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Technical Review of Polysomnography*

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Polysomnography has developed from our understanding of sleep and its associated physiologic processes. This important tool extends the clinical examination into dynamic states that typically do not permit intrusive inspection. The two critical components of polysomnography are the determination of sleep-wake stage and identification of related bodily processes. In this article, the authors review the current standards for clinical polysomnography and discuss technical considerations that influence the accuracy of recorded data.
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Our interest in the processes of sleep have developed over a long period of time. From the earliest records of medical accounts by Aristotle and Galen,[1] sleep has been understood as part of health. Over the last century, however, the study has been redirected toward understanding sleep as an active process by defining sleep and its associated physiology. MacWilliams[2] demonstrated in 1923 that BP decreased during sleep and fluctuated during certain periods. In 1937, Loomis et al[3] showed that EEG changes correlated with non-rapid eye movement (NREM) sleep, while 16 years later, Aserinsky and Kleitman[4] demonstrated the features of rapid eye movement (REM) sleep. These studies set the stage for more definitive work to evaluate the physiology dependent on sleep stage. This work led researchers in the 1960s to study patients with sleep complaints.

From this foundation, polysomnography was applied to the clinical arena, and the discipline of sleep medicine began.[5] In efforts to standardize sleep staging, Rechtshaffen and Kales[6] developed a manual for the scoring of normal adult sleep, which remained the discipline standard for 40 years. This was recently replaced by the more comprehensive American Academy of Sleep Medicine (AASM) Manual for Scoring Sleep Stages and Associated Events.[7]

Polysomnography is devoted to recording multiple parameters during sleep. To accomplish this, clinicians must acquire the following two major groups of parameters: those essential to determine sleep stage; and those demonstrating related physiology. Several physiologic parameters change with sleep stage including the following: heart rate; BP; respiratory function; and even renal function.[8] Despite these associated changes, sleep stages are defined by the following three parameters: EEG; electrooculogram (EOG); and electromyography of the submentalis (EMGsub). These parameters are not necessarily the best parameters, but they do represent our current definition of the sleep-wake state. Additional parameters focus on issues of breathing, circulation, movement, and occasionally other systems. Polysomnographers must also understand that, to study sleep and its related physiology, clinicians must use probes that by their very nature will alter sleep. Sleep clinicians must strike

Table 1—Sleep Staging Requirements*

Stage	EEG Findings	Eye Movements (EOG)	EMGsub
W	**> 50% of an epoch has alpha rhythm over occipital region**	*Typically, no eye movements seen*	**Normal to high muscle tone**
N1	**Attenuation of alpha rhythm for > 50% of the epoch replaced with mixed frequency low-amplitude rhythm or a slowing of PDR from waking of ≥ 1 Hz if no alpha rhythm was noted**; *Vertex sharp waves*; N1 stage continues until beginning of N2 stage or arousal	*Slow, rolling eye movements typically*	*Variable, typically less than wake*
N2	**K complexes and/or sleep spindles occurring in the first half of an epoch**; *Low-amplitude, mixed frequency EEG*; N2 stage persists until transition to N3 stage, R stage, or an arousal	*Typically, no eye movements, but slow eye movements may persist*	*Variable amplitude, typically lower than W and higher than R*
N3†	**Slow-wave activity (0.5–2 Hz, > 75 μV) for > 20% of an epoch**; Sleep spindles may persist; N3 persists until transition to N2, R, or an arousal.	*Typically, no eye movements seen*	*Variable amplitude, typically lower than N2 and can be as low as R*
R	**Low-amplitude, mixed frequency EEG**; *Saw-tooth waves*; R persists until transition to N1, transition to N2, between K complexes without eye movements, or an arousal	**REMs**	**Low muscle tone**

*W = wakefulness; N1 = NREM stage 1 sleep; N2 = NREM stage 2 sleep; N3 = NREM stage 3 sleep; R = REM sleep stage. Bolded items are requirements for staging. Italicized items are nonrequired, associated findings that may be present in that sleep stage. Table adapted from AASM Manual for the Scoring of Sleep and Associated Events.[7]
†Previously known as NREM stage 3 and NREM stage 4 sleep.

a difficult balance between accurately estimating sleep physiology with minimal disruption. In this article, the authors will review the technical aspects of determining sleep stage and related physiology.

