

A RESEARCH STUDY ON MINIMIZING NEUROLOGICAL INJURY DURING CARDIAC SURGERY: CONTEMPORARY INTRAOPERATIVE STRATEGIES AND CLINICAL EVIDENCE

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ABSTRACT

Background: Neurological problems after heart surgery are a cause of problems during and after the operation. These issues can lead to death long-term disability and badly affects brain function. Many patients who have bypass experience brain-related problems. These problems range from strokes to confusion after surgery and subtle memory or thinking issues that may not be obvious right away. Up to half of all patients may be affected. The causes are very complicated. Involve several factors. One cause is the movement of clots or debris into the brain during the surgery especially when the aorta is clamped and tubes are placed. Another is reduced blood flow to the brain because the brain's ability to control blood pressure fails. There is also a reaction in the body caused by the blood coming into contact with the machine. Finally, damage happens when blood flow returns to the brain, after a period of supply. This is called ischemia-reperfusion injury.

Methods: This review brings together a lot of clinical research from top cardiothoracic journals. It looks at large long-term studies and major clinical trials. It also includes meta-analyses that combine data from many sources. The focus is, on protective measures used during surgery. These include aortic imaging techniques, real-time monitoring of cerebral autoregulation, careful temperature control, selective antegrade cerebral perfusion, multimodal neuromonitoring and various pharmacological neuroprotective protocols. Each of these areas is examined closely to understand how they help protect patients during surgery.

Results: Epiaortic ultrasound has been proven to be more superior than manual palpation and transesophageal echocardiography for detecting ascending aortic atheroma, which enables dynamic

changes during surgery to greatly reduce the risk of embolic stroke. Personalization of mean arterial pressure based on continuous cerebral oximetry index measurements successfully prevents tissue injury due to hypoperfusion. With regard to aortic arch replacement necessitating circulatory arrest, moderate hypothermia (24.1-28.0°C) along with selective antegrade cerebral perfusion is associated with better patient outcomes compared with deep hypothermic circulatory arrest, giving rise to odds ratios of 0.64 for death and 0.62 for stroke.

Conclusions: Moving from empirical perfusion guidelines to a comprehensive, patient-centered intraoperative neuroprotection strategy will lower the rate of neurological complications. Future research efforts should be directed at conducting extensive multi-center clinical trials, using machine learning algorithms, and establishing neurological definitions.

Keywords:

Cardiac surgery; perioperative stroke; neuroprotection; cerebral perfusion; near-infrared spectroscopy; cardiopulmonary bypass; postoperative delirium; epiaortic ultrasound.

INTRODUCTION

Neurological injury remains one of the serious problems that can happen after adult and child heart surgery. Even though we have machines for heart pumps, tools and medicines problems with the brain and spinal cord still happen and cause many deaths around the time of the operation and long-term loss of function. Neurological injury covers a range of problems after heart surgery. It can include permanent strokes, brief attacks that look like strokes, confusion after the operation and small changes in thinking that are hard to see. A clear stroke shows up in 1% to 3% of people who get a normal bypass or a single valve change. The rate rises sharply to more than 8% in very risky jobs such, as big aortic arch repairs many valve changes or combined operations that open the heart (Gaudino et al. 2019; Yousef et al. 2025). In addition to obvious neurologic impairment, subclinical brain damage is extremely common. In MRI scans employing diffusion-weighted imaging (DWI), ischemic brain injuries have been observed in 30% to 50% of symptomless cardiac surgery patients after surgery (Rodriguez et al., 2006). Acute postoperative delirium is a disorder of impaired focus, environment awareness, and executive function that has been found to occur in 10% to 30% of cardiac surgery patients (de la Varga-Martínez et al., 2023). Clinical registry analysis indicates that postoperative delirium increases the risk of sustained cognitive impairment, rapid progression to dementia, functional dependency, and overall mortality at

five years' follow-up (Saczynski et al., 2012; Crocker et al., 2016).

Postoperative cognitive dysfunction (POCD) which affects functioning short-term memory, processing speed and motor coordination is seen in up to 50% of adult patients when they leave the hospital. It continues in 20% to 30% of people six months after the procedure (de la Varga-Martínez et al. 2023). These brain problems create a challenge for healthcare systems. They cause longer stays in the care unit (ICU) longer hospital visits, more readmissions and higher overall costs for healthcare. Because of this preventing brain damage during surgery has become a goal, in modern cardiothoracic surgery and neuroanesthesia.

