IN THE UNITED STATES, NEARLY 60,000 PATIENTS PER DAY RECEIVE GENERAL anesthesia for surgery. General anesthesia is a drug-induced, reversible condition that includes specific behavioral and physiological traits — unconsciousness, amnesia, analgesia, and akinesia — with concomitant stability of the autonomic, cardiovascular, respiratory, and thermoregulatory systems. General anesthesia produces distinct patterns on the electroencephalogram (EEG), the most common of which is a progressive increase in low-frequency, high-amplitude activity as the level of general anesthesia deepens (Fig. 1). How anesthetic drugs induce and maintain the behavioral states of general anesthesia is an important question in medicine and neuroscience. Substantial insights can be gained by considering the relationship of general anesthesia to sleep and to coma.

Humans spend approximately one third of their lives asleep. Sleep, a state of decreased arousal that is actively generated by nuclei in the hypothalamus, brain stem, and basal forebrain, is crucial for the maintenance of health. Normal human sleep cycles between two states — rapid-eye-movement (REM) sleep and non-REM sleep — at approximately 90-minute intervals. REM sleep is characterized by rapid eye movements, dreaming, irregularities of respiration and heart rate, penile and clitoral erection, and airway and skeletal-muscle hypotonia. In REM sleep, the EEG shows active high-frequency, low-amplitude rhythms (Fig. 1). Non-REM sleep has three distinct EEG stages, with higher-amplitude, lower-frequency rhythms accompanied by waxing and waning muscle tone, decreased body temperature, and decreased heart rate.

Coma is a state of profound unresponsiveness, usually the result of a severe brain injury. Comatose patients typically lie with eyes closed and cannot be roused to respond appropriately to vigorous stimulation. A comatose patient may grimace, move limbs, and have stereotypical withdrawal responses to painful stimuli yet make no localizing responses or discrete defensive movements. As the coma deepens, the patient’s responsiveness even to painful stimuli may diminish or disappear. Although the patterns of EEG activity observed in comatose patients depend on the extent of the brain injury, they frequently resemble the high–amplitude, low-frequency activity seen in patients under general anesthesia (Fig. 1). General anesthesia is, in fact, a reversible drug-induced coma. Nevertheless, anesthesiologists refer to it as “sleep” to avoid disquieting patients. Unfortunately, anesthesiologists also use the word “sleep” in technical descriptions to refer to unconsciousness induced by anesthetic drugs. (For a glossary of terms commonly used in the field of anesthesiology, see the Supplementary Appendix, available with the full text of this article at NEJM.org.)

This review discusses the clinical and neurophysiological features of general anesthesia and their relationships to sleep and coma, focusing on the neural mechanisms of unconsciousness induced by selected intravenous anesthetic drugs.
The clinical signs and EEG patterns of general anesthesia–induced unconsciousness can be described in relation to the three periods in which they appear: induction, maintenance, and emergence.

**INDUCTION PERIOD**

Before induction, the patient has a normal, active EEG, with prominent alpha activity (10 Hz) when the eyes are closed (Fig. 1). Administration of a small dose of a hypnotic drug such as propofol, a barbiturate, or etomidate, all of which act on γ-aminobutyric acid type A (GABA<sub>A</sub>) receptors, induces a state of sedation in which the patient is calm and easily arousable, with the eyes generally closed. As the dose is slowly increased, the patient may enter a state of paradoxical excitation, characterized by purposeless or defensive movements, incoherent speech, euphoria or dysphoria, and an increase in beta activity on the EEG (13 to 25 Hz). This state is termed paradoxical because the drug that is intended to induce unconsciousness induces excitation instead.