Sleep State Determination

The principles of sleep stage determination are established by the following three parameters: EEG; EOG; and EMGsub. EEG is the primary parameter used, but muscle tone and eye movements add additional information (Table 1). The importance of EEG in determining sleep stage rests on the recognition of specific EEG figures; therefore, special attention must be directed toward the accurate assessment of EEG.

EEG

Since Hans Berger recorded the first human EEG in 1929, the summation of delicate electrical fields emanating from cortical neuronal synaptic activity has been used as a marker of brain activity.[9] These fields are largely recordable due to the radial positioning of most cortical synapses. In the awake adult, EEG fields typically are in the amplitude range of 10 to 50 μV and the frequency range of 8 to 13 Hz. During resting wakefulness, the posterior dominant rhythm is the predominant waveform in the occipital region; however, this waveform is attenuated with the onset of sleep and eye opening (Table 2, Fig 1).[10]

The accurate assessment of these electrical fields requires the appropriate placement of electrodes and attention to the recording device. Electrodes should be 10-mm gold cups that are attached to the

Table 2—EEG Frequencies*

EEG Waves	Frequencies, Hz
Delta	0–4
Theta	> 4, < 8
Alpha	8–13
Beta	> 13

*Mnemonic for EEG frequencies is "D-TAB," or Delta, Theta, Alpha, and Beta EEG frequencies in ascending order of frequency. Please note that although all slow waves are in the delta frequency range, not all delta waves are slow waves.
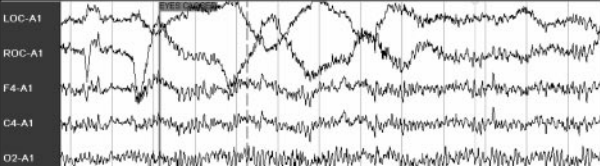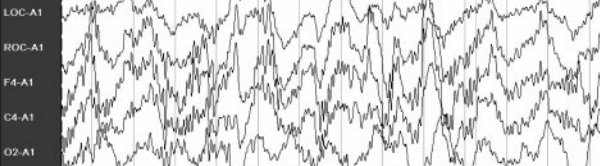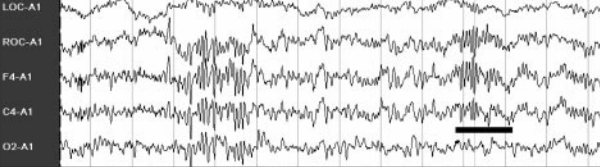
EEG Rhythm	Characteristics	Best seen	Examples
Posterior Dominant Rhythm (PDR)	8.5-12Hz	Occipital	
Slow Waves	0.5-2Hz; amplitude ≥75µV.	Frontal	
Spindle	11-16 Hz; duration ≥ 0.5s.	Central	
K-Complex	Diphasic; large amplitude, duration ≥ 0.5s.	Frontal	

FIGURE 1. Definitions and examples of sleep figures encountered on an EEG. Please note that although all slow waves are in the delta frequency range, not all delta waves are slow waves.
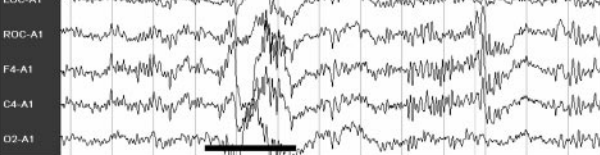
scalp with collodion or paste. To maintain impedance of < 5 Kohm throughout the night, skin should be cleaned to remove any oils or dead skin, and conducting gel added to promote an adequate electrical connection. Electrodes should be positioned according to the international 10–20 electrode placement system for sleep (Fig 2). Developed by Jasper,[11] the 10–20 system uses a division of 10% and 20% distances between four primary skull based landmarks (*ie*, nasion, inion, and each auditory canal) to create a grid. This allows for variations in skull shape and promotes placement over similar brain regions between individuals. The electrodes are labeled by letter and number. Letters are assigned according to the underlying brain area, while numbers are designated so that even numbers denote the right side of the skull and numbers are larger further from the midline. As recommended by the AASM, electrical fields conducted via these electrodes should be amplified and converted to digital signal by sampling at 500 Hz (minimum, 200 Hz) with a registry length of 12 to 16 bits.[7]

