Neuroanesthesia and Related Aspects

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Abstract: Neurosurgical procedures are now quite safe due to invaluable advances in neuroanesthesia techniques. During an operation, the maintenance of low ICP is essential both for anesthesiologists and neurosurgeons. So, the basics of ICP and details of the causes of raised ICP as well as its management are described in the first part of this section. The pharmacological drugs utilized for neuroanesthesia are described shortly after, and the steps of practically inducing neuroanesthesia are also mentioned. Inducing neuroanesthesia in special situations (such as aneurysm surgery, sitting-position surgery, post-fossa surgery, etc.) is also discussed in this chapter. Finally, an account of awake craniotomy is also provided in brief.

Abbreviations

ADH	antidiuretic hormone	ICA	internal carotid artery
AVM	arterio-venous malformation	ICP	intracranial pressure
BBB	blood–brain barrier	ICU	intensive care unit
CBF	cerebral blood flow	MAC	minimum alveolar concentration
CBV	cerebral blood volume	MAP	mean arterial pressure
CMRO2	cerebral metabolic rate of O2	NMDA	N-methyl D-aspartate
CNS	central nervous system	NO	nitric oxide
CPR	cardiopulmonary resuscitation	NPPB	normal perfusion pressure breakthrough
CPP	cerebral perfusion pressure	OSA	obstructive sleep apnea
CSF	cerebrospinal fluid	PEEP	positive end-expiratory pressure
CSWS	cerebral salt wasting syndrome	PVC	premature ventricular contraction
CT	computed tomography	SIADH	secretion of inappropriate ADH
CVP	cerebral venous pressure	TBI	traumatic brain injury
DBS	deep-brain stimulation	TIVA	total intravenous anesthesia
DI	diabetes insipidus	VA	ventriculo-atrial
DPH	delayed postoperative hemorrhage	VAE	venous air embolism
EEG	electro-encephalo gram	VT	ventricular tachycardia
HDU	high-dependency unit		

1. Neuro-Anesthesia

1.1. Introduction

The disordered physiology caused by neurosurgical disease and the special demands of neurosurgical techniques pose unique challenges for a neuro-anesthesiologist. The brain is contained in a rigid, closed box, and its function is highly dependent on the (relatively constant) maintenance of the cerebral blood flow within that confined area. Any cerebral injuries and the disease process may jeopardize cerebral circulation in ways that predispose one to cerebral ischemia and ultimately neuronal damage. Anesthetic drugs and techniques have significant effects on both the physiology and pathology of the brain. The alterations they produce in cerebral function can be used to ensure good operating conditions for neurosurgery and to limit the extent of potential perioperative neuronal damage. On the other hand, failure to practice these standard methods in a proper contextual way may lead to disastrous consequences. Modern drugs and monitoring systems grant an anesthesiologist considerable control over cerebral and cardiovascular functions; as a result, many surgical procedures that had been considered very risky even a few decades ago have become routine practices for today's neurosurgeon.

1.2. Disorders of ICP

1.2.1. The Intracranial Pressure

The skull is essentially a closed box containing the brain, which weighs about 1400 g in an adult, and about 150 mL of cerebrospinal fluid (CSF), of which half is in the cranial space and the other half is in the spinal CSF space. The brain (and the spinal cord) also contains a significant amount of both arterial and venous blood in

a dynamic state. The cerebral metabolic demand regulates cerebral blood flow (CBF), which is roughly 50 mL per 100 g of brain per minute (on average). Inside the skull vault, a distinct pressure called intracranial pressure (ICP) exists, with a normal value of up to 2 kPa (15 mm Hg). This pressure is the result of many interacting forces, including CSF dynamics, and arterial pressure forcing blood into the skull.

1.2.2. Raised ICP

The four intracranial constituents (brain, CSF, arterial blood, and venous blood), two of which are essentially solid and liquid, are incompressible, but two of them (CSF and venous blood) are connected with low-pressure systems outside the skull. Once intracranial space occupation begins due to any tumor, hematoma, or abscess, the process of a rise in ICP starts (Table 1). The mechanisms that compensate for the presence of a SOL rely on these extracranial connections. As the SOL develops, intracranial CSF is lost to the spinal space of the CSF, and venous blood from the thin-walled cerebral veins is lost to the great veins in the chest. The ICP does not, therefore, rise in the early stages of intracranial space occupation. There is a limit to the amount of space occupation that can be accommodated in this way; once, this limit is reached, the ICP shoots up. The Monroe–Kellie Doctrine addresses this issue, and, according to this theory, the contents of the skull are in a constant-volume state. The total volumes of brain tissues, cerebrospinal fluid (CSF), and intracranial blood are fixed in this way. When the volume of one component is increased, the volume of one or two of the other components is reduced. A decrease in cerebral blood flow or a herniation of the brain is a clinical indication of a component's volume change.

Table 1. Etiologies of intracranial hypertension.

Primary or Intracranial	Secondary or Extracranial (Mostly Related to Faults in the Technique Employed)
Brain neoplasm	Airway obstruction
Trauma (epidural and subdural hematomas, cerebral contusions)	Inadequate muscle relaxation
Nontraumatic brain hemorrhage	Positive end expiratory pressure (PEEP)
Cerebral infarction	Raised Intrathoracic pressure
Hydrocephalus	Hypercarbia or hypoxia
Idiopathic intracranial hypertension	Hypotension (hypovolemia) or hypertension (pain/cough)
Other (example—pneumocephalus, abscesses, cysts)	Volume overload
	Posture (head rotation, Trendelenburg position)
	Hyperpyrexia
	Seizures
	Drug and metabolic (such as, vasodilators)

Source: Table by authors.

If a patient afflicted with such a condition is not treated, the cycle will continue until the patient dies from neurological impairment or a catastrophic herniation. Acute elevations in ICP (plateau waves) lasting 1 to 15 minutes can be linked to periodic rises in arterial blood pressure with a reduction in reflex heart rate (the Cushing response).

The volume of the posterior fossa is much lower than that of the supratentorial space. Any SOL developing in this compartment shows a sharp rise in ICP partly because of its lower volume and partly because it may obstruct CSF flow and hence lead to hydrocephalus at a very early stage.

In patients with a traumatic brain injury (TBI), special aspects should be examined, as lesions might be varied and numerous variables can lead to an increase in ICP (Adelson et al. 2003):

1. Traumatically caused masses—hematomas in the epidural or subdural space, hemorrhagic contusions, foreign bodies, and depressed skull fractures;
2. Cerebral edema;
3. Hyperemia due to vasomotor paralysis or autoregulation loss;
4. Hypoventilation with consequent hypercarbia and cerebral vasodilation;
5. Hydrocephalus caused by a blockage in the route taken by the CSF or its absorption;
6. Mechanical ventilation, posturing, agitation, or Valsalva maneuvers, which result in increased intrathoracic or intra-abdominal pressure.

Vascular engorgement was assumed to be the most important cause of elevated ICP after the evacuation of traumatic mass lesions. According to recent research, cerebral edema is the primary cause in the majority of instances.

