped mark. Once the catheter is in place, the guidewire is removed and the catheter is secured with tape either to the tip of the nose or upper lip.
(f) Once the catheter is inserted, the patient is asked to open his or her mouth and say, 'Ahh'. Using a tongue depressor and flashlight, the technologist should check that the catheter can be visualized behind the tongue at the back of the throat. Rarely, the catheter is observed to

be coiled in the mouth rather than having descended straight down the esophagus. If found coiled in the mouth, the catheter should be pulled out and re-inserted. Once the guidewire is removed from the catheter, it can be re-inserted into the catheter *only* if the catheter is no longer in the patient. This is to avoid injuring the patient or perforating the catheter.

(g) If there is an unsuccessful attempt at insertion through one nostril, the technologist should consider trying the other nostril. The anatomy may be more conducive to catheter insertion on the other side.

(h) A patient refusing to have a catheter inserted can be encouraged but obviously should never be forced. In the cases of infants or young children, the parents or guardians will make the decision for catheter insertion. Infants and young children often need to be held by one person while the technologist inserts the catheter.

2.6. Catheter connections

The free end of the esophageal catheter should be connected to the extension tube arising from the dome. The roller clamp on the IV line should be opened, and the 3-cm^3 flush chamber above the high-pressure low-flow valve should be squeezed so that saline flows through the system and fills the catheter. This saline should be allowed to flow for approximately 4–5 s to ensure that it has completely filled the system and that any air bubbles are removed. The pressure infusor should be checked to verify that it is inflated to and maintained at 300 mmHg pressure. A constant drip rate of 3 cm^3 per h through the catheter should be maintained; this will not interfere with the esophageal pressure measurements. The patient should now lie down on the bed. The transducer platform should be adjusted so that the height of the transducer is at approximately the level of the patient's esophagus while the patient is in the supine position.

2.7. Patient bio-calibrations

The patient should be lying down, awake, with his or her mouth closed, and gently breathing. The signal should be oscillating between the pre-established baseline and the patient's absolute P_{es} (esophageal pressure) baseline, usually between -5 and -10 cm H_2O. If this is not occurring, then the platform should be adjusted so that the baseline moves within this range or the system needs to be opened and saline flushed through the dome and catheter. By moving the platform downward, the baseline will move upward, and conversely, by moving the platform upward, the baseline will move downward. The patient is then instructed to take several deep breaths. Correspondingly, the esophageal pressure deflections should be in the downward (positive) direction. If the deflection during normal breathing swings upward from baseline (negative) instead of downward (positive) to show esophageal pressure increases, then the catheter is most likely incorrectly placed in the stomach, and needs to be withdrawn until an appropriate signal is obtained. The patient is then instructed to do a Mueller maneuver, and there should be a corresponding downward positive signal deflection. The patient should then lie quietly, with normal breathing. The patient is then instructed to do a Valsalva maneuver, and there should be a corresponding upward negative signal deflection. It is also useful to have the patient roll on his or her left and right sides to assess baseline esophageal pressure levels.

2.8. Scoring esophageal pressure

Delta esophageal pressure (ΔP_{es}) is determined by measurement of the peak-to-trough difference in the waveform on a breath-to-breath basis [4]. Fluctuations of ΔP_{es} of less than 10 cm H_2O are considered normal. In addition, absolute P_{es} negative peak values of less than -10 cm H_2O are considered in the normal range (i.e. -7 cm H_2O is normal, and -25 cm H_2O is abnormal). These normative cutoffs are largely based on clinical experience; however, there are a few studies establishing or validating different cutoff values (reviewed in Ref. [5]). Variation in the esophageal pressure waveform during normal physiologic events, such as swallowing and coughing, should be disregarded during measurements of ΔP_{es} and absolute P_{es} values.