These electrodes are paired to create channels, and the difference between the electrodes is amplified by a differential amplifier. For sleep recordings, electrodes are paired to maximize the interelectrode
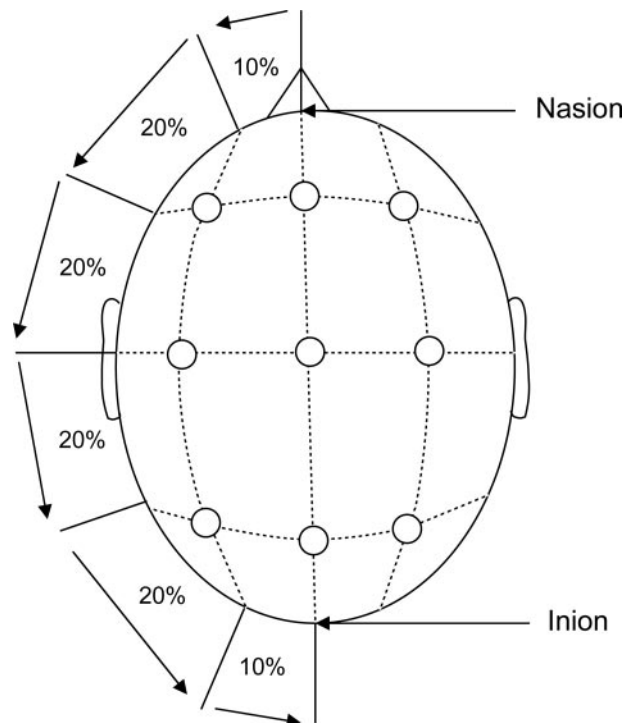
FIGURE 2. Visual representation of the international 10–20 based electrode placement system of sleep. Adapted from Iber et al.[7]
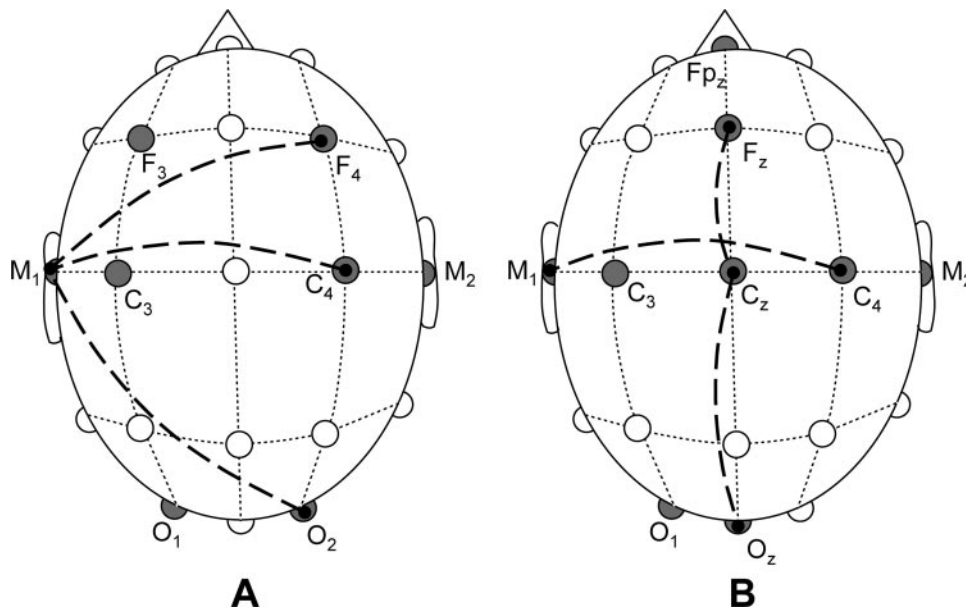
FIGURE 3. Recommended F_4-M_1, C_4-M_1, O_2-M_1 (*left*, *A*), and alternate F_z-C_z, C_z-O_z, C_4-M_1 (*right*, *B*) placements of EEG electrodes, with backup electrodes shown as set forth by the AASM. Adapted from Iber et al.[7]

distance so that spatially large waveforms are not cancelled by the amplifier. The AASM recommends[7] recording the right frontal parasagittal, central, and occipital regions paired with the opposite mastoid region (Fig 3). Each of these areas generates important waveforms that contribute to identifying the sleep stage. The AASM manual[7] allows for an alternate placement of midline frontal to midline central and midline central to midline occipital. This combination of electrodes, or montage, allows for central activity to appear as a phase reversal but minimizes the viewed amplitude of slow waves. Overall, these montages provide limited spatial resolution across the head and limit the ability to record interictal discharges, focal epileptic seizures, and normal variants from distant areas. These types of discharges are also difficult to interpret on a typical 30-s epoch window and may be more accurately determined on a 10-s window. Increasing the number of locations covered by electrodes and the ability to change window size are thus critical for the detection and delineation of these discharges.[12]

