Chapter

Intensive Care Management in Cerebral Aneurysm and Arteriovenous Malformations

Sedef Tavukçu Özkan

Abstract

Aneurysmal subarachnoid hemorrhage is an important group of intracranial hemorrhage with a high risk of disability and mortality. The initial amount of bleeding, rebleeding, and delayed cerebral ischemia are considered as the most important factors in determining the prognosis of aneurysm-induced bleeding. In arteriovenous malformations, its location and deep venous drainage play a role in the prognosis. Cardiac complications, neurogenic pulmonary edema, hypertension, hyperglycemia, infections, and prolonged mechanical ventilation in aneurysmal subarachnoid hemorrhage lead to morbidity and mortality. Aneurysm bleeding control, appropriate fluid replacement to ensure euvolemia, when necessary external ventricular drainage and/or decompressive craniectomy, mannitol or hypertonic saline application, and infection control are the main principles of treatment.

Keywords: aneurysmal subarachnoid hemorrhage, cerebral arteriovenous malformation, cerebral vasospasm, delayed cerebral ischemia, intracranial pressure

1. Definition and etiology

The modern definition of cerebral artery aneurysms began in 1874 with Duret's description of the middle cerebral artery (MCA). It is known that 20% of all aneurysms are composed of MCA aneurysms and 90% of aneurysms originate from anterior circulation. It is more common in women aged 35–60 years [1]. Subarachnoid hemorrhage (SAH) is a major health problem worldwide with a high mortality rate. Despite a 17% decrease in case fatality in the last three decades associated with improved management strategies, 30-day mortality and sudden death rate unfortunately are still high, around 35 and 15%, respectively [2].

Cerebral arteriovenous malformations (AVM) are composed of a complexity of abnormal arteries and veins and are a major source of brain hemorrhage, resulting in morbidity and mortality, representing a diagnostic and therapeutic challenge in young adults. Cerebral AVM generally represents 1 and 3% of the total annual risk for epilepsy and bleeding in patients with AVM. The rate risk of bleeding in undamaged AVMs is 2.2% per year, and the rate of torn lesions is 4.5% per year. Important risk factors for the development of bleeding due to AVM include deep localization, deep venous drainage, associated aneurysms, pregnancy, age, and gender. Disconnection of arteriovenous malformations from circulation and prevention

Formation of intracranial aneurysms	Hypertension Smoking Chronic alcohol use Family history Female sex Polycystic kidney disease Marfan syndrome Ehler-Danlos syndrome Fibromuscular dysplasia Neurofibromatosis type I

Table 1.
Risk factors for the formation of intracranial aneurysms.

Rupture of intracranial aneurysms	Female sex Smoking Hypertension Cocaine abuse Sympathomimetic drug use Posterior circulation aneurysms Type of aneurysms Giant aneurysms

Table 2.
Risk factors for the rupture of intracranial aneurysms.

of epileptic seizures remain the mainstay of treatment. The size, location, and presence of deep venous drainage (using the Spetzler-Martin score) determine the mortality and management of the arteriovenous malformations.

The most common causes of aneurysm remain hemodynamic instability, degenerative changes, vascular injury, atherosclerosis, vasculopathy, high flow, arteriovenous malformation, and fistula. In addition, the important risk factors for the development of cerebral aneurysms are hypertension, smoking, chronic alcohol use, family history of intracranial aneurysms in first-degree relatives, and female sex. Autosomal dominant polycystic kidney disease is an inherited systemic disorder that is strongly associated with intracranial aneurysms. Autosomal dominant polycystic kidney disease has a prevalence rate 2–4 times higher than the general population. Other conditions such as Marfan syndrome, Ehler-Danlos syndrome type IV, neurofibromatosis type I, hereditary hemorrhagic telangiectasia, Moyamoya disease, pseudoxanthoma elastum, and fibromuscular dysplasia are weakly associated with intracranial aneurysms. Multiple aneurysms are detected in 10–30% of cases. Both localization and type of aneurysm are important considerations in describing the risk for rupture. Aneurysm rupture is directly proportional to size, and ruptured aneurysm causes subdural, subarachnoid, or intracranial hematoma. 25% of the cases with ruptured aneurysm are lost and 50% of them have partial or complete recovery. Overall incidence of mortality and complications in ruptured aneurysm is 80%. Risk factors for the formation of and rupture of intracranial aneurysms are shown in **Tables 1** and **2** [1, 3, 4].

Aneurysms are classified according to their shape or size.

According to the shape:

1. Saccular (traumatic, mycotic, oncotic, flow-dependent vasculopathy, drug-induced).

2. Fusiform.

3. Dissecting.

According to the size:

1. Small (<15 mm).

2. Large (15–25 mm).

3. Giant (25–50 mm).

4. Super giant (>50 mm).

Saccular berry aneurysms account for 90% of the total aneurysm morphology, and their rupture is the most common cause of SAH. Fusiform aneurysms account for the remaining 10%, and their most common location is posteriorly. Atherosclerosis and dissection are found to be responsible as possible mechanisms for formation of fusiform aneurysms.

2. Clinical presentation of subarachnoid hemorrhage

The most common clinical reflection of aneurysm is SAH; it can occur in several ways: headache, bilateral temporal hemianopsia and bilateral lower limb weakness, unilateral nerve palsy, facial or orbital pain, nosebleed, progressive vision loss and/or ophthalmoplegia, and symptoms of brain stem dysfunction. Patients with complex middle cerebral artery aneurysms may present with intracranial hemorrhage, mass effects, epilepsy, or cerebral ischemia; in addition, the aneurysm may be incidentally discovered. A high mortality rate of 65–85% within 2 years has been reported, and aneurysm rupture survivors are often left with severe neurological deficits [5–9].

