SLEEP LABORATORY

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INTRODUCTION

Sleep is a fundamental, homeostatic process necessary for human existence and quality of life. Sleep disorders account for impairment of alertness (1); cognitive function (2), especially short-term memory and divided-attention tasks (3); mood (4); work productivity (5); and driving ability (and hence, an increase in automobile accidents). Obstructive sleep apnea has been clearly linked to cardiovascular disease.

There are > 80 sleep disorders, which generally increase in prevalence with age. Indeed, > 50% of adults over age 60 years suffer from some sleep-related complaint (6), including daytime fatigue, difficulty initiating or maintaining sleep, snoring, obstructive apnea, insomnia, restless legs syndrome, narcolepsy, or circadian rhythm disorders. Most disorders have attendant morbidity issues. For example, patients with sleep apnea have an increased risk of cardiovascular disease, stroke, and diabetes. Patients with protracted insomnia have

Encyclopedia of Medical Devices and Instrumentation, Second Edition, edited by John G. Webster

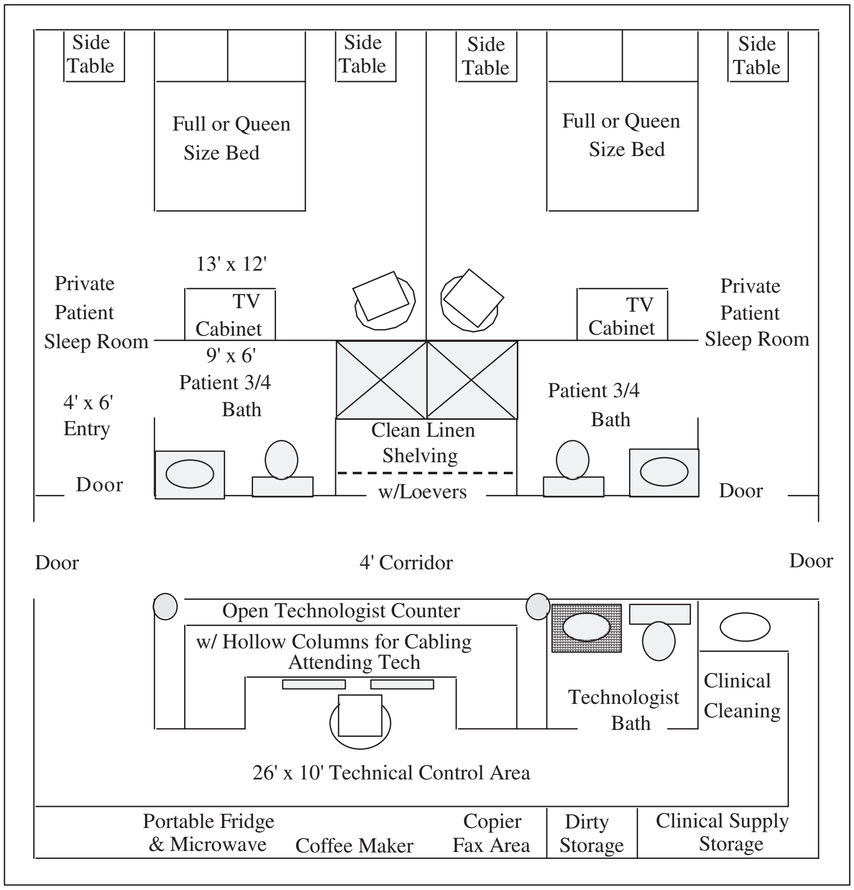

Figure 1. Sample sleep lab layout (26 ft $\times$ 32 ft 832 ft^2 for a two-bed sleep lab).

an increased risk of depression, anxiety, and substance abuse. Many sleep disturbances are secondary to other medical problems, such as nocturia, pain associated with arthritis, and cardiopulmonary disorders.

POLYSOMNOGRAPHIC RECORDING

The traditional evaluation of normal sleep and sleep disorders incorporates the gold standard, nocturnal polysomnography, performed in a sleep clinic or laboratory (Fig. 1). Growth of laboratories has occurred in the last 30 years to 2515 estimated labs, generally located in hospitals. Most current laboratories require a night tech, a scoring tech, a clinician, or a scientist to acquire and process sleep data. Some laboratories are freestanding or exist in private clinics. Contract service entities also provide outsourcing of sleep diagnostics.