Crescendo negative increases in absolute peak values are typically found during obstructive hypopneas and apneas as observed with polysomnography (Fig. 2). However, P_{es} crescendos lasting 10 s or longer and resulting in an electroencephalographic (EEG) arousal from sleep can occur independently of obstructive hypopneas or apneas (Fig. 3). These events are considered respiratory effort-related arousals, or RERAs. The RERA is associated with a rapid return of esophageal pressure to resting levels following the abnormal respiratory event ('P_{es} reversal'). Three other P_{es}-associated respiratory patterns observed with repetitive transient arousals [6] have been identified by Guilleminault and Chowdhuri [7]: (a) increased P_{es}, without crescendo, terminated by a P_{es} reversal; (b) one or two breath increases in P_{es} preceding a P_{es} reversal; and (c) tachypnea with normal P_{es}, abruptly terminated by a normal breath.

It is important not to overlook the rest of the polysomnographic data when reviewing a patient's esophageal pressure recording. For example, phasic increases in esophageal pressure may be associated with voluntary deep breathing; these events can be distinguished from sleep-disordered breathing by an EEG characteristic of wakefulness as well as a lack of oronasal airflow limitation. Tonic increases in esophageal pressure may normally occur during stages 3 and 4 of non-rapid eye movement (NREM) sleep; however, the phasic nature of RERAs allows them to be distinguished from the former events.

Lastly, the lack of intrathoracic pressure swings occurring simultaneously with the absence of oronasal airflow and thoraco-abdominal wall movement is diagnostic for a central apnea [8] (Fig. 4). Use of this technique allows the

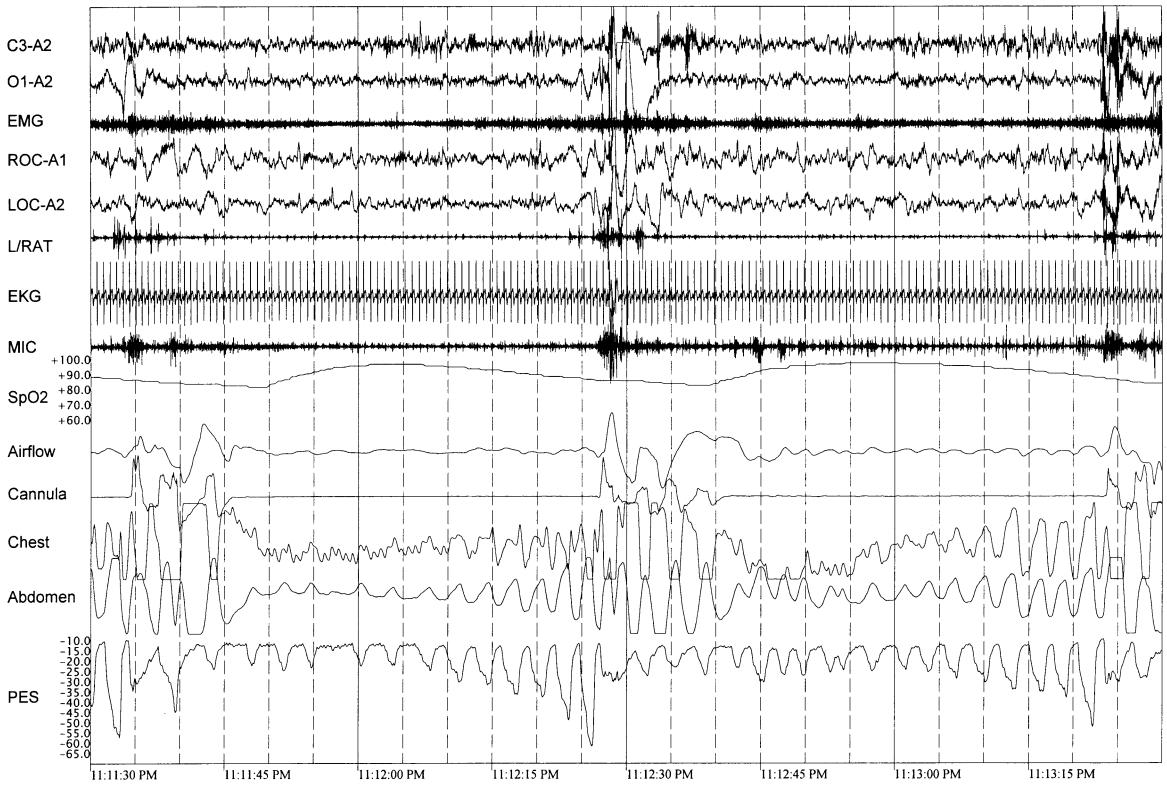

Fig. 2. Two-minute epoch depicting crescendos in esophageal pressure during repetitive obstructive apneas culminating in brief arousals from sleep in a patient with severe OSAHS. (Airflow, oronasal thermocouple; cannula, nasal pressure; P_{es}, esophageal pressure.)