Although the AASM recommends that EEG signals be displayed at a bandwidth of 0.3 to 35 Hz, the authors advise using a bandwidth of 0.3 to 70 Hz and avoid using the 60-Hz notch filter. This added bandwidth allows for the reader to recognize a 60-Hz artifact, which is important in determining the electrical integrity of the recording. Most 60-Hz fields are broad enough to influence properly attached electrodes equally. By design, a differential amplifier

cancels out equally the detected 60-Hz waveform through common mode rejection. If an electrode becomes dislodged or broken, the disparate 60-Hz signal will be amplified, indicating an instrumentation error (Fig 4). Thus, attention to the details of electrode application and signal acquisition improves the reliability and accuracy of sleep staging.

EOG

Eye movements aid in determining the continuum of waking to light sleep and are they hallmarks of REMs in REM sleep.[13] The eye is a unique electric dipole with a strong relative positive charge on the cornea and a minor negative charge at the retina. Electrodes may be placed just outside each outer canthus with the left outer canthus being 1 cm below the horizontal midline, and the right outer canthus 1 cm above the horizontal midline and referenced to a mastoid electrode (Fig 5). This provides relatively straightforward detection and identification of vertical and lateral eye movements as waveforms of opposite phase or polarity. An alternative montage designates each outer canthus electrode placed 1 cm below the horizontal midline and referenced to the midline frontal polar electrode. This montage shows lateral movements as being out-of-phase waveforms and vertical movements as being in-phase waveforms, providing easier electrical detection of vertical eye movements.[7] To avoid potential injury to the eye, the use of collodion is not recommended. The
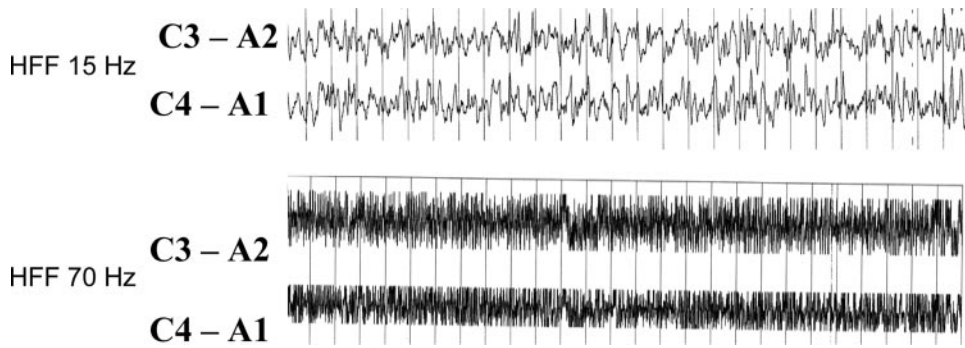
FIGURE 4. Excessive high-frequency filtering will obscure a 60-Hz artifact and may appear as typical physiologic activity. These electrographic samples were recorded from electrodes dangling from the side of a bed.

sample rate and bandwidth are similar to the EEG parameters. Eye movements are designated as being either rapid or slow. Although no clear studies have delineated REMs from slow eye movements in sleep, < 500 ms from the initiation of the deflection to the initial peak is used as the industry standard to define REM.

EMGsub

Muscle tone provides further support in determining sleep stage. The most important application is in distinguishing the waking state from REM sleep. Muscle tone diminishes gradually with depth of sleep in NREM sleep, but most skeletal muscles are atonic during REM sleep.[6,7] Muscle tone is measured as a function of the electrical fields generated by the membrane depolarization of submental mus-

cle fibers and typically recognized as activity of > 30 Hz. The EMGsub is recorded by surface electrodes placed 2 cm below the inferior edge of the mandible and 2 cm to the right and left of the midline. These electrodes are referenced to an electrode placed in the midline 1 cm above the inferior edge of the mandible. Electrodes may be attached with collodion or paste and secured with tape. The sample rate should be 500 Hz with a display bandwidth of 10 to 100 Hz.[7]