In the presence of rupture, aneurysmal SAH may cause coma in 20–30% of patients. In "poor-grade" patients, neurologic findings may include extensor posturing and loss of upper brain stem reflexes, and further progression may occur in hours from the ictus. A wide light-fixed pupil may indicate oculomotor palsy from a ruptured posterior communicating aneurysm or lateral brain stem displacement from a hematoma in the temporal or frontal lobe. Pinpoint pupils may indicate the presence of an acute hydrocephalus with ventricles often filled with blood. The causes of coma after aneurysmal SAH are shown in **Table 3**.

The severity of SAH is clinically assessed and graded using either the Hunt and Hess classification or the World Federation of Neurosurgeons (WFNS) scale (**Tables 4** and **5**). The WFNS, widely used, is a combination of focal neurological deficits and the Glasgow coma scale (GCS). Higher grades on both scales are

- Diffuse ischemic global cortical injury
- Early cerebral edema
- Acute hydrocephalus
- Hematoma in the temporal lobe and brain stem shift
- Hematoma in the pons
- Nonconvulsive status epilepticus

Table 3.
Causes of coma in aneurysmal subarachnoid hemorrhage.

Grade	Clinical description
0	Unruptured aneurysm
1	Asymptomatic or minimal headache and slight nuchal rigidity
2	Moderate/severe headache, nuchal rigidity, cranial nerve palsy
3	Drowsiness, confusion, or mild focal deficit
4	Stupor, severe hemiparesis, vegetative disturbance
5	Deep coma, decerebrate rigidity, moribund appearance

Hypertension, diabetes, arteriosclerosis, chronic pulmonary disease, or vasospasm assigns patient to the next less favorable category.

Table 4.
Modified Hunt and Hess classification [13].

Grade	Glasgow coma scale score	Motor deficit
I	15	Absent
II	14–13	Absent
III	14–13	Present
IV	12–7	Present/Absent
V	6–3	Present/Absent

Source: Ref. [10].

Table 5.
World Federation of neurosurgeons scale.

Grade	Fisher scale	% with symptomatic vasospasm	Modified Fisher scale	% with symptomatic vasospasm
I	Focal thin	21%	Focal or diffuse thin SAH, no IVH	24%
II	Diffuse thin SAH	25%	Focal or diffuse thin SAH, with IVH	33%
III	Thick SAH present	37%	Thick SAH present, no IVH	33%
IV	Focal or diffuse thin SAH with significant ICH or IVH	31%	Thick SAH present, with IVH	40%

Source: Ref. [11].

Table 6.
Fisher and modified fisher grading scale.

associated with the worst outcomes. The WFNS classification provides a more objective assessment. The first computerized tomography scan uses the Fisher grading scale to determine the amount, localization, prognosis, and severity of bleeding (**Table 6**). The risk of vasospasm is high in patients with Grade III and IV SAH.

The overall mortality in patients with SAH is over 30%, and approximately 10–20% of survivors show functional dependence despite intensive neurological care. Several extensive studies have been conducted to improve intensive neurological care in patients with SAH [12]. Poor-grade aneurysmal SAH (WFNS Grades IV and V)

reflect 20–30% of all aneurysmal SAH. Mortality is commonly associated with neurological injury resulting from the initial bleeding and rebleeding and from delayed cerebral ischemia (DCI). The volume of initial hemorrhage and initial neurological status following SAH remain major factors for mortality. Elderly patients and patients with coexisting medical conditions are at higher risk. The clinical goal is to prevent rebleeding and DCI [13–15].

In general, the prognosis of aneurysmal SAH is considered to be inversely related to grading at first presentation. Aggressive early interventions such as emergency surgical clip application or endovascular treatment of the aneurysm can lead to positive outcomes in poor-grade aneurysmal SAH patients. Subarachnoid hemorrhage patients can be followed with conservative treatment without invasive intervention. External ventricular drainage is a frequently preferred method in the case of hydrocephalus which can be observed during this clinical follow-up. In a multicenter, prospective observational study conducted with 324 patients, the relationship between the potential clinical risk factors and the prognosis of aneurysmal SAH in intracranial aneurysm patients was investigated. Results showed that age, female gender, ventilated respiratory status, pupil dilatation, low GCS, WFNS grade, intraventricular hemorrhage, higher Fisher grade, higher Modified Fisher grade, and a relatively poor outcome in aneurysmal SAH patients receiving conservative treatment play a major role. There are many studies showing that age has a strong relationship with clinical outcomes in aneurysmal SAH patients [16–23]. Global cerebral edema occurs in up to 57% of patients suffering from subarachnoid hemorrhage and is associated with prolonged hospital stay and poor outcome. The pathogenesis of brain injury after intracerebral hemorrhage is thought to be due to mechanical damage followed by ischemic, cytotoxic, and inflammatory changes in the underlying and surrounding tissue. Typically, a sudden rise in intracranial pressure at the moment of rupture reduces cerebral perfusion globally in both hemispheres and results in marked ischemic changes. Intraventricular extension of the hemorrhage and hydrocephalus may be a cause of coma, and thus, an improvement may be seen after ventriculostomy [3, 24, 25].

3. Delayed cerebral ischemia

Rebleeding after SAH remains one of the most serious early complications; the reported incidence is up to 15% in the first 24 hours, and the mortality rate is approximately 70% [26–28]. Prognosis is closely related to initial bleeding, rebleeding, and DCI. The presence of intraventricular and intracerebral hemorrhage also adversely affects prognosis. Cardiac symptoms and neurogenic pulmonary edema are considered indicative of SAH severity. Hypernatremia after SAH is considered as a poor neurological marker. DCI generally begins approximately 3 days after bleeding, and its most severe presence is 1 week after bleeding. Smoking is considered as a risk factor for the development of DCI. The mechanism of DCI is not completely known, but the degree of initial bleeding is likely to be multifactorial with the severity of a function. It is also known that DCI occurs in cerebral regions without signs of angiographic vasospasm. The general recommendation is that angiographic vasospasm should not be treated in the absence of DCI.