The sleep laboratory classically consists of diagnostic bedrooms, accompanied by a central technical area for collection of data, observation of patients, and data processing. Ancillary areas include a business office, exam rooms, a lounge area, a break area, and file storage, much like a clinical practice. Sleep diagnostics for the sleep bedroom are focused primarily on a monitoring EEG to determine sleep states, with expanded measurements to allow quantitative assessment of EEG (see Table 1). The sleep laboratory environment attempts to achieve a bedroom environment, with the patient interface allowing minimally invasive techniques.

Electroencephalography

The EEG is the fundamental measurement of polysomnography and consists of application of electrodes according to the International 10–20 electrode placement system (7) (Fig. 2). The skin interface is established through cleansing and removal of dead skin layers, with electrode application, typically using an electrode cup with a conductive medium. There are many derivations of electrode placement, but for sleep, typical placements are at occipital lobe sites (O1 or

Table 1. Sleep Laboratory Measures (Possible)

Eye movements	Inductance plethysmography
Pupillometry	Intercostal EMG
Arms, legs and chin electromyography	Esophageal pressure
Nasal and oral airflow	Esophageal pH
End tidal CO_2	Pulse oximetry
Nasal pressure-flow	Transcutaneous oximetry
Pneumotach	Transcutaneous CO_2
Snoring microphone	Electrocardiogram
Chest wall movement	Blood pressure
Abdominal movement	Penile tumescence
	Body position

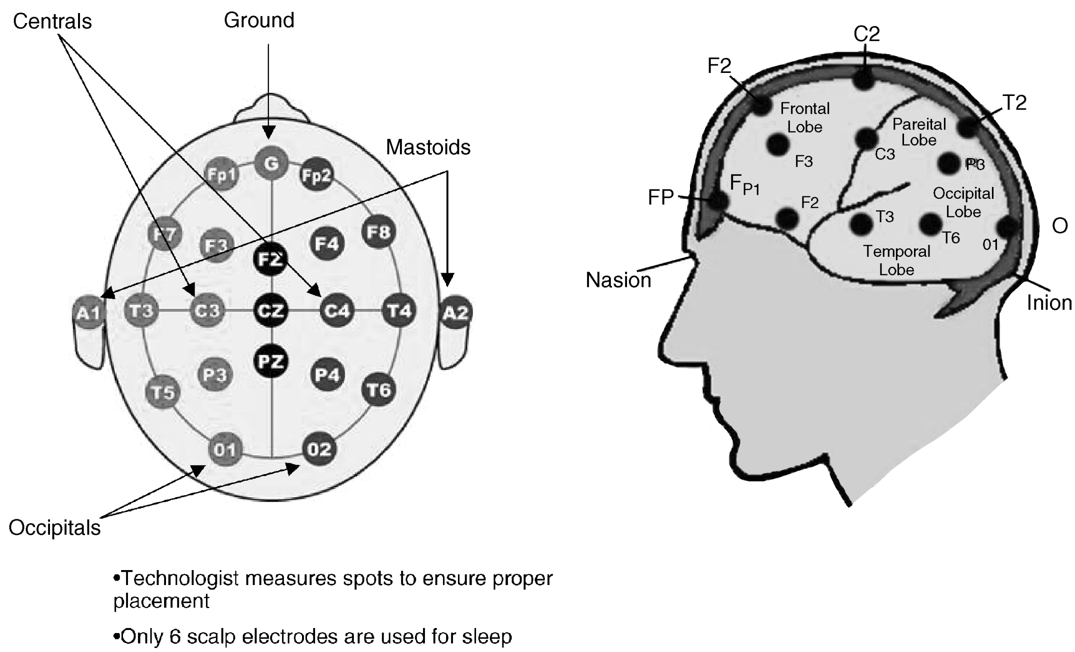

Figure 2. Electrode placement.

O2) with contralateral placement of a reference electrode on the mastoid process or earlobe. This gives the standard O1/A2 or O2/A1 electrode placement. Many labs also incorporate central electrode placement (usually C3/A2 or C4/A1). Occasionally, frontal electrodes are placed. The contralateral reference of electrodes typically allows a high amplitude of EEG signal, enabling adequate measurement of frequency and amplitude information. Normal sleep scoring rules have been based on central electrode placement. Occipital electrodes enhance alpha frequency (8–12 Hz) measurements and frontal electrodes enhance delta frequency (2–4 Hz) measurements.

Full montage EEG electrode placement is sometimes done to enhance the capture of nocturnal seizure activity. This replicates bipolar studies done for seizure monitoring and is especially useful for nocturnal movement disorder evaluation.