Sleep Stages

The combination of the EEG, EOG, and EMGsub provides the basis for sleep stage scoring (Table 1). The reader should score the stage based on the majority stage of a 30-s epoch. The wake stage is
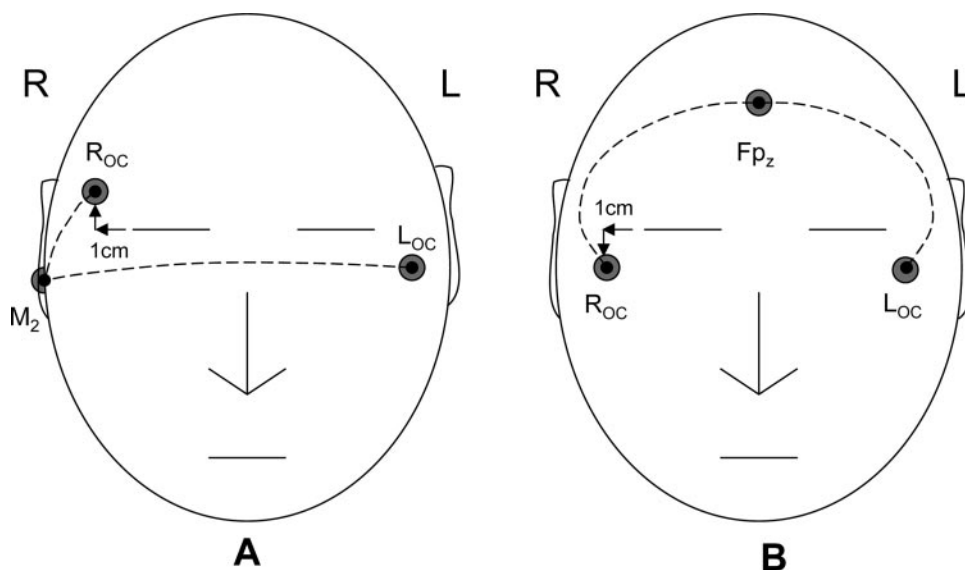

FIGURE 5. Recommended Roc-M2, Loc-M2 (*left*, *A*) and alternate Roc-Fpz, Loc-Fpz (*right*, *B*) placement of EOG electrodes as set forth by the AASM. Adapted from Iber et al.[7]

determined by the presence of a posterior dominant rhythm, REMs, and continued muscle tone. NREM stage 1 sleep is associated with a loss of the posterior dominant rhythm and a slowing of the background typically to a theta frequency. NREM stage 2 sleep is characterized by sleep spindles and K complexes (Fig 1), and the hallmark of NREM stage 3 sleep is a bandwidth of 0.5 to 2.0 Hz with 75-μV slow waves occupying at least 20% of the epoch. REM sleep has a low fast EEG, REMs, and the lowest muscle tone. Arousals are noted by a return of alpha frequency activity for 3 s in NREM sleep and alpha activity with an increase in EMGsub in REM stage sleep. Subsequent articles and the AASM manual provide greater detail concerning the scoring criteria.[7]

Related Physiology

Breathing and Respiration

Breathing pattern and respiratory responses are influenced by sleep stage. Light sleep is associated with mild periodic breathing, whereas NREM stage 3 sleep has very regimented breathing. Stage R sleep is associated with the greatest ventilatory variability especially during the bursts of eye movements.[14] A decreased physiologic response to low oxygen levels and elevated CO_2 levels occurs in NREM and REM sleep.[15] These variations in the regulation of breathing reveal potential specific vulnerabilities and dysfunction in the respiratory control system.

The measurement of breathing must incorporate aspects of the dynamic features of flow, effort, and consequence. Flow indicates the movement of air in and out of the chest cavity. Effort must be measured as a surrogate related to movement of the chest and diaphragm or the generation of negative inspiratory force. Parameters of flow and effort should be recorded at a sample rate of 100 Hz and displayed in a bandwidth of 0.1 to 15 Hz.[7] As a consequence of breathing, levels of oxygen rise and levels of CO_2 fall. The following is a brief review of the pertinent features of measuring these parameters.