DCI is usually treated by administration of nimodipine, via effect of maintenance of normal circulating blood volume and induced hypertension. Nimodipine is a calcium antagonist, and its oral administration is useful in the treatment of vasospasm and DCI. IV application of nimodipine is not recommended. High-dose IV nicardipine (0.15 mg/kg/hr for 14d) has been shown to reduce symptomatic vasospasm but not positively affect the 3-month neurological outcome in a prospective double-blind randomized controlled trial [4, 29–35].

The clinical goal is to prevent rebleeding and DCI, because, in patients with SAH, DCI is considered the most important preventable cause of death and poor neurological prognosis. Delayed cerebral ischemia affects up to 30% of patients and leaves the majority of survivors with motor deficits, cognitive dysfunction, and reduced quality of life. The risk of developing DCI is associated with the severity of initial bleeding [36].

In patients with GCS 8 or less with intracranial hemorrhage, endotracheal intubation should be considered to protect the airway or to clear tracheal secretions. Intubation should be performed with a rapid induction with minimal effect on hemodynamics and not increasing intracranial pressure. Drugs used in induction should be preferred accordingly (e.g., propofol). It should be remembered that propofol may cause a drop in blood pressure. Preventive isotonic liquid bolus should be applied if necessary. Post-expiratory positive pressure (PEEP) up to 12 mmHg is considered safe as long as the mean arterial pressure is maintained [37].

4. Factors determining prognosis in subarachnoid hemorrhage

The prognosis after SAH may vary from severe disability to death, depending on the complications usually seen in the first 2 weeks associated with the severity of bleeding.

Common causes of this deterioration include neurological events such as hydrocephalus, seizures, ischemia, and systemic conditions, such as fever and infections, respiratory failure, and electrolyte abnormalities. The level of consciousness is considered the most important early predictor of outcome. For these reasons, patients presenting with a GCS score of less than 13 have traditionally been defined as having poor-grade SAH (classified as grade 4 and 5 according to the Hunt and Hess or the WFNS grading scales 5 or more recently as VASOGRADE-Red 6). Brain injury refers to the acute consequences of SAH-associated sudden increase of intracranial pressure (ICP), which can cause decreased cerebral perfusion and transient global cerebral ischemia. The global cerebral ischemia can result in transient loss of consciousness or progressive intracranial hypertension [2, 38–41].

5. Complications and current treatment approaches

During aneurysmal SAH, extravasation of high-pressure arterial blood in the subarachnoid space is associated with a sudden ICP increase that, if severe and sustained, may compromise cerebral perfusion, causing global cerebral ischemia and early brain injury. Recently, the treatment of hypertension in intracranial hemorrhage patients has been discussed with INTERACT and ATACH training. The American Heart Association/American Stroke Association and Neurocritical Care guidelines include mean arterial blood pressure monitor, unsafe aneurysm types, and 110 or 160 mm Hg (or both) of the systolic blood bridge. Remember to keep it below 180 mm Hg. After aneurysm treatment, these parameters should not be made in such a way that spontaneous high blood pressure may be beneficial [29, 42–44].

Intracranial hypertension (ICP of at least 20 mm Hg) is a relatively common complication of SAH, especially in patients presenting with poor neurological condition. Multiple factors such as cerebral edema, intraparenchymal hematoma, acute communicating hydrocephalus, intraventricular hemorrhage, aneurysm rerupture, complications related to aneurysm treatment, early brain injury, and DCI may contribute to the development of intracranial hypertension. High ICP is associated with severe regulation of brain metabolism, increased risk of neurological deterioration,

and poor outcome, particularly in the absence of medical treatment. An ICP greater than 20 mm Hg is considered as an independent predictor of severe disability and death in aneurysmal SAH. Critical cerebral perfusion pressure levels (less than 70 mm Hg) are significantly associated with cerebral infarction after SAH [45–51].

If the autoregulation mechanism is intact when intracranial pressure rises, the body tries to keep the cerebral blood flow (CBF) constant. As the ICP rises, the brain perfusion pressure drops. Systemic vascular resistance decreases, and vasodilatation occurs at the limits of autoregulation to keep CBF stable. Cerebral blood flow is mainly regulated by arterial carbon dioxide tension ($PaCO_2$). Abnormal $PaCO_2$ levels are considered to cause major changes in CBF through vasoconstriction and vasodilation, respectively, possibly contributing to further brain injury [52–56].

Main management principles of intracranial hypertension after SAH are traditionally guided by the literature on traumatic brain injury, due to high numbers. It should be noted that pathophysiology is completely different in our scenario. The role of therapies such as hyperosmolar agents, hypothermia, barbiturates and decompressive craniotomy is not clear in SAH patients with intracranial hypertension resistant to first-line therapies. The first approach to elevated ICP is cerebral venous drainage, normoventilation ($PaCO_2$: 35–40 mm Hg), and positioning bed height from 30° to 45°. During sedation and aspiration of tracheal secretions and physiotherapy, neuromuscular blocking agents should be added if necessary. However, the role of these drugs for ICP management has not been fully established, and some authors report that they may be more harmful than useful [57].

The use of hyperosmolar agents, such as mannitol and hypertonic saline, are current popular options in the treatment of high ICP in SAH.