Three to ten days after suffering trauma, a secondary increase in ICP is frequently noted, primarily as a result of delayed hematoma formation, such as in the case of epidural hematomas, acute subdural hematomas, and traumatic hemorrhagic contusions with surrounding edema, which may necessitate evacuation (Unterberg et al. 1993). Cerebral vasospasm (Taneda et al. 1996), hypoventilation, and hyponatremia are all possible causes of delayed elevations in ICP.

1.2.3. Symptom and Signs of Raised ICP

A raised ICP (Table 1), either preexisting or developed during anesthesia or surgery, always puts the patient in great danger. In the preoperative assessment of a patient for neuroanesthesia, the issue of raised ICP should always be considered. Although many individuals with high ICP are asymptomatic at first, they eventually develop symptoms and signs such headaches, nausea, vomiting, papilledema, localized neurological impairments, and altered consciousness.

The clinical findings of raised ICP need to be distinguished from those as to the original lesion that produced the raised ICP. Miller suggested that headache, vomiting, papilledema, and drowsiness are the symptoms and signs likely to be due to raised ICP alone, whereas bradycardia, arterial hypertension, and papillary changes, although often occurring together with raised ICP, may arise from brainstem distortion or ischemia (Turner 2003).

1.2.4. Management of Raised ICP

Goals of Therapy

1. Keep the patient's ICP between 20 and 25 mm Hg.
2. Maintain a cerebral perfusion pressure (CPP) of greater than 60 mm Hg by keeping mean arterial pressure (MAP) at a healthy level.
3. Avoid anything that aggravates or causes an increase in ICP.

An outline of the diagnosis and treatment of raised intracranial pressure is shown in Figure 1.

1.3. Pharmacology Related to Neuroanesthesia

1.3.1. Intravenous Anesthetic Agents

Propofol

This drug is the most recent intravenous anesthetic drug in clinical use. It was discovered in 1977 and approved for clinical use in the America in 1989. Over the past few decades, it has replaced thiopental as the leading anesthetic agent mostly because of its excellent kinetic and dynamic profile that is closer to the ideal profile, suitable for short and prolonged use for both anesthesia and sedation (Table 2). Propofol is an alkyl phenol (2,6-isopropylphenol) and highly lipid-soluble; hence, it rapidly crosses the blood–brain barrier (BBB), causing sedation and hypnosis in a dose-dependent manner. However, its amnesic affect is greater in comparison with that of barbiturates and benzodiazepines, and a very high infusion rate may be required to prevent waking if used as the sole anesthetic (Glass 1993).

The electroencephalogram (EEG)-related effects of increasing the propofol concentration include transient beta excitation at low doses followed by a concentration-dependent decrease in median EEG frequency and an increase in EEG amplitude, leading to burst suppression at blood concentrations greater than 8 μg/mL. Propofol also increases the latency and decreases the amplitude of cortical middle-latency auditory evoked potentials in a dose-dependent manner (Thronton et al. 1989).

Although much less frequently than barbiturates and etomidate, propofol has been associated with some excitatory effects, which include occasional involuntary movements, myoclonus, dystonic posturing, and opisthotonos. They are subcortical in origin and do not show any features of epilepsy in an EEG. Propofol has dose-dependent anticonvulsant activity and has been successfully used to control status epilepticus (Rushton and Sneyd 2003).

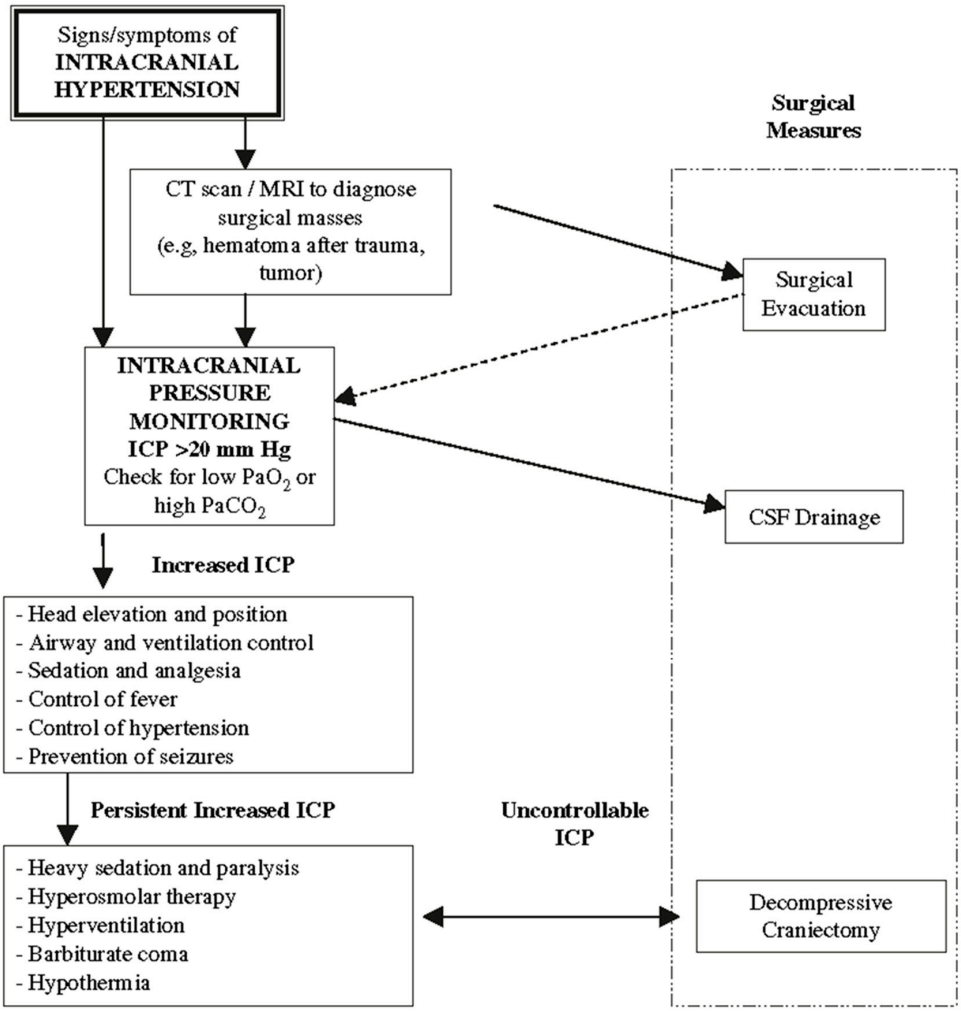

Figure 1. Outline of diagnosis and treatment of raised intracranial pressure. Source: Figure reprinted from Rangel-Castillo et al. (2008), used with permission.

Table 2. Summary of the advantages and disadvantages of this remarkable anesthetic (Propofol).

Advantages	Disadvantages
Pleasant sedation and recovery	Pain upon injection
Rapid onset and easy titration	It is a lipid emulsion carrier, so it supports bacterial growth
Suitable for both induction as well as maintenance of anesthesia	Possibility of hypotension, especially with limited cardiovascular reserve.
Suppression of airway reflexes	Expensive
Antiemetic effect	
Safe for patients with porphyria	

Source: Authors' compilation based on data from Rushton and Sneyd (2003).