The cause of perioperative brain injury in cardiac surgery patients has a complicated nature involving a variety of different physiological mechanisms. The major ones include particulate and gaseous microembolization, hypoperfusion due to insufficient perfusion pressure or flow, disruption of cerebral auto-regulation, development of systemic inflammatory response syndrome (SIRS) due to blood contact with foreign surfaces in the extracorporeal circuit, and oxidative stress resulting from ischemia-reperfusion periods (Ikram et al., 2018; Pezzato et al., 2025). The differentiation of early (occurs at emergence from anesthesia) and late (develops following the period of normal recovery) perioperative stroke shows that there are different clinical risk factors associated with the two: the

former is predominantly caused by debris and air embolization in the aorta, while the latter is associated with postoperative atrial fibrillation, systemic coagulation, or hemodynamic instability (Gaudino et al., 2019).

In the past neuroprotective strategies were based on cooling of the body and on set limits for blood flow during cardiopulmonary bypass. Today perioperative care has shifted to strategies that are customized for each patient. Important new steps in strategies include using epiaortic ultrasonography to steer aortic cannulation and cross-clamping watching the limits of cerebral autoregulation in real time to set patient-specific mean arterial pressure targets applying selective antegrade cerebral perfusion during aortic arch surgery and keeping a continuous multimodal neuro-monitoring system with near-infrared spectroscopy, transcranial Doppler and electroencephalography (Jarry et al. 2024; Patel et al. 2025). This article offers a review of modern intraoperative neuroprotective strategies looking at the clinical data the body's natural responses, the monitoring tools and the future paths that aim to cut down brain injury, in heart surgery.

Emerging Technologies and Future Directions

There has been an increased use of Artificial Intelligence together with Machine Learning in predicting outcomes of cardiac surgeries, including neurological complications. From a scoping review of 64 studies that have used artificial intelligence in open-heart surgery, XGBoost was identified as having the best results in 11 out of 32 studies utilizing this algorithm although the majority of the studies were retrospective and had no external validation. From another systematic review on the use of artificial intelligence in congenital heart surgery, models were identified as being better than risk stratification methods with an area under the curve of 0.52 to 0.997. Time cerebral monitoring that brings together near-infrared spectroscopy, transcranial Doppler and processed electroencephalography into one system might help doctors get a fuller picture of how the brain is doing. This could let them spot problems before

they turn into injury. If machine-learning tools are used on the data collected continuously they might find patterns that show a person's brain is getting worse before any symptoms appear. Advanced brain imaging, like using MRI during surgery in operating rooms can catch signs of low blood flow to the brain right away.. The equipment and setup needed make it hard to use everywhere.

Tailoring brain protection strategies to each patient's risk factors, genes and real-time brain data is the step. Of following the same plan for everyone this approach moves toward care that fits the individual. It's a step from one-size-fits-all treatment, to personalized medicine.

Conclusion

Neurological damage is one of the serious complications of cardiac surgery that carries huge morbidity and mortality burden. The etiologies are multi-faceted and involve mechanisms such as embolic, hypoperfusion, inflammation, and reperfusion. It demands a comprehensive strategy to prevent neurological damage during cardiac surgery. Current approaches to prevent neurological damage intraoperatively consist of manipulation of aorta guided by epiaortic ultrasound imaging, customized cerebral perfusion target based on autoregulation monitoring, hypothermia with antegrade cerebral perfusion as a preference at moderate levels in case of cardiopulmonary bypass surgery. These strategies have helped a little in improving brain health.. Clear standard neuroprotection protocols are still missing and medicines have not worked well. What scientists need to do is to run big studies at many hospitals that all use the same ways to measure neurological outcomes. They should also check ways to watch the brain and use computer programs that guess what might happen. Scientists should make precision neuroprotection approaches that fit each person's risk and the time physiological data that comes out while the person is being treated. Using monitoring plus machine-learning analytics looks very hopeful, for spotting and stopping cerebral injury early during cardiac surgery.