Studies have shown that hypertonic saline is effective in controlling ICP and improving cerebral blood flow. The last treatment steps at highly resistant ICP include barbiturate, induced hypothermia, and decompressive craniectomy. Therapeutic hypothermia has been shown to be effective in controlling ICP in SAH but has not been shown to be associated with improved functional outcome and low mortality rates.

There are studies showing that hypertonic saline is more effective than mannitol in lowering ICP in traumatic brain injury. But however, there is no specific recommendation to select hypertonic saline or mannitol as the first line for patients with high ICP caused by traumatic brain injury [58–66]. Recent literature reports effectivity of hypertonic saline like mannitol in reducing of ICP in SAH. However further studies are needed to evaluate safest and optimal dose concentration and impact on improvement of outcomes.

Decompressive craniectomy, an important approach in refractory ICP in SAH patients, is often discussed in patients with poor prognosis. Decompressive craniectomy has been associated with decreased mortality, significant decrease in ICP, increased cerebral oxygenation, and increased cerebral metabolism in many studies. However, severe disability or death was also observed in patients undergoing decompressive craniectomy for refractory ICP [67–72].

The hemodynamic approach, known as triple H therapy, has played a very important role in SAH treatment for many years. However, its safety and efficacy are discussed due to complications that may develop. In patients with SAH, a bolus normal saline fluid application is known to increase cerebral blood flow in areas of cerebral ischemia. The main purpose of fluid treatment in SAH is to maintain euvolemia and normal circulating blood volume. It should be noted that uncontrolled hypervolemia and hemodilution do not improve cerebral oxygen formation and may cause adverse events [73–77].

Noradrenaline perfusion may be added to the treatment to provide normotension in cases where appropriate blood pressure is not achieved despite fluid replacement

or in conditions limiting fluid therapy such as heart failure. If the pathology persists after blood pressure therapy in neurological examination, intravenous angioplasty or salvage therapy with intravenous infusion may be helpful. Prophylactic use of angioplasty is not recommended. Cardiac complications after SAH may vary from benign electrocardiogram changes to cardiogenic shock. Positive troponin value is common after SAH and is considered a good indicator of left ventricular dysfunction, which increases the risk of hypotension, pulmonary edema, and cerebral infarction. Treatment is symptomatic and most patients have spontaneous recovery within 2 weeks. However, aggressive ICU management may be necessary for severely impaired left ventricular functions. Dobutamine, levosimendan, milrinone, and even an intra-aortic balloon pump may be added to the treatment to maintain cerebral blood flow. It is known that the risk of heart failure and pulmonary complications is much higher in patients with low-grade SAH. Hypovolemia and pulmonary edema are known to increase the risk of delayed cerebral ischemia in this patient group. Long-term intensive care hospitalization may be required in SAH patients. This may result in pulmonary complications such as hospital-acquired pneumonia, cardiogenic or neurogenic pulmonary edema, aspiration pneumonia, and pulmonary embolism, which occurs in approximately 30% of patients.

Acute respiratory distress syndrome occurs in 27% of SAH patients and is an independent predictor of outcome. However, diuretics can be dangerous because of the risk of brain ischemia caused by hypovolemia. Early pulmonary edema and late pulmonary edema after SAH are caused by heart failure and inflammatory (i.e., non-cardiogenic) conditions, respectively.

Measurement of extravascular lung water index, cardiac index, and pulmonary vascular permeability index with Pulse Contour Cardiac Output (PiCCO) is considered to be useful in the identification of pulmonary edema in SAH patients [78–95]. Neither statin therapy nor magnesium infusions should be initiated for delayed cerebral ischemia. Cerebral vasospasm is just one component of delayed cerebral edema.

Hyponatremia is common in subarachnoid hemorrhage and is associated with longer hospitalization time, but not increased mortality. Sodium abnormalities are common and carry a risk of poor prognosis in acute SAH patients. We performed a 10-year observational sodium study. Hyponatremia was defined as serum sodium (sNa) concentration below 135 mmol/L, whereas hypernatremia as sNa above 150 mmol/L. Our 10-year targeted sodium management regimen in acute SAH patients showed that dysnatremias were frequent, predominantly hyponatremic state, due to cerebral salt wasting syndrome (CSW) and not syndrome of inappropriate antidiuretic hormone secretion (SIADH). Hypernatremia was shown to be an independent risk factor for inpatient mortality and poor outcome. The standard sodium protocol lowered the frequency of SIADH, which was encountered in only one patient over 5 years. However, it did not significantly reduce the incidence and outcome improvement of hyponatremia. Hypernatremia occurred more often and had a higher mortality and worse outcome than hyponatremia, but these patients were neurologically worse upon its onset. Hyponatremia is the most common electrolyte imbalance that occurs in 50% of patients after SAH. Two mechanisms are accepted for hyponatremia after SAH: CSW and SIADH. Cerebral salt wasting syndrome and SIADH have different pathogenesis. However, it is not always easy to distinguish in the clinic, and they can be observed in the same patient [96–100].