differentiation of subtle cases of obstructed versus central sleep-disordered breathing, including the detection of obstructive and central components within mixed apneas (Fig. 5). Importantly, one study showed that 37% of apneas originally scored as central apneas using strain gauge measures were later re-scored as obstructive or mixed apneas when esophageal manometry data were unmasked [9]. This demonstrates that the qualitative nature of data obtained from airflow sensors and devices for assessing thoraco-abdominal wall movement (e.g. piezo sensors and strain gauges) precludes accurate differentiation of obstructive and central apneas.

2.9. Post-study procedures

Following the sleep study, the IV roller clamp is closed to halt the saline drip. The tape attaching the catheter to the patient is removed. The patient is instructed to assume a supine position with head extended and to take a deep breath. The catheter is then removed from the patient's nostril in one smooth motion, and discarded. Optionally, patient bio-calibrations and equipment calibrations, using the procedures detailed above, can be performed at this point.

2.10. Troubleshooting

(a) A highly variable signal may result from disruption of the cable from transducer to amplifier, which can be eliminated by checking the integrity of the cable and all cable connections.

(b) If the baseline signal is increased or decreased compared to the calibrated baseline, the height of the transducer platform in relationship to the patient should be adjusted. The platform should be approximately at the level of the inserted P_{es} catheter in the patient's esophagus while the patient is in the supine position, to counter the effects of gravity on the system.

(c) A signal cutoff at the peak or trough may result from air bubbles in the system, which is remedied by flushing the entire system.

(d) Ballistocardiographic artifact (e.g. slight fluctuations in the sinusoidal pressure signal) may result from a high-frequency filter cutoff setting other than 3.0 Hz. If the artifact is still present despite the correct filter setting, the catheter should be re-inserted so that it is 1 cm lower in the esophagus.

(e) Small waveforms superimposed on the sinusoidal pressure signal may represent flow artifact produced by the saline drip. Re-positioning of the catheter may decrease the magnitude of this artifact.

(f) Disappearance of the sinusoidal waveform may result from accidental closure of the IV roller clamp, bends or kinks in the tubing, or dislodgment of the catheter from the esophagus and into the stomach. Checking the tubing