Propofol reduces cerebral oxygen consumption (cerebral metabolic rate of O2-CMRO2) and cerebral blood flow (CBF), ultimately decreasing ICP in patients with normal or raised ICP. In one study, researchers observed a 32% reduction in CSF pressure following a 1.5 mg/kg bolus injection (Ravussin et al. 1998). Cerebral autoregulation and reactivity to CO_2 are preserved, but MAP and CPP may fall in case of major cardiovascular depression. Propofol can induce a significant drop in CPP (50 mmHg) in patients with high ICP unless measures are taken to sustain mean arterial blood pressure (Butterworth et al. 2013).

Barbiturates

Because of their exceedingly brief duration of action, ultra-short-acting barbiturates are frequently utilized for anesthesia. After their introduction in 1930s, barbiturates, especially thiopental, played a pivotal role in

the field of intravenous anesthesia. Although propofol has largely supplanted their role in modern anesthesia, barbiturates (particularly thiopental) still have a prestigious status, especially when neuroprotection is an issue.

Thiopental and methohexital are the only two agents from the barbiturate family that are still being used as intravenous hypnotic agents. Both lead to a decrease in brain electrical activity and metabolism (Box 1). Thiopental depresses CMRO2 in a dose-related manner to a maximum of 55% of the conscious levels when the EEG becomes flat. No further fall in CMRO2 is observed if more thiopental is given. Reduced CMRO2 causes reduced CBF that results in a fall in ICP, and there is evidence that this fall is greater when the ICP is high. CPP is usually maintained or slightly reduced, giving some benefit to the patients with raised ICP.

Both the barbiturates affect EEG results in a dose-dependent manner. The awake α pattern progresses to a higher amplitude and has a slower frequency δ and slower θ waves until burst suppression precedes a flat EEG. Thiopental is a potent anticonvulsant, but methohexital possesses proconvulsant properties (Reddy et al. 1993).

Box 1. Summary of the neuroprotective properties of thiopental.

Decreases CMRO2, CBF and ICP
Potent hypnotic with good CVS profile
Potent anticonvulsant
Antiepileptic
Free radical scavenger of CNS (Smith et al. 1980)
Facilitates CSF absorption

Etomidate

Etomidate is an imidazole (an organic aromatic heterocyclic compound) derivative. Its ability to quickly induce hypnosis and cause minimal respiratory depression and its high therapeutic index for cardiovascular side-effects make it a good choice during the rapid sequence induction of a compromised patient. A high incidence of myoclonus (50–80%) is observed during the induction of hypnosis in the absence of premedication. It causes increased EEG activity in epileptogenic foci, and this finding has been used during intraoperative mapping prior to surgical ablation. However, in patients receiving etomidate who have no previous history of epilepsy, no clinical or EEG evidence of epileptic seizures has been found; rather, it exhibits potent anticonvulsant characteristics (Modica et al. 1990). Etomidate reduces CBF (36%) and CMRO2 (45%) and thus ICP, but because decreases in CBF occur before decreases in cerebral metabolic activity, there is a risk of cerebral ischemia in areas of critical perfusion.

Increased mortality in a group of patients sedated with etomidate infusions in an ICU was associated with low cortisol levels and attributed to etomidate-induced suppression of adrenal cortisol synthesis. However, the effect of a single bolus is short-lived (6 to 8 h), and the corresponding clinical significance is unclear; hence, etomidate is safe to use for the induction of anesthesia and short-term maintenance (Ledingham and Watt 1993).

Ketamine

Ketamine is the only phencyclidine derivative available for clinical use, and this group of drugs is characterized by an unusual "dissociative" anesthetic state, strong analgesic property, cardiorespiratory stability, and a troublesome emergence phenomenon.

The endpoint of induction is not distinct; in the unique cataleptic state, patients' eyes may remain wide open, and cranial nerve reflexes are more or less preserved, although not necessarily protective. Ketamine bears a complex neuropharmacology. Noncompetitive antagonism of glutamate at N-methyl D-aspartate (NMDA) ligand-gated calcium channels accounts for most of its anesthetic, analgesic, amnestic, and psychomimetic effects. Ketamine also interacts with non-NMDA glutamate receptors, including cholinergic, adrenergic, and opioid receptors. Its ability to inhibit neuronal voltage-dependent sodium channels gives it a local-anesthetic property.

Ketamine increases both CMRO2 and CBF (50–60%) and thereby ICP. This phenomenon is particularly marked in the presence of an intracranial pathology, and it is not coupled with a sympathetically mediated rise in MAP. So, it is conventionally contraindicated for patients with intracranial pathology or if there is a raised ICP.

However, ketamine-induced raised ICP can be attenuated by reducing the P_aCO2 concentration through hyperventilation or using the depressant effects of other intravenous anesthetic drugs. Additionally, according to some investigators, Ketamine may have a neuroprotective effect. Ketamine's blockade of NMDA receptors during periods of increased glutamate concentrations, as commonly found in TBI, may be protective against neuronal cell death.

Emergence reactions include vivid dreams, weird expressions, illusions, and body-image alterations occurring during the first hour of recovery. The incidence of these reactions is higher in adults than in children and in women compared with men, and the psychomimetic side-effects are aggravated by centrally active anticholinergic drugs, including atropine. Premedication with benzodiazepines or a combination of propofol and ketamine are good remedies for these undesirable side effects (Butterworth et al. 2018a).

Benzodiazepines

The primary role of benzodiazepines in anesthesia is sedation and the supplementation of an opioid. Although they have potent sedative, amnestic, and anticonvulsive properties, they provide slow-onset, poor-quality anesthesia when given alone. Their wide range of central effects also includes anxiolysis and centrally mediated muscle relaxation.

Benzodiazepines induce a dose-related decrease in cerebral metabolism as well as cerebral blood circulation and thus should have a beneficial effect on ICP, but hypercarbia and hypoxia from their sedative–depressive effect may cause a dangerous rise in ICP in a patient with compromised intracranial compliance (Butterworth et al. 2018b).

Even though both diazepam and midazolam are excellent anticonvulsants in clinical use, midazolam is the only benzodiazepine suitable for induction during anesthesia and procedural sedation, especially in the case of neuroanesthesia, where an early and clearheaded recovery is highly desirable.

1.3.2. Volatile Anesthetic Agents

Volatile anesthetic agents tend to uncouple the relation between CMRO2 and CBF. This action is well demonstrated by the action of halothane: 1% halothane induces a 26-percent drop in CMRO2 but also a 27-percent increase in CBF and hence a significant increase in ICP (Christensen et al. 1967). Low concentrations of halothane (a mean alveolar concentration (MAC) of 0.6) have little effect on the CBF, but an MAC of 1.1 may triple its effect.

Both isoflurane and sevoflurane are modern ethers and affect the CBF in a less harmful way than halothane (the only hydrocarbon still in use for clinical anesthesia), and both agents significantly reduce CMRO2. However, the cerebral vasodilator effect of sevoflurane is quite a bit weaker than that of isoflurane, and this vapor may be of considerable value in neuroanesthesia because of its low blood gas solubility that allows prompt induction and early recovery.