DOI: http://dx.doi.org/10.5772/intechopen.89714

Author details

Sedef Tavukçu Özkan[1,2]

1 Department of Anesthesiology and Reanimation, İstinye University School of Medicine, Istanbul, Turkey

2 ICU, VM Medical Park Hospital Pendik, Istanbul, Turkey

*Address all correspondence to: sedefto@gmail.com

References

[1] Sarıhasan B. Nöroanestezi. Serebral Anevrizmalar ve AVM da Anestezi Yönetimi. In: Sarıhasan B, Madenoğlu H, Şatırlar ZO, Türe H, Karacalar KS, editors. Kayseri: M GrupMatbaacılık; 2017. pp. 235-247

[2] de Oliveira Manoel AL, Goffi A, Marotta TR, Schweizer TA, Abrahamson S, Macdonald RL. The critical care management of poor-grade subarachnoid haemorrhage. Critical Care. 2016;**20**:21

[3] Wıjdıcks EFM. The comatose patient. In: Comatose and Aneurysmal Subarachnoid Hemorrhage. New York: Oxford University Press; 2008. pp. 268-274

[4] D'Souza S. Aneurysmal subarachnoid hemorrhage. Journal of Neurosurgical Anesthesiology. 2015;**27**(3):222-240

[5] Zhu W, Liu P, Tian Y, et al. Complex middle cerebral artery aneurysms: A new classification based on the angioarchitecture and surgical strategies. Acta Neurochirurgica. 2013;**155**:1481-1491

[6] Choi IS, David C. Giant intracranial aneurysms: Development, clinical presentation and treatment. European Journal of Radiology. 2003;**46**:178-194

[7] Drake CG, Peerless SJ. Giant fusiform intracranial aneurysms: Review of 120 patients treated surgically from 1965 to 1992. Journal of Neurosurgery. 1997;**87**:141-162

[8] Gomes F, Dujovny M, Umansky F, et al. Microsurgical anatomy of the recurrent artery of Heubner. Journal of Neurosurgery. 1984;**60**:130-139

[9] Gomes FB, Dujovny M, Umansky F, et al. Microanatomy of the anterior cerebral artery. Surgical Neurology. 1986;**26**:129-141

[10] Drake CG. Report of World Federation of Neurological Surgeons Committee on a Universal SAH grading scale. The Journal of Neurosurgery. 1988;**68**:985

[11] Claassen J, Bernardini GL, Kreiter K, Bates J, Du YE, Copeland D, et al. Effect of cisternal and ventricular blood on risk of delayed cerebral ischemia after subarachnoid hemorrhage: The Fisher scale revisited. Stroke. 2001;**32**(9):2012-2020

[12] Yokoyama S, Hifumi T, Okazaki T, et al. Association of abnormal carbon dioxide levels with poor neurological outcomes in aneurysmal subarachnoid hemorrhage: A retrospective observational study. Journal of Intensive Care. 2018;**6**:83

[13] Rosen DS, Macdonald RL. Subarachnoid hemorrhage grading scales: A systematic review. Neurocritical Care. 2005;**2**:110-118

[14] Broderick JP, Brott TG, Duldner JE, et al. Initial and recurrent bleeding are the major causes of death following subarachnoid hemorrhage. Stroke. 1994;**25**:1342-1347

[15] Kassell NF, Torner JC, Haley EC Jr, Adams HP, Kongable GL. The international cooperative study on the timing of aneurysm surgery. Part 1: Overall management results. Journal of Neurosurgery. 1990;**73**:18-36

[16] Zheng K, Zhong M, Zhao B, et al. Poor-grade aneurysmal subarachnoid hemorrhage: Risk factors affecting clinical outcomes in intracranial aneurysm patients in a multi-center study. Frontiers in Neurology. 2019;**10**:123

[17] Hutchinson PJ, Seeley HM, Kirkpatrick PJ. Factors implicated in deaths from subarachnoid haemorrhage:

Are they avoidable? British Journal of Neurosurgery. 1998;**12**:37-40

[18] Ransom ER, Mocco J, Komotar RJ, et al. External ventricular drainage response in poor grade aneurysmal subarachnoid hemorrhage: Effect on preoperative grading and prognosis. Neurocritical Care. 2007;**6**:174-180

[19] Schuss P, Konczalla J, Platz J, et al. Aneurysm-related subarachnoid hemorrhage and acute subdural hematoma: Single center series and systematic review. Journal of Neurosurgery. 2013;**118**:984-990

[20] Van den Berg R, Foumani M, Schroder RD, et al. Predictors of outcome in World Federation of Neurologic Surgeons grade V aneurysmal subarachnoid hemorrhage patients. Critical Care Medicine. 2011;**39**:2722-2727

[21] Wostrack M, Sandow N, Vajkoczy P, et al. Subarachnoid haemorrhage WFNS grade V: Is maximal treatment worthwhile? Acta Neurochirurgica. 2013;**155**:579-586

[22] HutterBO,Kreitschmann-AndermahrI, Gilsbach JM. Health-related quality of life after aneurysmal subarachnoid hemorrhage: Impacts of bleeding severity, computerized tomography findings, surgery, vasospasm, and neurological grade. Journal of Neurosurgery. 2001;**94**:241-251

[23] Hutter BO, Kreitschmann-Andermahr I, Mayfrank L, et al. Functional outcome after aneurysmal subarachnoid hemorrhage. Acta Neurochirurgica. Supplement. 1999;**72**:157-174

[24] Bernstein JE, Savla P, Dong F, et al. Inflammatory markers and severity of Intracerebral. Cureus. 2018;**10**:123

[25] Rass V, Ianosi BA, Wegmann A, et al. Delayed resolution of cerebral edema is associated with poor outcome after nontraumatic subarachnoid hemorrhage. Stroke. 2019;**50**(4):828-836

[26] Germans MR, Coert BA, Vandertop WP, et al. Time intervals from subarachnoid hemorrhage to rebleed. Journal of Neurology. 2014;**261**:1425-1431

[27] Fujii Y, Takeuchi S, Sasaki O, et al. Ultra-early rebleeding in spontaneous subarachnoid hemorrhage. Journal of Neurosurgery. 1996;**84**:35-42

[28] Starke RM, Connolly ES, Participants in the International Multi-disciplinary Consensus Conference on the Critical Care Management of Subarachnoid Hemorrhage. Rebleeding after aneurysmal subarachnoid hemorrhage. Neurocritical Care. 2011;**15**:241-246