Electrooculography

The electrooculogram (EOG) is a measurement of eye activity. Phasic bursts of rapid eye movement occur during rapid eye movement sleep (REM sleep). The EOG is important for recognition of REM sleep, as well as for detecting the transition from wakefulness to Stage 1 sleep, which is characterized by slow, rolling eye movements.

The EOG recordings are possible due to a small electropotential difference from the cornea to the retina. The electrodes are positioned at the right outer canthus (ROC) and the left outer canthus (LOC), eferenced to auricular electrodes. Thus, ROC/A1 and LOC/A2 will register as out-of-phase pen deflections. This facilitates artifact recognition, as well as EEG activity recorded in the eye electrodes. EOG placements incorporate a somewhat superior placement of the electrode on one eye and inferior on the other eye, which allows recognition of vertical eye movements.

Electromyography

Three electromyographic (EMG) electrodes placed in the mentalis–submentalis area allow detection of EMG activity. During sleep, there is a gradual decline in EMG activity, and the dramatic reduction of muscle tone during REM, makes the EMG an important confirmation of REM sleep. Again, adequate removal of oils and dead skin cells with a conductive electrode placement enhances signal processing.

Electrodes or strain gauge sensors are also commonly placed on the tibialis muscles (Fig. 3). The EMG and movement signals from the lower extremities, and sometimes the arms, allow measures of isolated movements, as well as periodic limb movements that may be seen in restless legs syndrome, periodic limb movements of sleep, REM behavior disorder, seizures, parasomnias, and other disorders.

Figure 3. Electrodes applied to legs.

Figure 4. Technologist monitors through the night.

Other Measures and Filtering of Signals

Other biological measures have been incorporated into the polysomnographic measurements. These include body position, body movement, transient arousals, respiratory abnormalities, heart rate, oxygen saturation, esophageal pH, and esophageal pressure.

Video monitoring, as well as audio monitoring, are desirable features and occur in most laboratories. Video recordings with infrared or low light allow correlations of behavioral states with the physiologic measures.

The multiple channels of biological data are gathered in a bundle of electrical wires (the ponytail) at the back of the scalp. The electrical signals require signal processing, amplification, filtering, monitoring, and subsequent collation. The impact of signal output, sampling rates, filtering, and video recording are all factors in the design and in the monitoring of the patient (Fig. 4), as well as scoring information that is processed according to peer-reviewed criteria and event definitions.

The essential measurements in a sleep laboratory involve sleep staging (described below) and this requires calibration, with close attention to signal amplitude and filtering. Frequency measurements ranging from 2–50 Hz are common for measurement of EEG signals. The EMG signals have much higher frequency and sample filtering usually up to 75 Hz, with a notch filter at 60 Hz used to reduce alternating current noise. Signals <10 Hz are usually filtered for an EMG signal.

SCORING AND INTERPRETING PSG

Sleep Staging

Standard sleep stage scoring is guided by Rechtschaffen and Kale's scoring rules (8). The standard EEG recording is negative-up with amplitude measured from peak to valley of the waveform. Delta rhythm is 2–4 Hz; theta is 4–8 Hz; alpha rhythm is 8–12 Hz; beta rhythm is 13–30 Hz; and gamma is >30 Hz. Sleep is scored in 30 s epochs, with a chart speed equivalent to 10 $mm \cdot s^{-1}$. The EEG, EOG, and EMG signals are necessary for sleep state assessment and are used to study clinical and research physiology, as well as pathologic processes. The epoch is scored based on the majority population of EEG/EOG/EMG activity during the 30 s epoch.

Sleep is thus staged as non-REM sleep Stages 1, 2, 3, and 4 and REM sleep. The data are collated in both graphic, as well as tabulated, form to present information from lights-out to sleep onset, as well as quantifying total sleep time, time in bed, sleep efficiency (sleep time divided by time in bed), wake after sleep onset, and sleep stage distribution. A sleep histogram of the night of sleep summarizes the stage distribution pictorially.

Special rules are established for movement, arousals, and periodic limb movements in sleep, as well as consideration for specific disease processes. For example, narcolepsy may be associated with excessive motor activity during sleep, with an elevated EMG amplitude, particularly during phasic rapid eye movement sleep. Obstructive sleep apnea patients may have <15 s of sleep during a 30 s epoch due to arousals from obstructive events, forcing the scoring of the epoch as awake. Special rules to allow for these variances are in place.