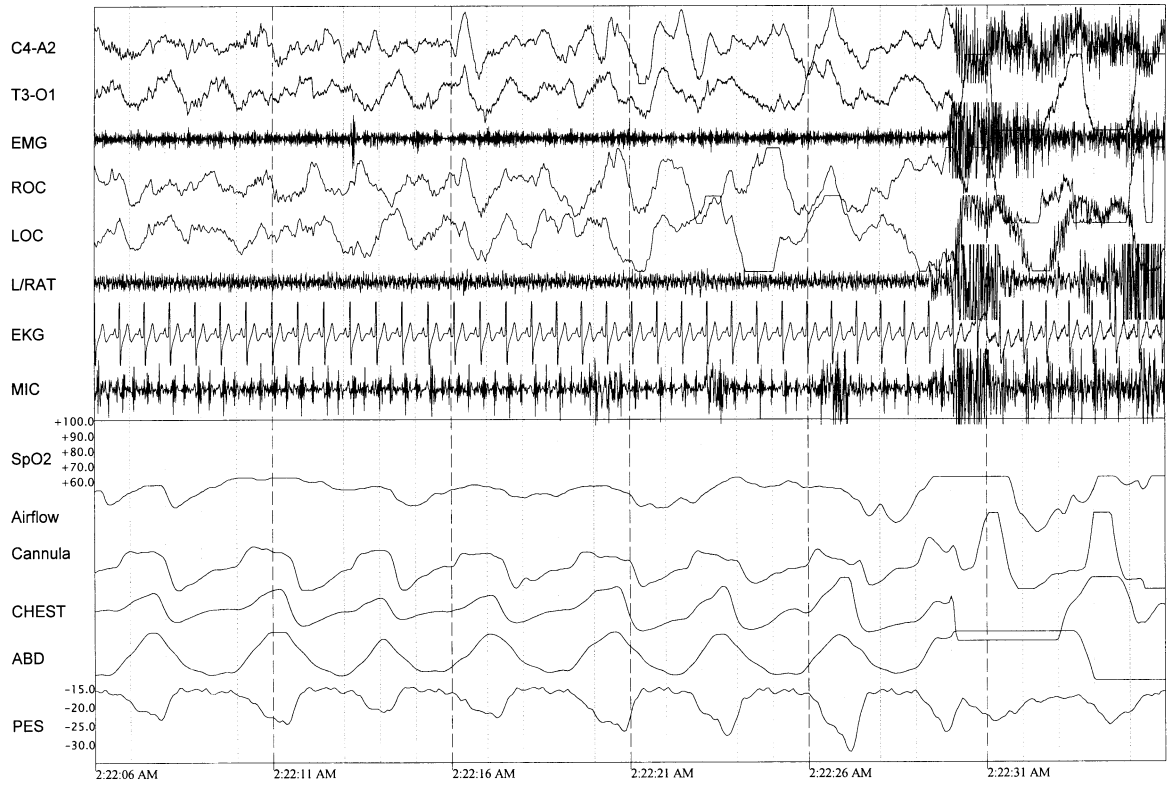

Fig. 3. Thirty-second epoch depicting a crescendo in esophageal pressure *not* associated with an obstructive apnea or hypopnea, yet culminating in an arousal from sleep. (Airflow, oronasal thermocouple; cannula, nasal pressure; P_{es}, esophageal pressure.)

and re-positioning the catheter will typically restore the signal.

3. Indications and contraindications for use of esophageal manometry

One of the hallmark indications for the use of esophageal manometry is the detection of RERAs, characteristic of the upper airway resistance syndrome (UARS). The proposed diagnosis of UARS [7,10] is based on these episodes of increased respiratory effort resulting in an arousal index of more than 10 events per h of sleep combined with a complaint of excessive daytime sleepiness [10,11]. Since frequent RERAs result in daytime sleepiness [12], UARS has been associated with hypersomnolence, as well as an increased risk of cardiovascular disease [13–15].

There is controversy whether UARS patients have more episodes of increased upper airway resistance than normal subjects [16]; however, there are recent data indicating that significant EEG changes can be identified in association with P_{es} events in UARS patients, even when arousals cannot be detected according to standard criteria [17]. In the case of patients with the obstructive sleep apnea–hypopnea syndrome (OSAHS), it is recognized [18] that standard measures of sleep-disordered breathing severity, such as the apnea–hypopnea index, do not include RERAs, but the relatively new terminology of 'sleep-related obstructive breathing events' [1] does include these abnormal respiratory events.

As discussed above, this technique is also useful in distinguishing obstructive versus central respiratory events [8]. Esophageal manometry also assists clinicians in selecting the optimal level of nasal continuous positive airway pressure (CPAP) during a titration study by its sensitivity in detecting increased respiratory effort [19]. This technique may also be helpful in identifying subtle cases of sleep-disordered breathing as a reason for persistent sleepiness in patients who have had upper airway surgery for OSAHS [20].

At Stanford University, every patient scheduled for in-laboratory diagnostic polysomnographic testing is also scheduled for esophageal manometry. Although no published data exist to support this view, we do not routinely insert esophageal pressure catheters in children less than 1 year of age because of concerns of splinting open a child's small airway with the catheter or obstructing his or her naris resulting in increased upper airway resistance. Although there are additional concerns that esophageal catheters may contribute to sleep disruption in children [21], esophageal manometry may be more sensitive in detecting subtle cases of sleep-disordered breathing in children compared to trans-cutaneous and end-tidal capnography [22], and these subtle cases may be particularly underdiagnosed in children [23,24]. In addition to children,