[29] Connolly ES Jr, Rabinstein AA, Carhuapoma JR, Derdeyn CP, Dion J, Higashida RT. Guidelines for the management of aneurysmal subarachnoid hemorrhage: A guideline for healthcare professionals from the American Heart Association/American Stroke Association. Stroke. 2012;**43**:1711-1737

[30] Diringer MN, Bleck TP, Claude Hemphill JIII, et al. Neurocritical Care Society. Critical care management of patients following aneurysmal subarachnoid hemorrhage: Recommendations from the neurocritical care society's multidisciplinary consensus conference. Neurocritical Care. 2011;**15**:211-240

[31] DeRooji NK, Rinkel GJ, Dankbaar JW, et al. Delayed cerebral ischemia after subarachnoid hemorrhage: A systemic review of clinical, laboratory, and radiological predictors. Stroke. 2013;**44**:43-54

[32] Dorhout Mees SM, Rinkel GJE, Feigin VL, et al. Calcium antagonists for

aneurysmal subarachnoid hemorrhage. Stroke. 2008;**39**:514-515

[33] Barker FG II, Ogilvy CS. Efficacy of prophylactic nimodipine for delayed ischemic deficit after subarachnoid hemorrhage: A metaanalysis. Journal of Neurosurgery. 1996;**84**:405-414

[34] Haley EC Jr, Kassell NF, Torner JC. A randomized controlled trial of high-dose intravenous nicardipine in aneurysmal subarachnoid hemorrhage. A report of the cooperative aneurysm study. Journal of Neurosurgery. 1993;**78**:537-547

[35] Güçyetmez B. Klinik Yoğun Bakım. Nörolojik Problemler. Subaraknoid Kanamaya Yaklaşım. In: Albert RK, Slutsky A, Ranieri M, Takala J, Torres A, Akpir K, Tuğrul S, editors. İstanbul: İstanbul Tıp Kitabevi; 2009. pp. 405-415

[36] Francoeur CL, Mayer SA. Management of delayed cerebral ischemia after subarachnoid hemorrhage. Critical Care. 2016;**20**(1):277

[37] Çolak T, Küçükceran K. Critical Care Emergency Medicine. İntraserebral Hemoraji. In: Farcy DA, Chıu CW, Marshall JP, Osborn TM, Cander B, Gül M, Çakır ZG, Okumuş M, editors. İstanbul: İstanbul Tıp Kitabevleri. 2. Baskı; 2018. pp. 249-359

[38] Ropper AH. Lateral displacement of the brain and level of consciousness in patients with an acute hemispheral mass. The New England Journal of Medicine. 1986;**314**:953-958

[39] Ropper AH, Shafran B. Brain edema after stroke. Clinical syndrome and intracranial pressure. Archives of Neurology. 1984;**41**:26-29

[40] Zazulia AR, Diringer MN, Derdeyn CP, Powers WJ. Progression of mass effect after intracerebral hemorrhage. Stroke. 1999;**30**:1167-1173

[41] Corry JJ, Varelas P, Abdelhak T, et al. Variable change in renal function by hypertonic saline. World Journal of Critical Care Medicine. 2014;**3**(2):61-67

[42] Diringer MN, Bleck TP, Hemphill C, et al. Neurocritical care society: Critical care management of patients following aneurysmal subarachnoid hemorrhage: Recommendations from the neurocritical care society's multidisciplinary consensus conference. Neurocritical Care. 2011;**15**:211-240

[43] Steiner T, Juvela S, Unterberg A, et al. European stroke organization guidelines for the management of intracranial aneurysms and subarachnoid haemorrhage. Cerebrovascular Diseases. 2013;**35**:93-112

[44] Ryttlefors M, Howells T, Nilsson P, et al. Secondary insults in subarachnoid hemorrhage: Occurrence and impact on outcome and clinical deterioration. Neurosurgery. 2007;**61**:704-705

[45] Mack WJ, King RG, Ducruet AF, et al. Intracranial pressure following aneurysmal subarachnoid hemorrhage: Monitoring practices and outcome data. Neurosurgical Focus. 2003;**14**:e3

[46] Bailes JE, Spetzler RF, Hadley MN, et al. Management morbidity and mortality of poor-grade aneurysm patients. Journal of Neurosurgery. 1990;**72**:559-566

[47] Zoerle T, Lombardo A, Colombo A, et al. Intracranial pressure after subarachnoid hemorrhage. Critical Care Medicine. 2015;**43**:168-176

[48] Heuer GG, Smith MJ, Elliott JP, et al. Relationship between intracranial pressure and other clinical variables in patients with aneurysmal subarachnoid hemorrhage. Journal of Neurosurgery. 2004;**101**:408-416

[49] Nagel A, Graetz D, Schink T, et al. Relevance of intracranial hypertension for cerebral metabolism in aneurysmal subarachnoid hemorrhage. Journal of Neurosurgery. 2009;**111**:94-101

[50] Soehle M, Chatfield DA, Czosnyka M, et al. Predictive value of initial clinical status, intracranial pressure and transcranial Doppler pulsatility after subarachnoid haemorrhage. Acta Neurochirurgica. 2007;**149**:575-583

[51] Väth A, Kunze E, Roosen K, Meixensberger J. Therapeutic aspects of brain tissue pO_2 monitoring after subarachnoid hemorrhage. Acta Neurochirurgica. Supplement. 2002;**81**:307-309

[52] Yokoyama S, Hifumi T, Okazaki T, et al. Association of abnormal carbon dioxide levels with poor neurological outcomes in aneurysmal subarachnoid hemorrhage: Retrospective observational study. Journal of Intensive Care. 2018;**6**:83