Sevoflurane and isoflurane cause similar dose-dependent changes in EEG; as the concentration of vapor increases towards an MAC of 1, there is an increase in the voltage amplitude and frequency of the EEG, but above this concentration, both frequency and amplitude start to decrease. Burst suppression occurs at an MAC of 1.5, and at an MAC of 2, the EEG becomes flat.

Nitrous oxide (NO) is the only anesthetic drug that has been used continuously and safely for clinical anesthesia for nearly the last 175 years. It is an inert agent that is not metabolized but induces excellent perioperative analgesia and has a good recovery profile.

However, there are also debates over the use of nitrous oxide to treat the general neurosurgical population; for example, some researchers believe there is a link between nitrous oxide and the development of tension pneumocephalus after surgery, as nitrous oxide may diffuse into air pockets left within the skull following closure of the wound. Moreover, it can further complicate venous air embolism (VAE) if not stopped at the beginning of this event. Like other volatile anesthetics, it induces a significant rise in CBF and ICP, and to add to its odd effects, NO can also induce a slight rise in cerebral metabolism.

1.3.3. Muscle Relaxants

All the neuromuscular blockers are highly charged, and water-soluble molecules hence do not cross the blood–brain barrier (BBB). Therefore, they should not have any direct effects on the CNS. However, the use of suxamethonium (succinylcholine) has been said to cause raised ICP, and a possible explanation for this is that fasciculation causes a rise in intra-abdominal pressure and therefore raised central venous pressure (CVP). But this may not be the entire story. Minton et al. gave succinylcholine to a patient with intracranial space occupation both before and after muscle paralysis had been established with vecuronium. When given before the patient was paralyzed, succinylcholine caused a consistent rise in ICP from a mean of 15 mmHg to 20 mmHg (5 mmHg). After vecuronium had been given, the increase generated by succinylcholine was still present, but it was

smaller—with the maximum increase being only 3mmHg. The evidence suggests that increased muscle spindle activity generating afferent neuronal traffic produces an increase in cerebral activity and therefore regional CBF (Minton et al. 1986).

1.4. Practical Conduct Regarding Anesthesia for Neurosurgical Patients

1.4.1. Preanesthetic Evaluation and Preparation

Preanesthetic evaluation is a clinical assessment, risk classification, and optimization process performed before surgery in order to reduce perioperative morbidity and death. The majority of neurosurgery procedures are regarded as moderate to high-risk surgeries and warrant close communication between the surgical and anesthesia teams regarding preoperative findings and possible operative techniques. In this case, the clinical assessment should be carried out in a standard manner, but complications arising from the neurological lesion must be given extra attention; in addition, the patient's position during surgery and the special needs of neuromonitoring are other major issues that require a careful preanesthetic work-up.

1.4.2. Premedication

Heavy premedication, particularly with narcotics and sedatives, should be avoided for neurosurgical patients. Any depression in the level of consciousness or rate of respiration may cause an increase in PaCO2 levels and hence ICP. The administration of anticonvulsant and corticosteroid medication should be continued until surgery. In case of an emergency (and obviously anxiety as well), for adult patients with intracranial tumors, benzodiazepines, especially midazolam, if used in small doses, can induce calmness without affecting ventilation significantly, which will, in turn, help to achieve a sound preanesthetic hemodynamic status. Preanesthetic use of modern antiemetics anticholinergics or H2 blockers does not affect ICP in a noteworthy manner.

1.4.3. Induction of Anesthesia

For patients with a disturbed intracranial-pressure-to-volume relationship, the induction of anesthesia and endotracheal intubation are important periods, especially if a high ICP already exists. Intravenous medications such as propofol, thiopental, or etomidate, which induce a quick, dependable state of unconsciousness without raising ICP, are commonly used to induce hypnosis. Many authorities suggest modest hyperventilation at this point.

1.4.4. Intubation

Once the patient has been rendered unconscious, endotracheal intubation is performed, mostly with the help of a nondepolarizing neuromuscular blocker. The principal author has found rocuronium to be the most convenient in this regard. Succinylcholine administration has been linked to a brief increase in ICP; moreover, it may cause sudden life-threatening hyperkalemia in patients with longstanding paralysis (and many other neurologic conditions) who may have upregulated extra-junctional (premature) nicotinic receptors. However, succinylcholine remains the preferred drug for rapid sequence induction or when a difficult airway is a problem, as hypoxia and hypercarbia are far more dangerous for a patient with intracranial hypertension than the usual side effects of succinylcholine. However, patients' association with malignant hyperthermia, a relatively rare genetic disorder of skeletal muscles, still remains an absolute contraindication for using any depolarizing agent.

A direct laryngoscopy should be performed when profound neuromuscular blockade has been achieved and the patient is in a deep coma. Additional intravenous anesthetic doses, such as IV lidocaine, esmolol, fentanyl, and remifentanyl, have all been successfully utilized to reduce the response to laryngoscopy or other intraoperative stimulations such as pinion placement and skin incision. During induction, arterial hypertension raises CBV and causes cerebral edema. Sustained hypertension can cause considerable increases in ICP, lower CPP, and put one at risk of suffering brain herniation. Excessive blood pressure lowering can be equally harmful, as it impairs CPP.

1.4.5. Positioning

After intubating the trachea and checking that the tube is in the correct position, efforts are focused on establishing a safe and sound connection between the patient and the ventilator. Normally, an armored tube should be used and fixed such that the cerebral venous drainage remains totally unobstructed. Although most

craniotomies are accomplished in the supine position, the prone, park bench, and sitting positions are not uncommon, and, in most cases, the skull is kept fixed using a Mayfield head holder. Here, 15–30° head elevation would aid in CSF and venous drainage, and some degree of rotation is needed for comfortable exposure; all the positioning maneuvers can potentially displace or disconnect the breathing unit. Neurosurgical operations may last for several hours, and the airway, venous access, and monitoring equipment must be instituted and secured so that they are completely reliable for the whole operative period. Because the patient's airway cannot be easily evaluated after a surgical drape, and as the operating table is frequently turned 90° or 180° away from the anesthesiologist, the chance of unexpected disconnections occurring may be increased (Butterworth et al. 2018b).

1.4.6. Maintenance of Anesthesia

Throughout the surgery, the anesthesiologist should consider the provision of good intracranial operating conditions when choosing drugs and techniques. The main aims are shown in Box 2 below (Turner 2003).

Box 2. The aims of the maintenance of anesthesia.

1. Maintaining adequate cerebral perfusion pressure
2. Maintaining stable MAP
3. Avoiding factors leading to increased ICP
   a. Hypoxia
   b. Hypercarbia
   c. vasodilating drugs
   d. cerebral venous obstruction
   e. incomplete muscle relaxation
4. Reducing brain bulk
5. Protecting against the sudden development of cerebral ischemia

Inhalation anesthesia, total intravenous techniques (TIVA), or a combination of an opioid, an intravenous hypnotic (most commonly propofol), and a low-dose-inhalation drug can all be used to maintain anesthesia. Rapid emergence and prompt neurological examination are facilitated by TIVA with remifentanil and propofol. Dexmetedomidine, alpha-2 adrenoceptor (a2-AR) agonist, can be used during both awake and unconscious craniotomies, yielding identical results (Butterworth et al. 2018a).