Sleep-Disordered Breathing

Abnormal breathing during sleep is one of the most common disorders and accounts for as much as 70% of patients presenting to a sleep laboratory. Some laboratories specialize in sleep-disordered breathing alone. Snoring with increase in upper airway resistance due to functional relaxation of dilator muscles in the pharynx is a common disorder, ranging from 20% to 40% of the adult population and 13% of children. Anatomic changes, particularly tonsillar hypertrophy, add to the increase in upper airway resistance. This increase in the work of breathing may cause unstable breathing, with episodes of apnea or hypopnea, with associated changes in oxygenation, autonomic tone, and sleep state.

Obstructive apnea is defined as 10 s of cessation of airflow, despite a continued effort to breathe, in the adult population. Hypopnea is defined as a discernable reduction in flow or effort that produces a 4% desaturation. Central apnea is cessation of flow associated with cessation of effort for at least 10 s in the adult population. In the pediatric population, the duration for defining apneas is shorter. In some laboratories, hypopneas are also defined as a discernable reduction in flow or effort, which terminates in a 3% desaturation or an arousal. Mass loading of the diaphragm due to obesity and intrinsic central nervous system regulation of breathing are other variables to be considered clinically, as well as in research.

Current laboratories monitor flow, effort, and oxygen saturation as surrogate measures of minute ventilation and gas exchange. The intent is to assess the effort to breathe, the results of the output of ventilation, and, ideally, gas exchange, especially O_2 content or oxygen saturation. These measurements along with clinical correlation provide risk assessment and guide treatment plans.

Methods to detect airflow include pneumotachography, nasal airway pressure, thermistors, and thermocouples, as well as expired CO_2. Nasal airway pressures resemble the signals from a pneumotachograph, and therefore give a

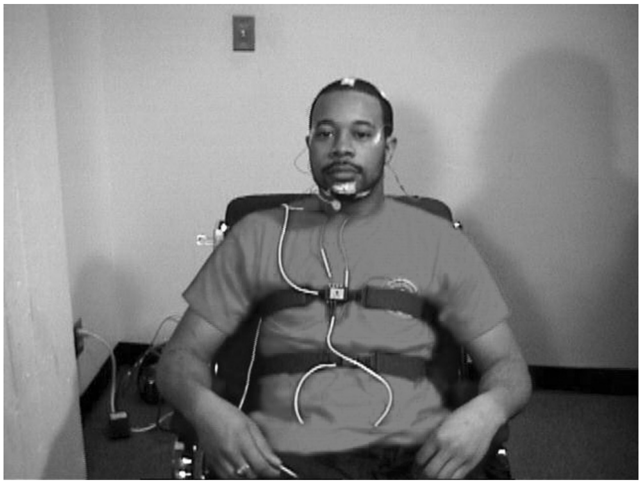

Figure 5. Sleep setup with respiratory belts.

qualitative measure of increase in upper airway resistance. The pressure gradient intranasally compared to ambient atmospheric pressure is used to calculate the flow. Effort signals may be generated by flexible bands around the chest and the abdomen to detect movement. This is the most common technique (Fig. 5). Strain gauges, impedance pneumography, inductance plethysmography, and intercostal muscle electromyography have been used. Snoring sensors include microphones and piezoelectric assessment of vibration.

Oxygen content is most commonly measured by pulse oximetry. Decrease in oxygen saturation during sleep is most commonly due to changes in ventilation. Oxygen desaturation is an important criterion for scoring respiratory events, and thus critical for diagnostic studies. Intrinsic lung disease or cardiac disease may produce ventilation-perfusion mismatch and may also produce decreases in O_2 saturation. In a stable state, however, most decreases in oxygen saturation reflect changes in minute ventilation.

Pulse oximetry uses a two wavelength light transmitter, using spectrophotoelectrical techniques based on oxyhemoglobin absorption. Pulsatile tissues are necessary for pulse oximetry, and therefore these are usually applied to the finger, earlobe, or nasal sites. Reduction in pulsation, skin pigment, and dyshemoglobinemias may interfere with signal processing. The sampling rate, filtering, and proprietary algorithms for signal processing may affect the resolution of the signal.

Transcutaneous oxygen and carbon dioxide are other techniques available, but they are not commonly used, except in neonates. Transcutaneous CO_2 may be useful to assess chronic hypoventilation, but the resolution time for these measures limits their use in routine polysomnography.

Esophageal pressure measurements using an esophageal balloon provide a highly accurate measure of intrapleural pressure and, therefore, work of breathing. Some sleep centers use esophageal pressure measurements; however, this is not routine, as the invasive technique disturbs sleep. However, esophageal pressure measurements enhance the ability to measure upper airway resistance syndrome and central alveolar hypoventilation. Cardiac data primarily consists of heart rate and rhythm. Limited EKG electrodes, equivalent to lead II (right arm–left arm) or precordial leads (V5 or V6) are used, depending on the electrical axis and lab protocol. Clinical studies focus on high, mean, and low heart rates, as well as semiquantitative data on arrhythmias as to frequency and type. These are correlated with respiratory events or sleep state.