[53] Kinoshita K. Traumatic brain injury: Pathophysiology for neurocritical care. Journal of Intensive Care. 2016;**4**:29

[54] Westermaier T, Stetter C, Kunze E, et al. Controlled hypercapnia enhances cerebral blood flow and brain tissue oxygenation after aneurysmal subarachnoid hemorrhage: Results of a phase 1 study. Neurocritical Care. 2016;**25**:205-214

[55] Pynnonen L, Falkenbach P, Kamarainen A, et al. Therapeutic hypothermia after cardiac arrest - cerebral perfusion and metabolism during upper and lower threshold normocapnia. Resuscitation. 2011;**82**:1174-1179

[56] Floyd TF, Clark JM, Gelfand R, et al. Independent cerebral vasoconstrictive effects of hyperoxia and accompanying arterial hypocapnia at 1 ATA. Journal of Applied Physiology. 2003;**1985**(95):2453-2461

[57] Sanfilippo F, Santonocito C, Veenith T, Astuto M, Maybauer MO. The role of neuromuscular blockade in patients with traumatic brain injury: A systematic review. Neurocritical Care. 2015;**22**:325-334

[58] Li M, Chen T, Chen SD, et al. Comparison of equimolar doses of mannitol and hypertonic saline for the treatment of elevated intracranial pressure after traumatic brain injury: A systematic review and meta-analysis. Medicine (Baltimore). 2015;**94**(17):e736

[59] Gu J, Huang H, Huang Y, et al. Hypertonic saline or mannitol for treating elevated intracranial pressure in traumatic brain injury: A meta-analysis of randomized controlled trials. Neurosurgical Review. 2019;**42**(2):499-509

[60] Tseng MY, Al-Rawi PG, Czosnyka M, et al. Enhancement of cerebral blood flow using systemic hypertonic saline therapy improves outcome in patients with poor-grade spontaneous subarachnoid hemorrhage. Journal of Neurosurgery. 2007;**107**:274-282

[61] Al-Rawi PG, Tseng MY, Richards HK, et al. Hypertonic saline in patients with poor-grade subarachnoid hemorrhage improves cerebral blood flow, brain tissue oxygen, and pH. Stroke. 2009;**41**:122-128

[62] Tseng M-Y, Al-Rawi PG, Pickard JD, et al. Effect of hypertonic saline on cerebral blood flow in poor-grade patients with subarachnoid hemorrhage. Stroke. 2003;**34**:1389-1396

[63] Suarez JI, Qureshi AI, Parekh PD, et al. Administration of hypertonic (3%) sodium chloride/acetate in hyponatremic patients with symptomatic vasospasm following subarachnoid hemorrhage. Journal of Neurosurgical Anesthesiology. 1999;**11**:178-184

[64] Bentsen G, Breivik H, Lundar T, et al. Hypertonic saline (7.2%) in 6% hydroxyethyl starch reduces intracranial pressure and improves hemodynamics in a placebo-controlled study involving stable patients with subarachnoid hemorrhage. Critical Care Medicine. 2006;**34**:2912-2917

[65] Mak CHK, Lu YY, Wong GK. Review and recommendations on management of refractory raised intracranial pressure in aneurysmal subarachnoid hemorrhage. Vascular Health and Risk Management. 2013;**9**:353-359

[66] Inamasu J, Ichikizaki K. Mild hypothermia in neurologic emergency: An update. Annals of Emergency Medicine. 2002;**40**:220-230

[67] Buschmann U, Yonekawa Y, Fortunati M, et al. Decompressive hemicraniectomy in patients with subarachnoid hemorrhage and intractable intracranial hypertension. Acta Neurochirurgica. 2007;**149**:59-65

[68] Schirmer CM, Hoit DA, Malek AM. Decompressive hemicraniectomy for the treatment of intractable intracranial hypertension after aneurysmal subarachnoid hemorrhage. Stroke. 2007;**38**:987-992

[69] Stuart RM, Claassen J, Schmidt M, et al. Multimodality neuromonitoring and decompressive hemicraniectomy after subarachnoid hemorrhage. Neurocritical Care. 2011;**15**:146-150

[70] Jaeger M, Soehle M, Meixensberger J. Effects of decompressive craniectomy on brain tissue oxygen in patients with intracranial hypertension. Journal of Neurology, Neurosurgery, and Psychiatry. 2003;**74**:513-515

[71] Stiefel MF, Heuer GG, Smith MJ, et al. Cerebral oxygenation following decompressive hemicraniectomy for the treatment of refractory intracranial hypertension. Journal of Neurosurgery. 2004;**101**:241-247

[72] Nagel A, Graetz D, Vajkoczy P, et al. Decompressive craniectomy in aneurysmal subarachnoid hemorrhage: Relation to cerebral perfusion pressure and metabolism. Neurocritical Care. 2009;**11**:384-394

[73] de Oliveira Manoel AL, Turkel-Parrella D, Duggal A, et al. Managing aneurysmal subarachnoid hemorrhage: It takes a team. Cleveland Clinic Journal of Medicine. 2015;**82**:177-192

[74] Macdonald RL. Delayed neurological deterioration after subarachnoid haemorrhage. Nature Reviews. Neurology. 2013;**10**:44-58

[75] Egge A, Waterloo K, Sjøholm H, et al. Prophylactichyperdynamicpostoperative fluid therapy after aneurysmal subarachnoid hemorrhage: A clinical, prospective, randomized, controlled study. Neurosurgery. 2001;**49**:593-605

[76] Lennihan L, Mayer SA, Fink ME, et al. Effect of hypervolemic therapy on cerebral blood flow after subarachnoid hemorrhage: A randomized controlled trial. Stroke. 2000;**31**:383-391