As more of the hypnotic agent is administered — typically as a bolus over a period of 10 to 15 seconds — an increasingly irregular respiratory pattern develops that progresses to apnea, at which point bag-mask ventilation must be initi-
ated to support breathing. There is a concomitant loss of response to oral commands and skeletal-muscle tone. Loss of consciousness can be easily assessed by having patients follow the movement of the anesthesiologist’s finger with their eyes. As unconsciousness ensues, eye tracking stops, nystagmus may appear, and blinking increases. The oculocephalic, eyelash, and corneal reflexes are lost, yet the pupillary light reflex remains. There can be either an increase or a decrease in blood pressure, whereas the heart rate typically increases. Administering an opioid or a benzodiazepine before or during induction may mitigate the increased heart-rate response, and vasopressors may be given to maintain blood pressure. Tracheal intubation is usually performed at the end of induction, after the administration of a muscle relaxant.

MAINTENANCE PERIOD

General anesthesia is maintained by a combination of hypnotic agents, inhalational agents, opioids, muscle relaxants, sedatives, and cardiovascular drugs, along with ventilatory and thermoregulatory support. During the maintenance period, changes in the heart rate and blood pressure are among the clinical signs used to monitor the level of general anesthesia (see the Supplementary Appendix). When the state of general anesthesia is inadequate for the level of nociceptive stimulation from surgery, the heart rate and blood pressure can increase dramatically, alerting the anesthesiologist to the possibility of increased nociception and arousal. Other indicators of inadequate general anesthesia are perspiration, tearing, changes in pupil size, the return of muscle tone, movement, and changes in EEG measures of brain activity. At levels appropriate for surgery, general anesthesia can functionally approximate brain-stem death, because patients are unconscious, have depressed brain-stem reflexes, do not respond to nociceptive stimuli, have no apneic drive, and require cardiorespiratory and thermoregulatory support.

Four EEG patterns define the phases of the maintenance period (Fig. 1). Phase 1, a light state of general anesthesia, is characterized by a decrease in EEG beta activity (13 to 30 Hz) and an increase in EEG alpha activity (8 to 12 Hz) and delta activity (0 to 4 Hz). During phase 2, the intermediate state, beta activity decreases and alpha and delta activity increases, with so-called anteriorization — that is, an increase in alpha and delta activity in the anterior EEG leads relative to the posterior leads. The EEG in phase 2 resembles that seen in stage 3, non-REM (or slow-wave) sleep. Phase 3 is a deeper state, in which the EEG is characterized by flat periods interspersed with periods of alpha and beta activity — a pattern called burst suppression. As this state of general anesthesia deepens, the time between the periods of alpha activity lengthens, and the amplitudes of the alpha and beta activity decrease. Surgery is usually performed during phases 2 and 3. In phase 4, the most profound state of general anesthesia, the EEG is isoelectric (completely flat). An isoelectric EEG may be purposely induced by the administration of a barbiturate or propofol to protect the brain during neurosurgery or to stop generalized seizures.

EMERGENCE PERIOD

Emergence from general anesthesia is a passive process that depends on the amounts of drugs administered; their sites of action, potency, and pharmacokinetics; the patient’s physiological characteristics; and the type and duration of the surgery. Recovery from general anesthesia is generally assessed by monitoring physiological and behavioral signs. The return of spontaneous respirations is typically one of the first clinical signs observed once peripheral neuromuscular blockade is decreased. This marks the patient’s return from a functional state that approximates brain-stem death (Table 1). The heart rate and blood pressure typically increase, provided that these responses are not pharmacologically blocked. Salivation and tearing begin, followed by nonlocalizing responses to painful stimulation, suggesting that the patient’s state is most similar to a vegetative state with the notable exception that the eyes remain closed. As skeletal-muscle tone returns, the patient begins to grimace, swallow, gag, and cough and make defensive movements, such as reaching for the endotracheal or nasogastric tube. At this point the anesthesiologist will perform extubation, provided that there is sufficient return of brain-stem reflexes to maintain spontaneous respirations and airway protection, even if there is no response to oral commands. The eyes may still not open spontaneously. As the patient emerges from general anesthesia, the EEG patterns proceed in approximately reverse order from phases 2 or 3 of the maintenance period to an active EEG that is consistent with a fully awake state (Fig. 1).
charge from the postanesthesia care unit, the patient passes through a minimally conscious state. In a study in rodents, direct injection of a barbiturate into the mesopontine tegmental area led to unconsciousness. Such observations confirm brain-injury studies showing that brain-stem unconsciousness typically involves the lateral dorsal tegmental areas of the pons and the midbrain paramedian region. Apnea can be explained, in part, by the actions of the hypnotic agent on GABAergic interneurons in the respiratory control network in the ventral medulla and pons.