The volatile agents used during the maintenance of anesthesia have been subject to controversy for some time. All these volatile agents increase CBF and thereby have the potential to increase brain bulk and ICP. Some authors have shown that volatile agents may be used quite effectively as long as hyperventilation is employed at the same time. Others have suggested that this is not the case, especially if the compensatory systems for intracranial space occupation are nearing their limits.

The use of nitrous oxide in neuroanesthesia has also been an area of debate and discussion for many years. The main advantage in this regard is that by combining nitrous oxide with other anesthetics and analgesics, the dose of each drug can be minimized to a significant extent so that recovery is likely to occur faster, which may be helpful in postoperative neurological assessment. But the risk is that nitrous oxide can enter a gas-filled cavity and expand it significantly, so in the case of an event of VAE or preexisting pneumocephalus (from trauma or surgery), its effect may be highly detrimental.

Hyperventilation has been an important part of neuroanesthesia for many years because of its ability to reduce ICP by inducing cerebral vasoconstriction. This vasoconstriction also works in favor of fluid reabsorption from the cerebral extracellular space. Consequently, hyperventilation helps to provide improved operative conditions. Intraoperative surgical requirements (a reduction in brain bulk) may call for this technique, but its use in these cases risks increasing cerebral ischemia. Concerns about the fact that hyperventilation "uncoupled" the link between CMRO2 and the CBF, reducing oxygen supply without reducing metabolism, have led to a re-evaluation of this technique. Yet, some authorities suggest a mild hypocapnia (PaCO2 roughly 30–35 mmHg) and others recommend an increased PaO2 for those cases in whom vigorous hyperventilation is planned (Matta et al. 1994).

1.4.7. Intraoperative Muscle Relaxation

Muscle relaxants are typically indicated for most of the neurosurgical procedures that require general anesthesia. Patients' spontaneous movement could lead to an increase in intracranial volume and pressure, greater

surgical hemorrhaging, or head and brain injuries from pinions or other surgical devices. It should be remembered that, as resurgence from muscle relaxants begins, abdominal and thoracic muscle tone will recover faster than that of the arm or leg, and a rise in intra-abdominal or intra-thoracic pressures (and therefore in CVP and ICP) may go unobserved. If the brain is found to be tight at any point in surgery, checking that venous drainage from the head is clear and unimpeded is the foremost check that should be carried out, and part of this check is to confirm adequate muscle relaxation.

1.4.8. Reversal of Muscle Relaxation and Extubation

At the end of an operation, the effects of anesthetics and muscle relaxants should have worn off or pharmacologically reversed. This enables real-time monitoring of neurologic function and the early detection of any surgery-related complications. The aim should be to ensure full recovery, but with no coughing, straining, or inadequate breathing events. To avoid the hazards of these potentially dangerous incidences, the reversal of muscle relaxation should not be attempted until the dressing is complete and the patient is off of the head frame.

Delayed awakening may be seen following heavy doses of opioids or sedatives, but metabolic derangement, hypothermia, and perioperative neurological injuries (i.e., ischemia, hematomas, and pneumocephalus) are also common causes. When patients do not respond as expected, they must be taken directly from the operating room to a CT scanner for examination. It is possible that a re-exploration is currently required. If consciousness was depressed prior to surgery or new neurologic deficits are expected as a result of surgery, it may be best to postpone extubation until airway reflexes have returned to a reliable level and the amount of spontaneous ventilation is adequate for avoiding post-anesthesia airway obstruction and hypoventilation. Generally, neurosurgical cases should be cared for in an HDU or ICU after recovery from anesthesia for the close monitoring of vitals and neurologic status.

1.4.9. Fluid Therapy

When the blood–brain barrier is intact, iso-osmolar crystalloid solutions such as lactated Ringer's solution and 0.9% sodium chloride are frequently used since they have no effect on brain water or edema production. Any crystalloid solution provided in significant volumes can increase CBV and ICP in patients with brain tumors, regardless of the crystalloid solution chosen. Glucose-rich fluids are generally avoided as hyperglycemia is common due to corticosteroid therapy; moreover, aqueous glucose solutions leave behind hypo-osmolar free water when the carbohydrate is taken up by the cells, which may adversely affect the water homeostasis of the CNS. Colloid solutions including blood and blood products can be used to restore intravascular volume deficits, while a balanced salt solution is preferred for maintenance.

1.4.10. Postoperative Analgesia

Postoperative pain after neurosurgery has been shown to be less severe than that for other forms of surgery (Dunbar et al. 1999), although some patients experience severe pain, as commonly seen after a frontal craniotomy. Concerns regarding opioids' analgesic side effects such as nausea, vomiting, over-sedation, and increased ICP due to respiratory depression have often resulted in inadequate postoperative pain control measures taken for neurosurgical patients. Due to neurologic impairments, these patients may have trouble articulating their need for analgesics or be entirely unable to do so, adding to the difficulty (Vadivelu et al. 2016).

Risk evaluation, patient education, and, if necessary, the administration of oral drugs begin in the preoperative period. Commonly employed drugs in this regard include opioids (with careful selection, titration, and monitoring), NSAIDs, acetaminophen, gabapentin, and ketamine. While changing surgical procedures may help with pain relief, effective anesthesia administration and the use of various analgesic strategies such as scalp blocks and infiltration or the employment of adjuvants like corticosteroids and alpha-2 adrenergic agonists may be effective components of analgesic strategies applied after neurosurgery.

Multimodal analgesia, nonpharmacological approaches, standardized pain management procedures, and patient empowerment in pain management are all feasible paths to success.

1.5. Special Issues

1.5.1. Anesthesia for Intracranial Aneurysms

The rupture of an intracranial aneurysm is the commonest cause of spontaneous subarachnoid hemorrhage, while patients with unruptured aneurysms usually present with headaches and focal neurological deficits, most commonly third-nerve palsy. Elective clipping or obliteration of the aneurysm via intravascular coiling under angiographic supervision is performed in the operating room or, more commonly, the radiology suite.

During intracranial aneurysm surgery (coiling and clipping), the goals of anesthesia or procedural sedation are to reduce the risk of aneurysm rupture, prevent cerebral ischemia, and facilitate operative exposure. As a result, large changes in systemic blood pressure should be avoided, and CPP should be kept stable. It is reasonable to avoid large drops in ICP before dural opening for patients with cerebral aneurysms without increased ICP and for those with unruptured aneurysms so as not to reduce the tamponading force on the aneurysm's exterior surface. Systemic hypertension may enhance flow in vasospastic arteries, but it may also increase the risk of aneurysm re-bleeding in patients with vasospasms (Pasternak and Lanier 2012).

An exsanguinating hemorrhage can occur as a result of aneurysm surgery due to rupture or re-bleeding. As a result, blood should be made ready before these operations begin. Anesthetic therapy of a ruptured aneurysm includes intensive volume resuscitation to maintain normovolemia, as well as induced hypotension to reduce hemorrhage and allow the neurosurgeon to gain control of the aneurysm. When a burst aneurysm is temporarily clipped to gain control, the systemic blood pressure can be returned to normal or even slightly increased to promote collateral blood flow while the vessel is occluded by the occlusion clip. If prolonged periods of occlusion are required, the injection of suppressing anesthetics, particularly barbiturates, may give protection against regional ischemia or infarction.