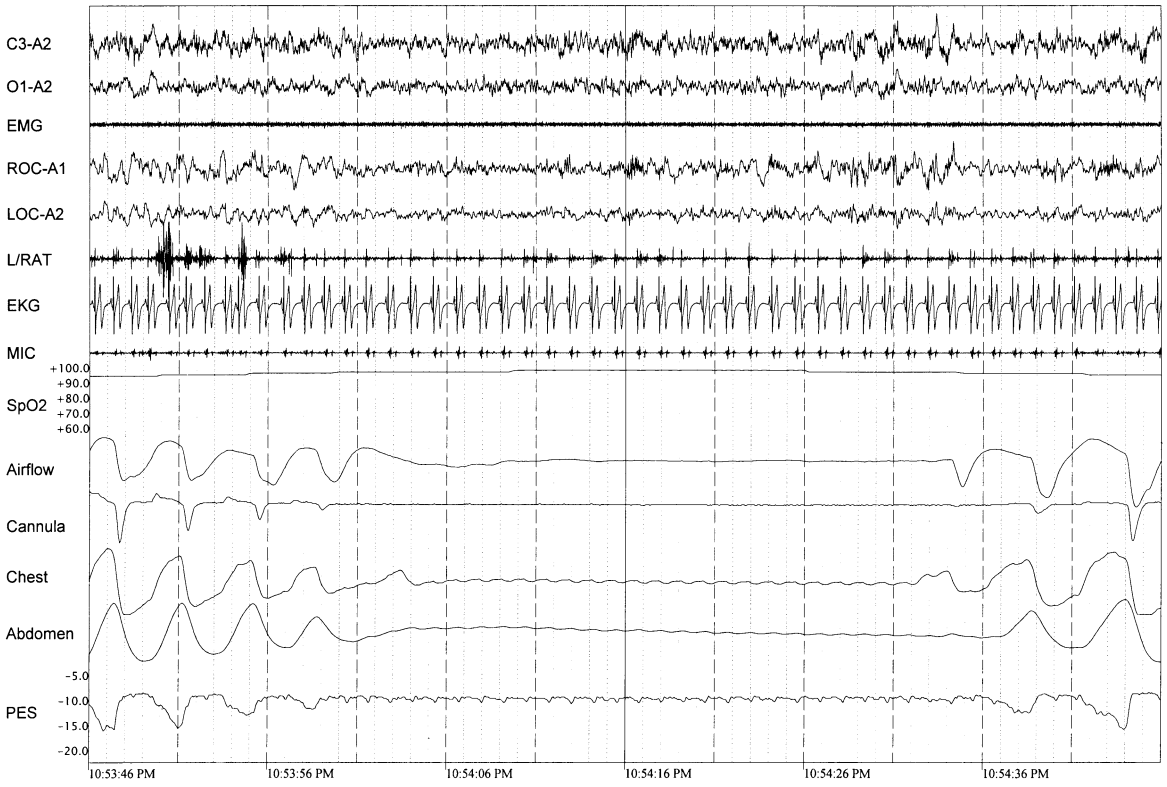

Fig. 4. Sixty-second epoch depicting absence of oronasal airflow, nasal pressure, and thoraco-abdominal wall movement, as well as a lack of esophageal pressure fluctuations, which is compatible with a central apnea. (Airflow, oronasal thermocouple; cannula, nasal pressure; P_{es}, esophageal pressure.)

esophageal manometry is especially useful in assessing populations that typically are not, but should be, associated with sleep-disordered breathing, such as thin, female, or adolescent and young adult patients [25,26].

In the rare event that the patient is unable to tolerate the esophageal pressure catheter at first, the technologist should attempt to reinsert the catheter later, but seeking the assistance of another technologist for the second attempt is advisable. If the patient refuses the catheter, the technologist should contact the on-call sleep medicine physician to notify him or her of the patient's refusal. In this case, the on-call physician should discuss with the patient the diagnostic need for the catheter and subsequent monitoring. In most instances, after recognizing the importance of this procedure, the patient will change his or her mind and accept catheter placement.