The rapid atonia that occurs after bolus administration of propofol is most likely due to the actions of this drug in the spinal cord and in the pontine and medullary reticular nuclei that control the antigravity muscles. Certain observations are consistent with this concept of propofol’s mechanism of action — for example, the atonia that follows the inadvertent injection of local anesthetics into the subarachnoid space or basilar artery during an interscalene block or the inadvertent injection of alcohol into the cervical spinal cord during a facet block. Furthermore, observations in patients who have pontine strokes and locked-in syndromes support this concept, as do observations with the muscle-relaxing and soporific effects of the GABA agonist baclofen. Such observations may explain why near the end of surgery, small doses of propofol can be used to provide rapid muscle relaxation of short duration and why, in this case, propofol is preferable to muscle relaxants that have a slower onset and longer duration of action. In contrast to the drug-induced atonia described above, rigidity and spasticity are typically seen in patients who are in a coma or a vegetative state, and muscle tone is preserved during slow-wave sleep.

Signs of the loss of brain-stem function (apnea, atonia, and losses of the oculocephalic and corneal reflexes) and hence unconsciousness reliably indicate when to initiate bag-mask ventilation or to place a laryngeal mask airway during induction of general anesthesia. Neural circuits involved in sleep provide additional insights into basal forebrain, brain-stem, and hypothalamic mechanisms of unconsciousness. During the awake state, the locus ceruleus provides norepinephrine-mediated inhibition of the ventrolateral preoptic nucleus in the hypothalamus. Therefore, GABA-mediated and galanin-mediated inhibition of the ascending arousal circuits by the ventrolateral preoptic nu-
Adenosine, one of the brain’s principal somnogens, accumulates from degradation of adenosine triphosphate during prolonged intervals of wakefulness. Binding of adenosine in the ventrolateral preoptic nucleus is associated with increased activity in this brain center. Adenosine binding and inhibition of the locus ceruleus lead to activation of the ventrolateral preoptic nucleus, which inhibits the ascending arousal circuits and promotes non-REM sleep. The sedative dexmedetomidine is an α₂-adrenergic agonist that inhibits the release of norepinephrine from the locus ceruleus and thus allows the ventrolateral preoptic nucleus to reduce arousal by inhibiting the ascending arousal circuits (Fig. 2B). The EEG patterns of dexmedetomidine-induced sedation closely resemble those of non-REM sleep.

Propofol also promotes unconsciousness, in part, by GABAₐ-mediated inhibition of release of the arousal-promoting neurotransmitter histamine in the cortex from the tuberomammillary nucleus in the hypothalamus.

The active EEG patterns observed during REM sleep are due in part to strong cholinergic inputs from the lateral dorsal tegmental and pedunculopontine tegmental nuclei to the medial pontine reticular formation and thalamus and from the basal forebrain to the cortex. The synthetic opioid fentanyl decreases arousal by reducing acetylcholine in the medial pontine reticular formation, whereas morphine decreases arousal by inhibiting the neurons in the lateral dorsal tegmental nucleus, medial pontine reticular formation, and basal forebrain (Fig. 2C). Opioids further contribute to unconsciousness by bind-
ing to opioid receptors in the periaqueductal gray,\textsuperscript{58} rostral ventral medulla,\textsuperscript{58,59} spinal cord,\textsuperscript{59} and possibly peripheral tissue\textsuperscript{60} to reduce nociceptive transmission in the central nervous system. That opioids act primarily in the nociceptive pathways rather than in the cortex to alter arousal and to partially alter cognition helps explain the high incidence of postoperative awareness in patients undergoing cardiac surgery, for which high-dose opioids have, until recently, been the primary anesthetic.\textsuperscript{61,62}