Delayed vasospasm is a common complication following both ruptured aneurysms and successful surgical interventions. "Triple H therapy (hypervolemia, hemodilution, and hypertension)" is added to the therapeutic regimen in patients with symptomatic vasospasms who do not respond to nimodipine. Infusions of papaverine, nicardipine, or angioplasty may be used to treat refractory vasospasms. As major fluctuations in both total intravascular volume and systemic blood pressure are very common throughout the perioperative period, hemodynamics monitoring via central venous line and intra-arterial catheters seems appropriate in most cases (Butterworth et al. 2018b).

1.5.2. Vascular Malformations

Low-flow vascular malformations like venous and cavernous angiomas have fewer complications than high-flow vascular lesions like arteriovenous malformations (AVMs) and arteriovenous fistulas. Because AVM resection is usually not an emergency procedure, preexisting medical conditions should be managed as best as possible, and neurological dysfunction caused by hemorrhages, a presumed AVM effect, or preoperative embolic events (infarction, edema, etc.) should be factored into the intraoperative and postoperative management plan.

The possibility of significant, fast, and chronic blood loss is an important consideration during the operation phase. This possibility tempers the choice of intraoperative monitoring, and sufficient blood, as well as access for its administration, must be easily available. Regarding neurosurgical patients, no anesthetic regimen has been rigorously proved to give "cerebral protection". The anesthetic drug chosen must be compatible with safe intracranial surgery, which includes brain relaxation, appropriate blood pressure management, and quick emergence. The following conditions are recommended: euvolemia, normotension, isotonicity, normoglycemia, and mild hypocapnia (Ogilvy et al. 2001).

Cerebral edema and delayed postoperative hemorrhage (DPH) can be troublesome issues during AVM treatment. NPPB (normal perfusion pressure breakthrough) or occlusive hyperemia have been hypothesized to be causes of brain edema and bleeding during or after surgery. According to the NPPB theory, a failure in autoregulation in the region of an ischemic brain around the AVM causes postoperative bleeding and edema. Chronic hypoperfusion in the region of the brain surrounding an AVM may promote maximal chronic vasodilation, resulting in the arteries' incapacity to vasoconstrict in response to the return of normal perfusion pressure after the AVM has been removed. 'Occlusive hyperemia' is an alternative theory for the origin of malignant postoperative edema and bleeding. According to this idea, malignant postoperative hemorrhage and edema are generated by either arterial stagnation and obstruction or venous outflow obstruction, both of which cause malignant postoperative hemorrhages and edema (Mullan et al. 1979).

Hyperventilation, diuretics such as furosemide or mannitol, and induced hypotension may be used as a perioperative solution to rapidly developing cerebral edema. High doses of barbiturates or propofol anesthesia, or a temporary craniectomy with postoperative ventilatory support, may be required in extreme situations (Pasternak and Lanier 2012). However, the etiology of edema and bleeding after brain AVM excision is still unknown, and to reduce the risk of DPH, stringent postoperative blood pressure control and a restrictive IV fluid management regime are required. For combating emergence hypertension, beta blockers are usually employed to pass up vasodilator-induced increases in cerebral blood flow (Niini et al. 2019).

1.5.3. Pituitary Surgery

Pituitary tumor surgery presents unique problems for an anesthesiologist because it combines ideas and techniques from endocrine- and neurosurgery. The anesthesiologist's challenges are multiplied, as the surgical method varies by patient, with some surgeons preferring the transcranial route to others' transsphenoidal approach and some patients undergoing awake craniotomy, functional neurosurgery, and interventional radiology (Venkatraghavan et al. 2006).

The pituitary gland is a master gland, and its tumors present clinically in one of three ways, namely, hormone hyper-secretion syndromes, hormone hypo-secretion, or mass effects, and any of them can ultimately have an extensive effect on human physiology in its entirety. In-depth knowledge of the anatomical as well as pathophysiological effects of the particular tumor in the patient of concern is very crucial for the safe delivery of anesthesia.

Acromegaly, which is caused by an overabundance of growth hormone, can make airway control harder during general anesthesia. Obstructive sleep apnea (OSA) is also common in acromegaly; it can raise the risk of postoperative respiratory obstruction and a compromise. Diabetes mellitus, as well as cardiac abnormalities such as left-ventricular hypertrophy, coronary artery disease, arrhythmias, conduction disturbances, valvular heart diseases, cardiomyopathies, and congestive heart failure, are frequently linked to pituitary hypersecretion, that is, acromegaly and Cushing's disease (Herrmann et al. 2002).

The oral cavity must be secured with throat packs in the trans-sphenoid approach because blood from the dissection of nasal tissues can pool in the oro-pharynx and leak down the endotracheal tube. The position during this approach is also associated with an increased risk of VAE (as a head-up position is required) and postoperative pneumocephalus. Some surgeons request the insertion of a lumbar drain catheter to aid in the dissection of the capsules of suprasellar tumors or to prevent postsurgical CSF rhinorrhea.

Symptomatic syndrome of inappropriate antidiuretic hormone secretion (SIADH), diabetes insipidus (DI), epistaxis, injury to the internal carotid artery (ICA), meningitis, CSF leakage, abdominal wound infection, a new visual deficit, postoperative hemorrhage, and mucocele formation are all postoperative complications of pituitary surgery.

Cortisol replacement is an uncommon routine after pituitary surgery and can be tailored to minimum doses within a few days, but those suffering from Cushing's disease must have heavy suppression of adrenocortical activity and would need to have been given therapeutic steroids for weeks to months.

1.5.4. Diabetes Insipidus (DI)

Diabetes insipidus (DI) is a frequent complication of pituitary and craniopharyngioma surgery and reflects an absence of vasopressin (ADH) as a consequence of the destruction of the posterior pituitary. Moreover, renal tubules may fail to respond to circulating ADH, and another form of DI can ensue, nephrogenic diabetes insipidus, while the first form is called neurogenic DI or vasopressin sensitive DI.

Classic manifestations of DI are polydipsia and a high output of diluted urine despite increased serum osmolarity. Perioperative DI is most likely a result of a reversible assault of the posterior pituitary and usually resolves within days.

After ruling out glycosuria, mannitol administration, and high-output renal failure, the presence of hypotonic (300 mosmol/kg) polyuria (2 mL/kg/h) and an elevated plasma osmolality (>300 mosmol/kg) is required to diagnose acute postoperative cerebral diabetes insipidus. In the acute phase, the plasma sodium concentration may be a more trustworthy guide than osmolality. Adults with a total 24 h production of over 3.5 L of hypotonic urine and a plasma sodium content of more than 143 mmol/L are diagnosed with hypotonic urine.

Antidiuretic medicines should only be administered if a diagnosis of cranial diabetes insipidus has been confirmed, as water overflow can produce cerebral edema and convulsions if not treated properly. Desmopressin (DDAVP) is a hormone produced by the pituitary gland. Antidiuresis is usually achieved by administering 01–0.02 g subcutaneously or intramuscularly (0.4 g for children) and should be accompanied by adequate fluid intake to maintain fluid balance (Seckl and Dunger 1989). There is also an oral preparation and a nasal spray with a metered dose. Until normal water balance is restored, plasma Na+ concentrations and osmolality should be constantly monitored.