There are data to indicate that the effects of monitoring esophageal pressure on sleep architecture are minimal [27]. Occasional side effects include mild coughing, gagging, or vomiting. However, the following circumstances warrant catheter removal and on-call physician notification:

(a) Coughing that is initially excessive or does not cease after a few minutes may indicate that the catheter has entered the trachea instead of the esophagus. The catheter should be immediately removed and re-insertion considered.

(b) Spitting up blood-tinged fluid can occur when the delicate mucosal lining of the nose is bruised. Blood can drip back into the throat and be spit up through the mouth. Appearance of a small amount of blood occasionally occurs, but, obviously, moderate or severe epistaxis is cause for concern. Compression of the nose should be used to staunch bleeding, but nasal packing may be required for extreme cases.

(c) Shortness of breath, fainting, or excessive and unremitting anxiety reactions merit a prompt call to the on-call physician. If a syncopal episode occurs, the patient should be placed flat on the bed or else in a slight Trendelenburg (i.e. head of bed lower than feet) position.

4. Esophageal manometry as the 'gold standard' for measurement of respiratory effort

As with any other technique, there are advantages and disadvantages for the use of esophageal manometry. The following are advantages of the described fluid-filled catheter system. (a) The fluid-filled catheter is well tolerated by the majority of patients (including children) due to its small diameter and flexibility. The catheter itself is designed for chronic tube feeding of hospitalized patients. (b) The system is easy to maintain and problems are simple to troubleshoot. (c) No sterilization is required since the catheters are single-