Flow

Air flow can be directly measured by pneumotachometry, but this is frequently cumbersome and uncomfortable for the patient. Standard sleep studies use the features of air temperature and nasal pressure as estimates of flow. Air temperature is a sensitive measure of respiratory air flow. On exhalation, air leaves at near body temperature and is at ambient air temperature on inspiration. These temperature differences can be measured using a thermistor or thermocouple. These sensors measure the change in voltage created when a change in temperature is applied to a conductor or resistor. A thermistor uses a small current and a temperature-dependent resistor. The more stable thermocouple is created when two dissimilar metals are placed in a circuit. To have voltage fluctuation near the range of body temperature, most thermocouples used in sleep laboratories are composed of either chromel or copper attached to constantan.[16] Thermosensors are very sensitive to even minor air flow and thus are best used to determine apneas (Fig 6, 7).[7] Due to their high sensitivity, even slight air flow will produce a large amplitude deflection; thus, thermosensors are poor detectors of partial flow limitations.[17]

Air pressure is another mechanism to estimate air flow. From a small tube placed at the entrance of the nares, nasal pressure is measured by a piezoelectric pressure sensor. These devices are very sensitive to hypopneas or partial limitations of flow but do not differentiate between very low and absent air flow. When compared to pneumotachometers, nasal pressure sensors demonstrate high sensitivity for respiratory events.[18,19] The AASM recommends[7] that nasal pressure devices be used to detect hypopneas (Fig 7). Nasal pressure signals may show more subtle flow limitations as a flattening of the inspiratory signal.[20] The combination of the two air flow sensors allows the clinician to accurately assess both hypopneas and apneas.

Turbulence is an important feature of compromised air flow. This turbulent air flow results in snoring, and the detection of snoring can be a useful aid in identifying upper airway resistance. Snoring can be detected by a variety of mechanisms focusing on high-frequency oscillations of turbulent air flow such as a small microphone or piezoelectrode placed
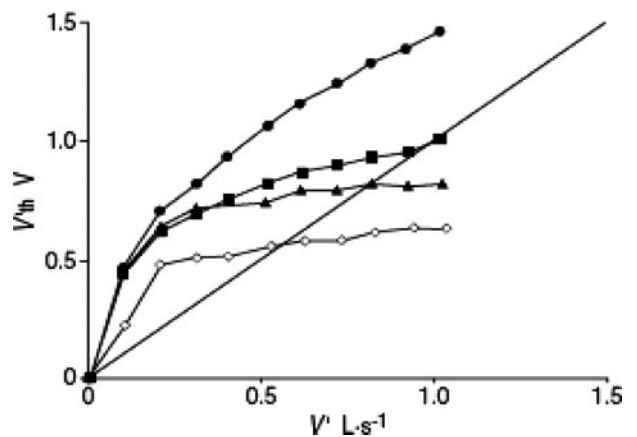

FIGURE 6. Flow measured as peak to peak (y-axis) generated by different distances between air source (artificial nose) and a thermistor for different distances (0 mm [●]; 10 mm [■]); 20 mm [▲]) and for a double section of artificial nose (○) at 10 mm compared to actual flow (x-axis). Adapted from Farré et al.[17]
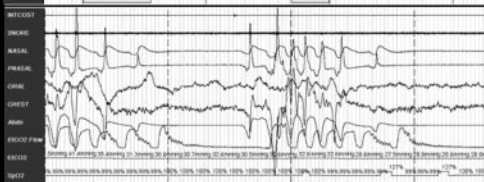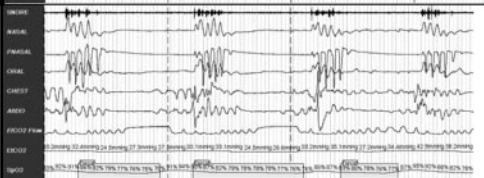
Event	Scoring Rules	Examples ⊢ 30s ⊣
Hypopnea	Nasal pressure drop in baseline of ≥ 30% at least 10s in duration** with a ≥4% desaturation in Pox **or** ≥ 50% drop in nasal pressure from baseline at least 10s in duration with either a 3% desaturation or an associated arousal.	
Obstructive Apnea (OA)	Drop in peak thermal sensor by ≥90% from baseline, duration of 10 seconds, persistence of respiratory effort during event.	
Cental Apnea*	Score a central apnea if the event meets the criteria for OA with the exception of an absence of any inspiratory effort during the event. In children, events must be 20s duration or at least 2 missed breaths with an associated arousal or a ≥3% desaturation.	
Mixed Apnea	Score a mixed apnea if it meets the criteria for an OA where the initial portion of the event shows an absence of inspiratory effort, and there is a resumption of effort during the second portion of the event.	