1.5.5. Syndrome of Inappropriate Antidiuretic Hormone Secretion (SIADH)

The unsuppressed release of antidiuretic hormone (ADH) from the pituitary gland or nonpituitary sources, as well as its persistent impact on vasopressin receptors, are characteristics of SIADH. This syndrome is characterized by inappropriate (primarily inadequate) water loss via kidneys resulting in hyponatremia as well as hypervolemia (or euvolemia), and it may result from a variety of conditions, including intracranial tumors, brain surgery, meningitis, head injuries, hypothyroidism, porphyria, and carcinoma of the lung.

Hyponatremia is the result of intravascular volume expansion secondary to a hormone-induced increase in the resorption of water by the renal tubules. Serum concentrations of sodium may drop below 110mEq/L, resulting in cerebral edema and convulsions. Schwartz and Bartter developed a clinical profile for SIADH in 1967 that is in use till today and given in the Box 3 below (Bartter and Schwartz 1967).

Box 3. Schwartz and Bartter criteria (of SIADH).

- Serum sodium levels less than 135 mEq/L
- Serum osmolality less than 275 mOsm/kg
- Urine sodium levels greater than 40 mEq/L (due to ADH-mediated free water absorption from renal collecting tubules)
- Urine osmolality more than 100 mOsm/kg
- The absence of clinical evidence of volume depletion (normal skin turgor, blood pressure within the reference range)
- Urine osmolality greater than 100 mOsm/kg
- The lack of other causes of hyponatremia, such as adrenal insufficiency, hypothyroidism, heart failure, pituitary insufficiency, renal illness with salt wastage, hepatic disease, and medicines that affect renal water excretion.
- Fluid restriction is used to treat hyponatremia.

Treatment of SIADH consists of fluid restriction, the antagonism of ADH at renal tubular receptors via demeclocycline, and the intravenous infusion of sodium chloride for correcting hyponatremia. Many of the cases respond well to fluid restrictions alone, but those who manifest acute neurological symptoms may require the administration of hypertonic saline. Conivaptan (intravenous) and tolvaptan (oral) are two more vasopressin receptor antagonists that have been licensed for severe persistent SIADH. By antagonizing V2 receptors, these medicines limit ADH-mediated free water retention and hence correct hyponatremia (Greenberg and Verbalis 2006).

1.5.6. Cerebral Salt-Wasting Syndrome (CSWS)

CSWS is another clinical condition linked with or possibly causing hyponatremia and volume disturbance that at times accompany intracranial problems like head trauma, cranioplasty, brain tumors, intracranial surgery, tubercular meningitis, and, most commonly, aneurysmal subarachnoid hemorrhages. CSWS was first proposed in 1950 by Peters and colleagues and is characterized by hyponatremia, increased urine sodium levels, and hypovolemia. The wastage of salt by the kidneys exhibited in CSWS is not well understood. Disruption of sympathetic neuronal input supplied to the kidneys and natriuresis produced by natriuretic peptides are two proposed mechanisms (Oh and Shin 2014).

Although it is still a matter of debate whether CSWS is a different disorder or a special type of SIADH, it is important to differentiate the two conditions as they are treated with quite converse treatment strategies. Because patients with cerebral salt wasting are hypovolemic while patients with SIADH range from being euvolemic to hypervolemic (Oh and Shin 2014), patients with cerebral salt wasting are given fluids and sodium supplements, while in the case of SIADH, the patients are assigned a course of fluid restriction.

As CSWS is always secondary to aneurysmal subarachnoid hemorrhages or another CNS insult, its treatment should focus primarily on dealing with the underlying disorder. Second, while treating hyponatremia, the patient must be volume-repleted. In cases of mild hyponatremia, this is usually accomplished by infusing isotonic saline, but in cases of moderate to severe hyponatremia, more aggressive sodium replenishment may be required, consisting of using hypertonic saline, such as 3% hypertonic saline, and/or salt tabs (consuming 1–2 g up to three times daily), as well as limiting free water intake. Fludrocortisone has also been recommended by certain professionals for the treatment of cerebral salt wasting (Yee et al. 2010).

1.5.7. Surgery in Posterior Fossa

The posterior cranial fossa (the infratentorial compartment) is a rigid box containing multiple vital structures like the pons and medulla, cerebellum. Small further increases in volume (e.g., for tumors and hematomas) within posterior fossa can result in a considerable rise in pressure and may lead to life-threatening brainstem compression or herniation. Any surgical procedure used for a mass in the posterior fossa can be highly challenging from an anesthetic perspective as it presents an array of potential problems, including possible trauma to the vital centers, obstructive hydrocephalus, pneumocephalus, and, due to an unusual positioning, postural hypotension and air embolism in venous spaces.

1.5.8. Brainstem Injury

In the brainstem, the cardiovascular centers, respiratory control areas, and nuclei of the lower cranial nerves are all close together. Systemic hypertension and bradycardia may result from brainstem manipulation, as well as hypotension and tachycardia. Cardiac dysrhythmias are also common and may range from acute sinus arrhythmia to premature ventricular contraction (PVC) or even life-threatening ventricular tachycardia (VT). These circulatory changes are also features of damage to the respiratory centers. Therefore, continuous monitoring via an ECG is extremely important. Another major complication of surgery in the posterior fossa is postoperative apnea (acquired central hypoventilation syndrome) resulting from brainstem injury or edema, a condition requiring prompt recognition and definitive management.

1.5.9. Sitting Position

Even though surgery for infratentorial tumors can be accomplished in supine, prone, park bench, and lateral positions, the sitting position is sometimes chosen as it improves surgical access by promoting gravity-assisted blood and CSF drainage and thus decreasing ICP. It improves surgical orientations and access to the midline structures and decreases the amount of surgical retraction needed to gain access to deeper structures. These advantages relating to sitting position are sometimes offset by associated cardiovascular instability and the potential hazard of a venous air embolism (VAE).

The depressant effects of anesthetic drugs on myocardial contractility and peripheral vascular tone may add to the troubles of physiologic changes caused by sitting posture. In the event of an abrupt cardiovascular collapse, patients must be quickly returned to the supine position for resuscitative efforts. The complications associated with sitting techniques also include pneumocephalus, macroglossia, quadriplegia, and peripheral nerve injuries. Table 3 summarizes these complications (Porter et al. 1999).

Table 3. Contraindications of sitting position surgery.

Absolute Contraindications	Relative Contraindications
Ventriculo-atrial (VA) shunt	Foramen ovale
Right-to-left cardiac shunt Right-atrial pressure greater than left-atrial pressure Cerebral ischemia when patient is upright and awake	Uncontrolled hypertension
	Extremes of age
	Severe autonomic neuropathy Craniovertebral anomaly or instability

Source: Table adapted from (Porter et al. 1999), used with permission.

Venous Air Embolism (VAE)

While VAE has been described in nearly every field of medicine, seated craniotomy is the quintessential 'at risk' scenario for this potentially fatal occurrence. The other procedures associated with a high incidence of VAE include central venous catheterization, Cesarean delivery, blunt or penetrating trauma, and laparoscopy.