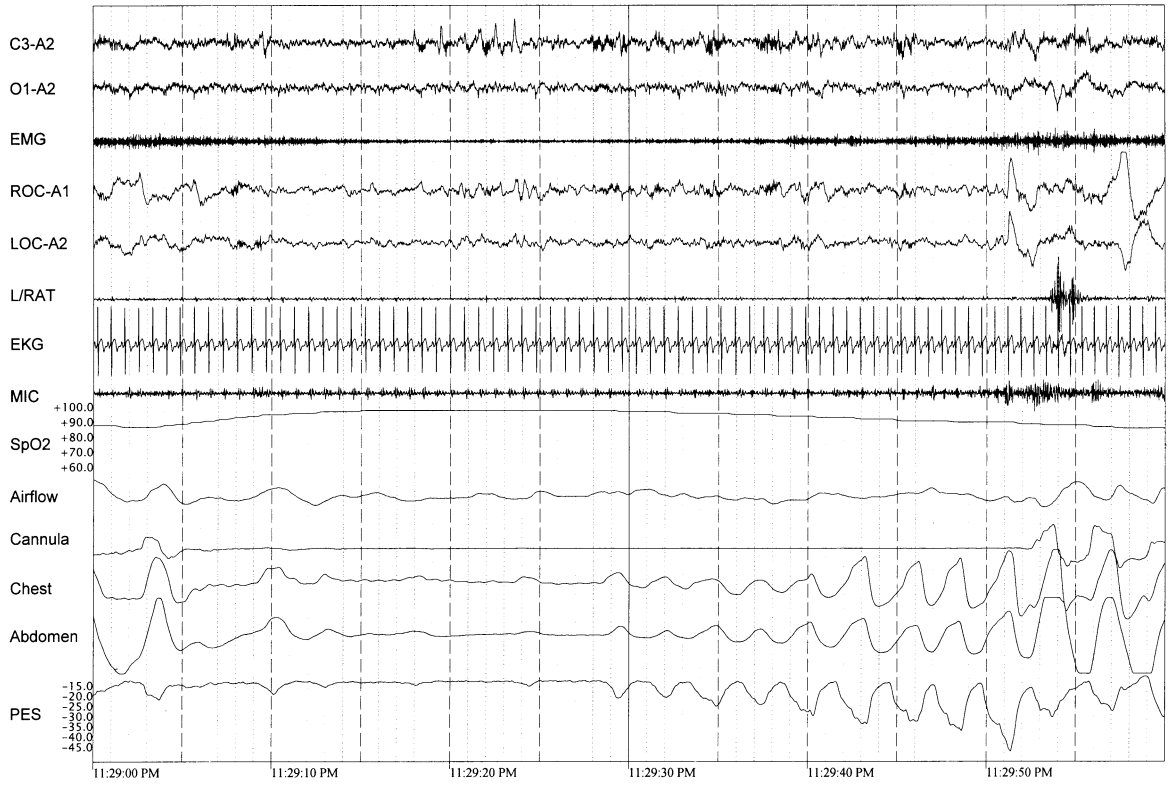

Fig. 5. Sixty-second epoch depicting a mixed apnea, with an initial central component followed by an obstructive component. The esophageal pressure recording shows a corresponding flattened signal during the central component, followed by a crescendo pattern during the obstructive component. (Airflow, oronasal thermocouple; cannula, nasal pressure; P_{es}, esophageal pressure.)

use and disposable. (d) There are minimal effects of this method of esophageal pressure monitoring on sleep architecture [27]. (e) The extra fluid (3 cm^3 per h) administered by the fluid-filled catheter technique would have negligible effects on the patient's volume status. (f) The duration for the entire process of calibrating the system, catheter preparation, catheter insertion, and patient bio-calibration is 15–30 min. (g) The fluid-filled esophageal catheter technique was validated [3,28] as a measurement of pleural surface pressure by an 'occlusion test' (comparison of changes in esophageal and mouth pressures during spontaneous respiratory efforts against a closed airway) [29,30].

The following are disadvantages of esophageal manometry, in general. (a) Although confirmatory studies do not exist, there is the possibility of stenting open the airway by the catheter itself. (b) Use of local anesthesia prior to catheter insertion may impair the arousal response to the airway occlusion in OSAHS [31]. (c) Some patients experience discomfort from the insertion or presence of the esophageal catheter.

The cost of the disposable patient supplies (including the high-pressure low-flow valve with single-line standard drip administration set) for esophageal manometry and the technologist time for insertion of the catheter is less than US $50. Besides the polysomnograph and water manometer, the only additional hardware costs are for the pressure transducer (US $100) and pressure infusor (US $21), both of which are re-usable. However, these costs do not include expenses associated with clerical activities (e.g. billing and procedure authorization), technologist scoring and physician interpretation fees, and other overhead costs, all of which have regional variation and are typically integrated into the total cost of the polysomnogram.

At the present time, there are no large-sample, systematic studies comparing various techniques for the assessment of respiratory effort. In addition, no comparison models or direct comparisons exist between the different systems for measuring esophageal pressure. The identification of upper airway resistance through assessment of respiratory effort is a primary reason for using the technique of esophageal manometry (in combination with measurement of airflow); alternative methods for assessing respiratory effort are briefly described below.

4.1. Esophageal manometry via balloon

This technique, similar to that of the fluid-filled esophageal catheter, measures esophageal pressure via a small rubber balloon attached to thin polyethylene tubing, which in turn is attached to a pressure transducer [8]. The aforementioned 'occlusion test' was used to validate this technique as a measurement of pleural surface pressure [32,33]. There may be less ballistocardiographic artifact recorded with this technique [34]. Although there were problems

associated with the early balloon catheters [30], such as holes, large diameter catheters, improper placement, and artifacts resulting from dislodgment, these problems appear to be diminished with use of the newer balloon catheters. However, the volume of air to the balloon may need to be adjusted in situations such as during the application of CPAP, when the balloon may collapse and cease detection of esophageal pressure fluctuations.

4.2. Catheter pressure transducers

This technique [8] measures esophageal pressure via a miniature pressure transducer located at the tip of flexible polyurethane tubing. This technique is comparable to that of the fluid-filled esophageal catheter; it is extremely accurate with minimal artifacts, but the catheters are expensive.