Clinical studies have shown that unconsciousness induced by propofol can be reversed by the administration of the cholinomimetic agent physostigmine.\textsuperscript{63} A combination of imaging,\textsuperscript{31} molecular,\textsuperscript{37} and neurophysiological\textsuperscript{30} studies suggests that propofol acts, in part, by enhancing GABA\textsubscript{A}-mediated inhibition by interneurons of pyramidal neurons in the cortex and subcortical areas,\textsuperscript{50} whereas physostigmine counteracts this effect by enhancing cholinergic activity throughout the cortex (Fig. 2A). Physostigmine is a standard treatment for emergence delirium.\textsuperscript{64,65} A state of confusion seen on emergence from general anesthesia.

The EEG patterns and other features of general anesthesia generally differ from those of sleep (Fig. 1). The highly active state of the cortex during REM sleep is mediated by a cholinergic drive emanating from the basal forebrain and from the lateral dorsal and pedunculopontine tegmental nuclei to the cortex via the thalamus.\textsuperscript{56} As discussed below, paradoxical excitation under general anesthesia may represent GABA\textsubscript{A}-mediated disinhibition in striothalamic pathways. The skeletal-muscle hypotonia observed during REM sleep is partially due to cholinergic activation of pontomedullary networks, resulting in glycine-mediated inhibition of alpha motor neurons in the spinal cord,\textsuperscript{66} whereas during paradoxical excitation, motor tone is preserved.\textsuperscript{13}

There is similarity between the EEG patterns seen in slow-wave sleep and those seen in phase 2 of the maintenance period of general anesthesia (Fig. 1). This period of general anesthesia is sufficiently deep to perform surgery. During sleep, the greatest decrease in pain perception occurs in the slow-wave stage. Arousal is possible during this stage, but it requires stronger stimulation than during other stages of sleep.\textsuperscript{67} Slow-wave sleep has been shown to represent the switch of the thalamus from its tonic to its bursting mode.\textsuperscript{68} The tonic mode favors transmission of somatosensory information through the thalamus, whereas the bursting mode inhibits transmission of such information. Phase 2 of the maintenance period of general anesthesia and slow-wave sleep represent profound decreases in cortical activity achieved by pharmacologic means and by an endogenous circuit mechanism, respectively.

**CENTRAL THALAMIC CIRCUITS AND CONTROL OF AROUSAL**

The central thalamus plays an important role in normal arousal regulation.\textsuperscript{69} The convergence in this area of ascending pathways from the brain stem and basal forebrain and descending pathways from the frontal cortex helps regulate forebrain arousal and maintain organized behavior during wakefulness. Both direct injury of the central thalamus and marked deafferentation of its neurons due to diffuse brain insults are associated with the severe impairment of arousal and of forebrain functional integration observed in several brain disorders.\textsuperscript{70} Electrical stimulation of the central thalamus in a minimally conscious patient has been reported to improve cognitive function, mobility, and oral feeding.\textsuperscript{71} Similarly, unconsciousness induced by general anesthesia has been reversed experimentally by the direct injection of cholinergic agonists into the central thalamus.\textsuperscript{72}