The amount of air entrainment and the pace of buildup are closely associated with VAE morbidity and mortality. The fatal volume for adults has been estimated to be between 200 and 300 mL, or 3 and 5 mL/kg, based on case reports of inadvertent intravascular air delivery. It has been suggested by the cited authors (Toung et al. 2001) that the smaller the required lethal amount, the closer the entrainment vein is to the right heart. A gas air-lock scenario is created quickly if the embolism is significant (about 5 mL/kg). Failure to relieve the tension of the ventricular wall may result in full outflow obstruction from the right ventricle. Right-sided heart failure and cardiovascular collapse occur quickly as a result of this. A venous air embolism may transform into an arterial embolism if a connection between the two systems exists; in that case, the emboli may pass directly to the cerebral or coronary circulation, thereby producing far more serious consequences, even with a smaller volume of air.

Early Detection of VAE: necessitates close clinical monitoring. High-risk instances demand the use of appropriate detection devices as well as a high level of suspicion. The clinical markers in this regard (hypertension, tachycardia, cardiac dysrhythmias, and cyanosis, for example) are usually late manifestations of VAE and are also non-specific. Modern devices and tools such as transesophageal echocardiography, precordial Doppler, contrast-enhanced transcranial Doppler, pulmonary artery catheters, end-tidal carbon dioxide, and end-tidal nitrogen all have a high sensitivity for detecting a VAE, but their use is more expensive and requires more advanced training. At the moment, end-tidal capnography (ETCO2) and precordial Doppler provide the best balance of sensitivity and cost.

Many preventive methods have been suggested, the most essential of which is diligent attention to volume status, as keeping a stable right-atrial pressure reduces the chance of air entrainment. Anti-shock compression garments have also been demonstrated to be useful in raising systemic venous pressure.

Management Highlights for VAE: The prevention of future air entry, a reduction in the entrained volume, and early hemodynamic resuscitation are the main goals of therapy when a VAE is suspected.

- To seal the entrance sites, surgeons should flush the operating site with saline.
- Jugular venous compression lowers head venous return and raises cerebral venous pressure. (1) Repositioning the wound below the level of the right atrium can potentially increase venous pressure at the operating site and (2) volume loading in the intravenous system. (3) The Valsulva maneuver can be used to raise intrathoracic pressure.
- A central venous catheter can be used to aspirate air.
- Using 100-percent oxygen allows nitrogen to be washed out, decreasing the size of air bubbles.
- If nitrous oxide is being used, its use should be stopped immediately because it is 34 times more soluble in blood than nitrogen and can dramatically increase the size of the entrained volume of air.
- The rapid initiation of CPR with defibrillation and chest compressions has been demonstrated to be effective for massive VAEs that result in cardiac stoppage. A closed-chest massage can be used to drive air out of the pulmonary outflow system and into the smaller pulmonary vessels even if cardiac resuscitation is not required (Ericsson et al. 1964).
- Several case reports and case series have been published demonstrating the potential benefits of hyperbaric oxygen therapy (HBO), particularly in the context of a cerebral arterial gas embolism (CAGE) (Burnand and Sebastian 2014).

1.5.10. Awake Craniotomy

Awake craniotomy is increasingly being recognized as the technique of choice for the removal of tumors from eloquent brain areas. It is essentialy useful in epilepsy surgery and deep-brain stimulation (DBS). It has also been employed to treat mycotic aneurysms and arterio-venous malformations in the brain's important sections.

Awake craniotomy is used to maximize tumor removal while maintaining neurological function. A successful awake procedure is built on careful patient selection, precise planning, and well-organized teamwork. All members of the team should interview the patient prior to surgery to establish confidence and engagement. Poor intraoperative patient communication is a common cause of failure. Patient refusal, an altered level of consciousness, a problematic airway, and the possibility of a massive hemorrhage are the major issues that might contraindicate an awake procedure.

Increased lesion excision (through awake procedure) is thought to be beneficial, with emerging evidence of enhanced survival, and it also limits damage to the eloquent cortex and the resultant postoperative neurological impairment. Other benefits include a shorter hospital stay, resulting in lower healthcare costs, and a lower incidence of postoperative problems such as nausea and vomiting (Burnand and Sebastian 2014).

The phrase "awake craniotomy" can be misleading because the patient is not entirely conscious throughout the procedure. Various amounts of sedation, or anesthesia, are required during the more surgically stimulating phases of the process (i.e., during opening and closure). During the mapping operation and the period of lesion resection, the patient is kept completely awake.

Although some patients can be handled with merely sedation, the most typical methods are sedation or an asleep–awake–asleep strategy, with or without airway equipment. For all anesthetic techniques, the patient usually has a scalp block applied (Figure 2) for pain management. The intra-operative challenges are many and include cardiovascular instability, seizures, somnolence, confrontation, airway obstruction, tight brain, oxygen desaturation, and shivering.

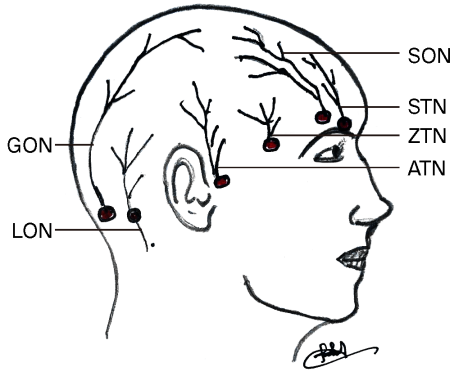

Figure 2. Illustration showing six sensory nerves supplying the scalp that need to be blocked with local anesthetic during a scalp block and an awake craniotomy. SON—supraorbital nerve; STN—supratrochlear nerve; ZTN—zygomatico-temporal nerve; ATN—auriculotemporal nerve; LON—lesser occipital nerve; GON—greater occipital nerve. Source: Figure by authors.

Individual anesthesiologists have different drug preferences. Anesthetics must have a rapid onset and offset, titratability, and minimum drawn-out effects to achieve seamless transitions and ease intraoperative mapping. Propofol, fentanyl, remifentanil, and dexmedetomidine (DEX) are the most regularly utilized anesthetics, while sevoflurane is also used at some facilities. DEX has the distinct advantage of causing minimal respiratory depression while inducing adequate drowsiness and analgesia, and it can be administered alone or in conjunction with other sedatives. It also has the advantage of not enhancing neurologic impairment, unlike propofol or midazolam. Some drugs, such as midazolam, atropine, and scopolamine, should be avoided or taken with caution as a general rule since they can impair neurocognitive function and cause disorientation or delirium. Patients undergoing seizure mapping should avoid taking any medications that reduce epileptiform activity, such as midazolam and anti-convulsant medications (Zhang and Gelb 2018). In case of intra-operative seizure, exposed cerebral cortex should be irrigated with ice-cold normal saline.

Author Contributions: Conceptualization, methodology, S.A.I. and F.H.C.; validation, formal analysis, investigation, resources, data curation, A.H. and M.S.A.; writing—original draft preparation, S.A.I. and F.H.C.; writing—review and editing, visualization, supervision, F.H.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

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