In patients with obstructive sleep apnea, efficacy of treatment is measured by applying positive airway pressure (PAP) or bilevel positive airway pressure (BiPAP). Flow signals are generated from the hardware device, allowing quantitative measures of flow and upper airway resistance based on waveform characteristics. Sleep state, body position, oxygen saturation, electrocardiogram, flow, and effort data are recorded to assure proper titration. The goal is to reduce the respiratory disturbance index, ideally < 5, and to minimize oxygen desaturations.

Daytime Sleepiness

Objective assessment of daytime sleepiness is another important laboratory diagnostic measure. The multiple sleep latency test involves a series of nap opportunities at 2 h intervals during the day. The standardized technique and normative data facilitate objective measures of excessive daytime sleepiness. This test is primarily used in the diagnosis of narcolepsy. The maintenance of wakefulness test is similar to the multiple sleep latency test, but requires the individual to attempt to remain awake during 20 or 40 min nap opportunities in a dark room.

Treatment Guidelines. Practice-based guidelines by the American Academy of Sleep Medicine and medical specialty societies have established guidelines for diagnosing and treating sleep disorders. These can be accessed on their website (www.aasmnet.org).

ADDITIONAL AMBULATORY MEASURES

Alternative or ancillary devices have been developed, primarily in the area of sleep-disordered breathing and brain state (sleep–wake estimate). Screening devices have been developed for obstructive sleep apnea primarily. Portable outpatient systems for unsupervised polysomnography are available. The unattended study is considered a level II evaluation. Level III is portable sleep apnea testing, monitoring airflow, effort, electrocardiogram, and oxygen saturation. Level IV is arterial oxygen saturation measurement alone.

Actigraphy incorporates an accelerometer used to measure wrist movement. Complex algorithms have been developed to estimate sleep/wake state, periodic limb movements, and circadian rhythm abnormalities. Actigraphy is particularly useful for long-term monitoring of patients in their homes, and for detection of daytime napping, which is usually not possible for EEG, as it is restricted to the night.

DIGITAL PGS AND FUTURE TRENDS

The EEG, EOG, and EMG signals were traditionally recorded in a sleep laboratory with limited channels on analog systems, with pen deflections recorded on paper. Digital recording systems are more often used now, replicating a chart-paper speed of 10 mm $\cdot$ s^{-1}. Digitized signals with current hardware and software systems allow enhanced collation of data, increased numbers of channels, enhanced filtering, and the potential for automated analysis. Archiving, data compression, and feature extraction are also possible.

Digitized signals of the ECG with high sampling rates, preferably at 200 Hz or higher, provide an opportunity for high resolution analysis. High resolution analysis might provide clearer insights into autonomic tone and vascular resistance and, the influence of sleep states, pathological conditions, and transient arousals. Further development of quantitative measures of ventilatory response, changes in gas exchange, as well as central nervous system and cardiovascular changes, could be helpful for diagnosing and treating sleep-disordered breathing.

Software processing collates data, presenting information in a tabular, as well as in a graphic, format. Clinicians and scientists review raw data, as well as human-supervised or scored changes. These changes can produce an audit trail referenced to the raw data. The fields of data can populate an electronic medical record, as well as a database, including demographics, comorbidities, medications, and fields of data from the polysomnogram, as well as the final diagnosis, treatment, and outcome measures.

Conceivably, advanced EEG analysis might reduce interscorer variability, thus better defining state and process. Enhanced resolution of EEG with improved consistency might allow better feature extraction, such as transient arousals and continuity measures that may improve research and clinical care. This could significantly improve the efficiency, cost and safety in drug development.

Opportunities for the future in sleep diagnostics are numerous. The duration of a polysomnogram, as well as long-term EEG monitoring, create challenges in the quality of the signal. Improvement of electrode–skin interface and conductivity are desirable. Application of wireless technologies to minimize the ponytail bundle of wires would be extremely useful. Audiovisual monitoring quality, advanced respiratory analysis, high resolution cardiac assessment, technical acquisition, collation, and data management are all current challenges.

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See also CONTINUOUS POSITIVE AIRWAY PRESSURE; ELECTROENCEPHALOGRAPHY; SLEEP STUDIES, COMPUTER ANALYSIS OF; VENTILATORY MONITORING.