[77] Jost SC, Diringer MN, Zazulia AR, et al. Effect of normal saline bolus on cerebral blood flow in regions with low baseline flow in patients with vasospasm following subarachnoid hemorrhage. Journal of Neurosurgery. 2005;**103**:25-30

[78] Kassell NF, Peerless SJ, Durward QJ, et al. Treatment of ischemic deficits from vasospasm with intravascular volume expansion and induced arterial hypertension. Neurosurgery. 1982;**11**:337-343

[79] Kimball MM, Velat GJ, Hoh BL, Participants in the International Multidisciplinary

Consensus Conference on the Critical Care Management of Subarachnoid Hemorrhage. Critical care guidelines on the endovascular management of cerebral vasospasm. Neurocritical Care. 2011;**15**:336-341

[80] Zwienenberg-Lee M, Hartman J, Rudisill N, et al. Effect of prophylactic transluminal balloon angioplasty on cerebral vasospasm and outcome in patients with fisher grade III subarachnoid hemorrhage: Results of a phase ii multicenter, randomized, clinical trial. Stroke. 2008;**39**:1759-1765

[81] Mayer SA, LiMandri G, Sherman D, et al. Electrocardiographic markers of abnormal left ventricular wall motion in acute subarachnoid hemorrhage. Journal of Neurosurgery. 1995;**83**:889-896

[82] Taccone FS, Lubicz B, Piagnerelli M, et al. Cardiogenic shock with stunned myocardium during triple-H therapy treated with intra-aortic balloon pump counterpulsation. Neurocritical Care. 2008;**10**:76-82

[83] Deibert E, Barzilai B, Braverman AC, et al. Clinical significance of elevated troponin I levels in patients with nontraumatic subarachnoid hemorrhage. Journal of Neurosurgery. 2003;**98**:741-746

[84] Banki N, Kopelnik A, Tung P, et al. Prospective analysis of prevalence, distribution, and rate of recovery of left ventricular systolic dysfunction in patients with subarachnoid hemorrhage. Journal of Neurosurgery. 2006;**105**:15-20

[85] Levy ML, Rabb CH, Zelman V, et al. Cardiac performance enhancement from dobutamine in patients refractory to hypervolemic therapy for cerebral vasospasm. Journal of Neurosurgery. 1993;**79**:494-499

[86] Busani S, Rinaldi L, Severino C, et al. Levosimendan in cardiac failure after subarachnoid hemorrhage. The Journal of Trauma. 2010;**68**:E108-E110

[87] Lannes M, Teitelbaum J, Pilar Cortés M, et al. Milrinone and homeostasis to treat cerebral vasospasm associated with subarachnoid hemorrhage: The Montreal neurological hospital protocol. Neurocritical Care. 2012;**16**:354-362

[88] Lazaridis C, Pradilla G, Nyquist PA, et al. Intra-aortic balloon pump counterpulsation in the setting of subarachnoid hemorrhage, cerebral vasospasm, and neurogenic stress cardiomyopathy. Case report and review of the literature. Neurocritical Care. 2010;**13**:101-108

[89] Yoneda H, Nakamura T, Shirao S, et al. Multicenter prospective cohort study on volume management after subarachnoid hemorrhage: Hemodynamic changes according to severity of subarachnoid hemorrhage and cerebral vasospasm. Stroke. 2013;**44**:2155-2161

[90] Hoff RG, Rinkel GJ, Verweij BH, et al. Pulmonary edema and blood volume after aneurysmal subarachnoid hemorrhage: A prospective observational study. Critical Care. 2010;**14**:R43

[91] Hoff R, Rinkel G, Verweij B, et al. Blood volume measurement to guide fluid therapy after aneurysmal subarachnoid hemorrhage: A prospective controlled study. Stroke. 2009;**40**:2575-2577

[92] Friedman JA, Pichelmann MA, Piepgras DG, et al. Pulmonary complications of aneurysmal subarachnoid hemorrhage. Neurosurgery. 2003;**52**:1025-1031

[93] Kahn JM, Caldwell EC, Deem S, et al. Acute lung injury in patients with subarachnoid hemorrhage: Incidence, risk factors, and outcome. Critical Care Medicine. 2006;**34**:196-202

[94] Obata Y, Takeda J, Sato Y, et al. A multicenter prospective cohort study of volume management after subarachnoid hemorrhage: Circulatory characteristics of pulmonary edema after subarachnoid hemorrhage. Journal of Neurosurgery. 2016;**125**(2):254-263

[95] Tagami T, Kuwamoto K, Watanabe A, et al. SAH PiCCO Study Group. Optimal range of global end-diastolic volume for fluid management after aneurysmal subarachnoid hemorrhage: A multicenter prospective cohort study. Critical Care Medicine. 2014;**42**(6):1348-1356

[96] Dority JS, Oldham JS. Subarachnoid hemorrhage: An update. Anesthesiology Clinics. 2016;**34**(3):577-600

[97] Spatenkova V, Bradac O, de Lacy P, et al. Dysnatremia as a poor prognostic indicator in patients with acute subarachnoid hemorrhage. Journal of Neurosurgical Sciences. 2017;**61**(4):371-379

[98] Spatenkova V, Bradac O, Skrabalek P. The impact of a standardized sodium protocol on incidence and outcome of dysnatremias in neurocritical care. Journal of Neurological Surgery Part A: Central European Neurosurgery. 2015;**76**(4):279-290

[99] Rabinstein AA, Bruder N. Management of hyponatremia and volume contraction. Neurocritical Care. 2011;**15**:354-360

[100] Audibert G, Steinmann G, de Talancé N, et al. Endocrine response after severe subarachnoid hemorrhage related to sodium and blood volume regulation. Anesthesia and Analgesia. 2009;**108**:1922-1928