4.3. Nasal pressure

Full-face masks and nasal cannulae have been used to identify flow limitation (i.e. a non-linear airflow–pressure relationship due to inspiratory resistance from inherent instability of the upper airway) by the shape of the inspiratory flow signal [35–41]. The relationship between nasal pressure and airflow may be quadratic [42]; the square root linearization of nasal pressure increases the accuracy of quantifying hypopneas and flow limitation [43]. In addition, nasal cannulae are easily tolerated, the detection of relative nasal flow variation does not require calibration and nasal pressure measurements combined with automated inspiratory flow-shape analysis may enable clinicians to distinguish patient groups based on upper airway dysfunction [44]. Studies have reported a good correspondence in the flow limitation [40] via nasal pressure and increased respiratory effort via esophageal manometry (Fig. 3). However, the common shunting of airflow through the mouth in response to nasal flow limitation, particularly for predominant or obligate mouth breathers, may decrease the sensitivity of nasal pressure assessment. Another comparative disadvantage is that nasal pressure relies on a more qualitative approach to identify and assess the severity of RERAs, as opposed to esophageal manometry. Lastly, there is also evidence that the nasal prongs used to assess nasal pressure during sleep may markedly increase nasal resistance in patients with nasal anatomic abnormalities [45], and inter-subject variability due to differences in airway shape and compliance may result in difficulty in interpreting the inspiratory flow signal [37].

4.4. Supraglottic pressure

Upper airway resistance by this technique is measured by the pressure differential between the mouth and hypopharynx just proximal to the glottis, combined with quantitative airflow measurement [46–49]. This technique has been used primarily in research settings typically with pressure catheters and a pneumotachograph attached to a sealed facemask. Unlike esophageal manometry coupled with assessment of airflow, which measures the total resistance of the respiratory system, this technique specifically measures resistance of the upper airway. The advantages and disadvantages of this technique are comparable to those of esophageal catheters.

4.5. Diaphragmatic electromyography (EMG) and respiratory inductance plethysmography

Diaphragmatic EMG is an indirect measurement of respiratory effort based on surface EMG measurement of diaphragmatic movement. Respiratory inductance plethysmography relies on volume changes of the chest and abdomen during the respiratory cycle. Signals from both of these techniques are difficult to reliably and continuously record, with factors such as body position and degree of obesity contributing to individual variation; in addition, data regarding the use of these methods for the assessment of respiratory effort are limited [50].

4.6. Snoring crescendos

This indirect assessment of respiratory effort relies on the comparison of the amplitude of the signals recorded from a snoring microphone on a breath-by-breath basis. However, snoring crescendos did not adequately compare to esophageal pressure crescendos in a limited study [51].

4.7. Pulse transit time (PTT)

PTT is the time spent for pulse pressure to travel from the aortic valve to the periphery, as measured by the time delay between the R-wave on the ECG and the arrival of the pulse wave at the finger [52]. Amplitude increases in PTT oscillations during the respiratory cycle are correlated with increases in esophageal pressure due to upper airway resistance [53], and this non-invasive, easily tolerated technique was reported to accurately distinguish between obstructive and central respiratory events [52]. There is also some evidence that PTT is also capable of detecting micro-arousals, through its ability to recognize the transient blood pressure surge accompanying RERAs or other abnormal respiratory events [54]. However, a pulse wave may not coincide with each respiratory cycle and may result in undersampling error [54,55]. PTT is also affected by a variety of other factors [52,56], such as autonomic tone fluctuations, left ventricular isometric contraction time, cardiac dysfunction and dysrhythmias, arterial wall compliance changes due to aging or atheroma, finger movements, electrode dislodgment, or physiologic variation in respiratory effort during REM sleep.

4.8. Forced oscillation technique (FOT)

This technique relies on the superimposition of a small-amplitude pressure oscillation onto the nasal mask of a patient [57]. FOT allows measures of airway resistance

from the oscillatory pressure and flow signals recorded at the nasal mask, as a means of detecting abnormal respiratory events [58,59] and for nasal CPAP titration. However, FOT requires use of a nasal mask and the potential for air leak from the mask or through the mouth would act as a shunt resistance that might underestimate airway resistance [57].

5. Directions for future research

At present, esophageal manometry is used in few sleep laboratories, despite the AASM's recommendation [1] for esophageal pressure measurement as the reference standard for detection of RERAs, central hypopneas/apneas, and Cheyne–Stokes breathing (in conjunction with pneumotachography). Given the demonstrated utility of this technique in the identification of sleep-disordered breathing events, reliability studies for esophageal manometry need to be conducted, normative values for esophageal pressure need to be established, and comparative trials between different manometric techniques need to be performed.

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