The central thalamus may mediate several of the phenomena seen in general anesthesia, as described above (Fig. 3). A possible explanation for the paradoxical excitation observed with a low dose of nearly every anesthetic drug\textsuperscript{1,4,13-16} is suggested by the circuit mechanism.\textsuperscript{69,73} which has been proposed to explain the paradoxical arousal of a patient from a minimally conscious state after administration of the GABA\textsubscript{A}-agonist zolpidem.\textsuperscript{74} After administration of zolpidem, the marked downregulation of the anterior-forebrain network that accompanied this patient’s brain injury was reversed, with notable functional improvement. The globus pallidus interna normally provides tonic inhibitory inputs to the central thalamus that are opposed by striatal inhibition of the pallidum. Binding of zolpidem in the GABA\textsubscript{A}-receptor–rich globus pallidus interna may suppress this tonic inhibitory input to the thalamus,\textsuperscript{75} fostering activation of thalamocortical and thalamostriatal circuits and, consequently, enhancing arousal (Fig. 3A). For anesthetic drugs that promote GABA\textsubscript{A} inhibition, paradoxical excitation may be explained by a similar action in these circuits. This hypothesis could also account
for the paradoxical excitation observed during endoscopy and the delirium observed in intensive care units that is commonly associated with sedation induced with benzodiazepines, which are GABAₐ agonists.⁷⁶,⁷⁷ The fact that purposeless movements are associated with paradoxical excitation is consistent with a possible basal ganglia mechanism.¹³

An imaging study in humans suggests a role for the corticobasal ganglia–thalamic circuit in propofol-induced unconsciousness.⁷⁸ This circuit may also underlie anteriorization (Fig. 3B). The delta and alpha rhythms seen on the EEG during general anesthesia and sleep⁷⁹ could arise from sustained hyperpolarization of pyramidal neurons in the lower output layers of the cortex owing to withdrawal (during sleep) or inhibition (during general anesthesia) of excitatory synaptic inputs.⁸⁰ Initiation of these changes in the anterior forebrain could be a consequence of active inhibition of the central thalamus that occurs when cortical inputs to the striatum are insufficient (Fig. 3A). A theoretical model has shown that as propofol is increased to a dose beyond that which produces paradoxical excitation, its actions in the thalamocortical circuits lead to a coherent alpha oscillation between the thalamus and the anterior forebrain.⁸¹

Finally, burst suppression is believed to be a strong, synchronized outflow of thalamic discharges to a widely unresponsive cortex⁸² (Fig. 1). It is a deeper state of general anesthesia than is phase 2 of the maintenance period, which resembles the tonic bursting mode of the thalamus seen in slow-wave sleep. Bursts become more widely separated during burst suppression as the level of general anesthesia deepens. This suggests that a larger fraction of the cortex is inactive during burst suppression relative to phase 2 of general anesthesia or slow-wave sleep. Supporting this hypothesis is the observation that burst suppression is also seen in coma due to diffuse anoxic damage,⁸³ induced hypothermia,⁸⁴ and epilepsy due to the Ohtahara syndrome.⁸⁵ The absence of burst suppression during sleep is an important electrophysiological distinction between sleep and general anesthesia.

**ACTIVE BRAIN STATES AND UNCONSCIOUSNESS**

In contrast to unconsciousness induced by most hypnotic agents, which is predominantly associated with slow EEG patterns, unconsciousness induced by the NMDA antagonist ketamine is associated with active EEG patterns.⁸⁶,⁸⁷ Seizures are commonly associated with active, highly organized EEG patterns. Unconsciousness due to seizures most likely results from organized, aberrant brain activity that impedes the normal communications necessary to maintain arousal and cognition.⁸⁸ Similarly, a highly active brain state most likely plays a role in unconsciousness induced by ketamine. Ketamine preferentially inhibits NMDA-mediated glutamatergic inputs to GABAergic interneurons, leading to aberrant excitatory activity in the cortex, hippocampus, and limbic system and ultimately unconsciousness (Fig. 4).⁸⁹,⁹⁰ Hallucinations may result because the aberrant activation allows the association of information in a manner that is inconsistent in time and space. The hallucinations can be mitigated by the concurrent administration of a benzodiazepine,⁹¹ which presumably acts to enhance...
MECHANISMS OF DISEASE

A Propofol

B Dexmedetomidine

C Opioids

Monoaminergic pathways
Cholinergic pathways
Lateral hypothalamus neurons

Neurotransmitters
ACH Acetylcholine
DA Dopamine
GABA γ-Aminobutyric acid
GAL Galanin
Glu Glutamate
His Histamine
NE Norepinephrine
SHT Serotonin

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Figure 3. Paradoxical Excitation, Cerebral Metabolism, and Electroencephalographic (EEG) Activity in Stages of Coma Recovery.