FIGURE 7. Rules for respiratory events and examples. * = For Cheyne-Stokes breathing scoring, one must have three consecutive cycles of cyclical crescendo/decrescendo change in breathing amplitude with at least five or more central apneas/hypopneas of 10 min duration. ** = For pediatrics, duration need only be two missed breaths for all events. For a more complete explanation, please see the AASM scoring manual.[7]

on the anterior neck. Nasal pressure can detect snoring by altering the display bandwidth to focus on these high frequencies (sample rate, 500 Hz; bandwidth, 10 to 100 Hz).[7] Other devices may also detect these vibrations through mechanical or electrical means.

Effort

The basis of respiratory effort is neuronal output from the respiratory control center. The estimation of effort is essential to the classification of respiratory events. Our current measures rely on an intact neuromuscular system. Our "gold standard" for effort, intrathoracic pressure monitoring, provides an accurate and sensitive determination of muscular effort to breathe. Unfortunately, this device is invasive and may disturb sleep. Alternatively, calibrated inductance plethysmography can quantitatively estimate chest and abdominal movement.[21] Inductance plethysmography utilizes wire coils to generate and measure a magnetic field. Coils may be aligned so that a change in diameter or shape results in a change in the electromagnetic field. These measures are recommended by the AASM manual[7] as the standard for respiratory effort estimation; however, these sensors become uncalibrated following movement. Intercostal electromyography may qualitatively assess effort.[22] Surface electrodes are placed < 3 cm apart over the fifth to eighth lateral intercostal space. Lower placement of these electrodes provides the observance of both diaphragmatic and intercostal activity. This is helpful especially during stage R sleep when intercostal muscles are atonic but diaphragmatic activity persists. Due to a lack of current studies showing equivalency, the use of alternative measures such as piezoelectrodes and strain gauges are not currently recommended.

VENTILATORY CONSEQUENCES: OXYGEN AND CO₂ MEASURES

The exchange of oxygen and CO_2 are measures of adequate ventilation. Oxygen levels are measured via a pulse oximeter transmitting two wavelengths of light to detect pulsation and oxygen saturation of hemoglobin.[23] This device depends on a clean connection to the epidermis, and results may be skewed by motion, skin pigmentation, or fingernail discolor-

ation.[24] Oximeters are typically placed on a finger or less commonly an earlobe or nose. The device should have a signal average time of not > 3 s.[7]

CO_2 levels can be estimated by continuous end-tidal sampling. A small tube is placed at the entrance of the nares and connected to the CO_2 detection unit. The signal does have a delay that is directly related to the length of the tubing. Typically, using infrared light to measure CO_2, these analyzers can correlate with arterial CO_2 levels but require regular calibration.[25] Units may read falsely low levels due to mouth breathing, the application of supplemental oxygen, continuous positive airway pressure, and the movement or blockage of the sampling tube of blocked or small nares as in children. CO_2 may also be measured by transcutaneous sensors. These sensors require the skin to be heated and are usually tolerated for only a few hours.

Respiratory Scoring

Scoring respiratory events is achieved by properly identifying disruptions in air flow, effort, and oxygenation. All adult respiratory events must be at least 10 s in duration, while for pediatric patients the duration of two breaths is considered to be sufficient to be considered a respiratory event. An apnea is a cessation of air flow and is scored when there is a 90% drop in peak thermal sensor excursion. By definition, a hypopnea is a partial limitation in air flow that is associated with either an arousal or an oxygen desaturation. Hypopneas should be scored using the nasal pressure signal. Note that there are two acceptable scoring criteria for hypopneas set forth by the AASM. Obstructive events are scored when effort continues or increases during the event. Central events are scored when there is an absence of effort. The Cheyne-Stokes breathing pattern is scored when there are at least three consecutive cycles of a crescendo/decrescendo breathing pattern along with a central apnea-hypopnea index of five events per hour of sleep, or a crescendo/decrescendo pattern lasting for 10 consecutive minutes. Hypoventilation in adults is scored when there is a rise in $PaCO_2$ of ≥ 10 mm Hg between wakefulness and sleep. In pediatric patients, sleep-related hypoventilation is defined as $> 25\%$ of the total sleep time being spent with a CO_2 level of ≥ 50 mm Hg. The reader should refer to the AASM scoring manual[7] for a more comprehensive review of adult and pediatric scoring rules.

Cardiac Function

The assessment of cardiac function is usually limited to the electrical field recorded in a modified lead II electrode placement.[7] Additional electrodes may aid in the delineation of waveforms and types of rhythms. The scoring of cardiac events is limited to bradycardia and tachycardia events, as noted in Table 3. Less intrusive finger BP monitors may be used to assess cardiovascular function, but these are still relegated mostly to research studies.

Movement

Sleep is a time of relatively limited movement. With NREM sleep, the muscle tone decreases and reaches skeletal atonia with stage R sleep. Limb movements are measured as electromyographic activity of the anterior muscle group of the lower legs and extensor surface of the forearms.[7] Surface electrodes are placed < 3 cm apart along the belly of the anterior tibialis muscle on each leg.[26] Upper extremity electrodes should be placed over the brachioradialis and wrist extensors. The electrode wires require anchoring along the body to avoid displacement. Each limb should be delegated a separate channel to aid in the identification of patterns of movement. The electrodes should have impedances below 10 Kohm, and preferably < 5 Kohm.[7] The signal should be sampled and displayed similarly to that in an EMGsub. Specific rules for scoring limb movements are noted in the AASM guidelines.[7]

Body position may potentially impact the development of respiratory events. Body position can be

Table 3—*Cardiac Rules for Scoring as Set Forth by the AASM**

Cardiac Event	Scoring Criteria
Bradycardia†	Sustained heart rate > 90 beats/min for adults
Tachycardia†	Sustained heart rate < 40 beats/min for persons ≥ 6 yr of age
Asystole	Cardiac pauses greater than 3 s for persons ≥ 6 yr of age
Wide complex tachycadia	Rhythm lasting a minimum of 3 consecutive beats at a heart rate > 100 beats/min with QRS duration of ≥ 120 ms
Narrow complex tachycardia	Rhythm lasting a minimum of 3 consecutive beats at a heart rate of > 100 beats/min with QRS duration of < 120 ms
Atrial fibrillation	Irregularly irregular ventricular rhythm associated with replacement of consistent P waves by rapid oscillations that vary in size, shape, and timing

*Adapted from Iber et al.[7]
†Typical sinus rates in children differ. For typical rates in children, refer to the study by Iber et al.[7]

Table 4—*Typical Classification for Diagnostic Studies To Evaluate Obstructive Sleep Apnea Based on Complexity of Study**

Study Types	Description
I	Most comprehensive; attended or in facility, full complement PSG; considered tom be the reference standard for the diagnosis of OSA
II	Minimum of seven channels (*eg*, EEG, EOG, EMG, ECG, air flow, respiratory effort, and oxygen saturation); attended or unattended
III	Minimum of four channels, including at least two channels for either air flow or one for air flow with one each for effort, heart rate, and oxygen saturation; attended or unattended
IV	Measures one or two parameters (*eg*, oxygen saturation or air flow); typically, unattended

*PSG = polysomnography; OSA = obstructive sleep apnea.

recorded by the technologist or measured by a position sensor. These position sensors can aid in denoting position, but are sometimes inaccurate when the patient is between classic lateral, supine, and prone positions.

Behavior Monitoring

Behaviors are best recorded with time-synchronized audio and video recording. Current standard infrared video cameras with infrared light sources provide images of excellent quality. Patients do not perceive the infrared light, but the viewer may see fine details of movement and behaviors. Continuous audiovisual recordings should be time-linked to the polysomnogram.[5] This permits association of physiologic data with discrete behaviors and aids with detecting other events such as the detection of mask leaks.

Other Parameters

Other physiologic parameters can be measured during polysomnography including but not limited to the following: esophageal acid levels; core body temperature; penile tumescence; sweat levels; and hormonal levels. Each of these provides additional information and associations of sleep-related physiology. As our understanding of the interrelationships between physiology and sleep grows, so too will our ability to identify individuals with specific state-dependent dysfunction.

Polysomnography Levels

Polysomnography can encompass many levels of measurements during sleep. The current guidelines specify four levels of studies (Table 4). These range from full attended studies (level I) to single-parameter unattended studies (level IV).[27,28] More importantly, the clinician must remain vigilant to understanding the principles underlying the accurate assessment of state and associated physiology while understanding the limitations of the current tools used in unlocking the complex mysteries of sleep.

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