Cortical damage causes loss of excitatory inputs from the frontal cortex to the median spiny neurons in the striatum, as shown in Panel A. Normal striatal inhibition of the globus pallidus interna is lost, and the globus pallidus interna tonically inhibits the thalamus. Zolpidem and propofol may bind to GABA<sub>1</sub> receptors in the globus pallidus interna, blocking its inhibitory inputs to the thalamus; as a result, excitatory cortical inputs from the thalamus are restored, causing paradoxical excitation. Panel B schematically depicts changes in cerebral metabolism as measured by positron emission tomographic (PET) scanning and on electroencephalography (EEG) at different stages of coma recovery. In the awake state, the EEG pattern is active and cerebral metabolism is globally active. Paradoxical excitation induced by the administration of zolpidem, which is associated with behavioral improvement in some minimally conscious patients, is reflected by an active EEG pattern with reduced prefrontal cortex metabolism. Patients in minimally conscious and vegetative states may show EEG anteriorization, with alpha, theta, and delta EEG patterns and decreased metabolism in the frontal cortex, striatum, and thalamus. Burst suppression in coma correlates with globally depressed metabolism. General anesthesia results in similar EEG patterns. A denotes anterior, and P posterior.
GABA<sub>A</sub>-mediated activity of the interneurons and hence leads to sedation. The potent antinociceptive effects of ketamine on NMDA receptors in the spinal cord and its inhibition of acetylcholine release from the pons also contribute to unconsciousness (Fig. 4).<sup>92-94</sup>

**EMERGENCE FROM GENERAL ANESTHESIA AND RECOVERY FROM COMA**

Recovery from an initial coma — if it occurs — may require hours to years. In contrast, emergence from general anesthesia typically requires minutes. Nevertheless, it is useful to compare emergence from general anesthesia and recovery from coma (Table 1). The early clinical signs of emergence from general anesthesia — return of regular breathing, salivation, tearing, swallowing, gagging, and grimacing — approximate the caudal–rostral progression in the brain stem of the return of sensory, motor, and autonomic function (Table 1). A later sign, such as response to oral commands, indicates the return of cortical function. The quantitative neurobehavioral metrics used to monitor recovery from coma could be used to track the emergence from general anesthesia from a functional state that can approximate brain-stem death to states similar to a vegetative state and, eventually, to a minimally conscious state.<sup>95</sup> The fact that general anesthesia can be functionally equivalent to brain-stem death indicates how deeply general anesthesia can depress brain function and perhaps explains why some patients do not fully recover consciousness for several hours after general anesthesia.
and why postoperative cognitive dysfunction could persist in elderly patients for several months.\textsuperscript{96} In conclusion, a better understanding of sleep and coma may lead to new approaches to general anesthesia based on new ways to alter consciousness,\textsuperscript{29,97,98} provide analgesia,\textsuperscript{99,100} induce amnesia, and provide muscle relaxation.\textsuperscript{66} Supported by the Massachusetts General Hospital Department of Anesthesia, Critical Care, and Pain Medicine and by the National Institutes of Health (NIH) Director’s Pioneer Award (DP1OD003646, to Dr. Brown); by the University of Michigan, Department of Anesthesiology, and by NIH grants (HL40881 and HL65272, to Dr. Lydic); and by grants from the James S. McDonnell Foundation (Dr. Schiff) and the NIH (HD59192, to Dr. Schiff).

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