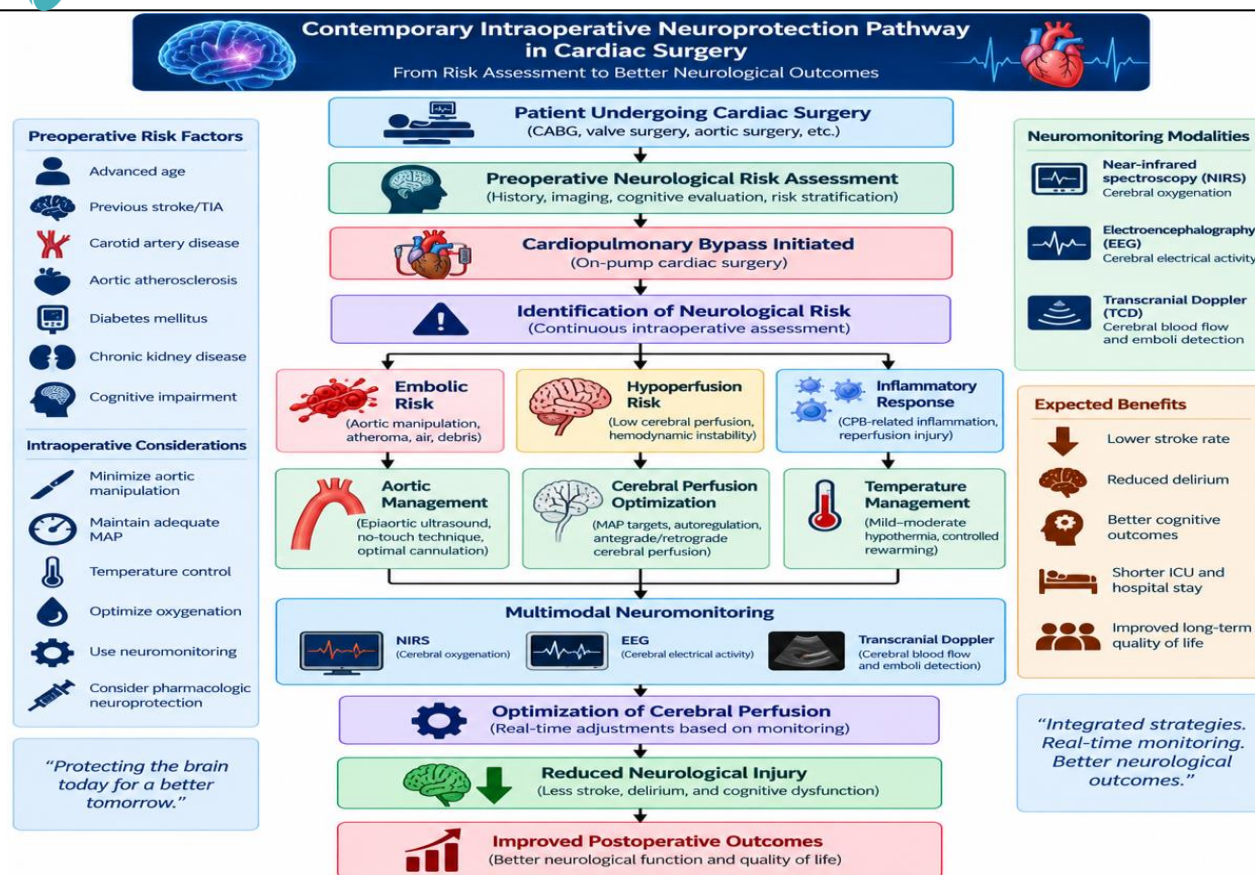


Figure 1. Contemporary Intraoperative Neuroprotection Pathway in Cardiac Surgery

Figure Legend: This flowchart illustrates the stepwise integration of neuroprotective strategies throughout the cardiac surgical procedure. Preoperative neurological risk assessment informs intraoperative decision-making.

Methodology

This review brings together the clinical literature in cardiac surgery, neuroanesthesia, and cardiothoracic medicine. The literature search process involved the use of a systematic approach to search the medical literature databases such as PubMed/MEDLINE and the Cochrane Central Register of Controlled Trials. The search terms used include cardiac surgery, cardiopulmonary bypass, neurologic injury, perioperative stroke, post-operative delirium, epi-aortic ultrasound, cerebral autoregulation, near-infrared

spectroscopy, transcranial Doppler, and antegrade cerebral perfusion.

Eligibility Criteria

The selection of articles was made according to their relation to neuroprotection in surgeries and their neurological results in adults and children undergoing cardiac surgeries. Preference was given to randomized controlled trials, prospective cohort studies, multicenter registries, systematic reviews, and meta-analysis papers published in high-quality medical journals. Papers limited only to non-cardiac surgery, animal models without any

translational studies to humans, and case reports were excluded from consideration.

Primary Outcome Measures and Analytical Categories

The primary clinical outcomes assessed in the included studies are as follows:

1. Incidence of ischemic and hemorrhagic stroke categorized by early and delayed onset. Delirium (POD) occurrence measured using established clinical evaluation tools. Postoperative cognitive dysfunction (POCD) evaluated through neuropsychological testing. All-cause operative mortality. Length of stay in the ICU and total hospital stay with a focus, on durations. Micro

embolic signal count, tracked using transcranial Doppler ultrasonography.

Results:

Clinical evidence suggests that brain injury in the operating room occurs through four principal pathways, namely, embolization, cerebral hypoperfusion, systemic inflammation, and reperfusion injury. The percentage of intraoperative neurological injuries that result from embolic particles dislodged from the ascending aorta during cannulation, cross-clamping, and anastomosis formation is estimated to be 40% (Ikram et al., 2018). Cerebral hypoperfusion associated with mean arterial blood pressure below LLA leads to 30% of cases, systemic inflammation to 20%, and reperfusion injury to 10% (Pezzato et al., 2025).

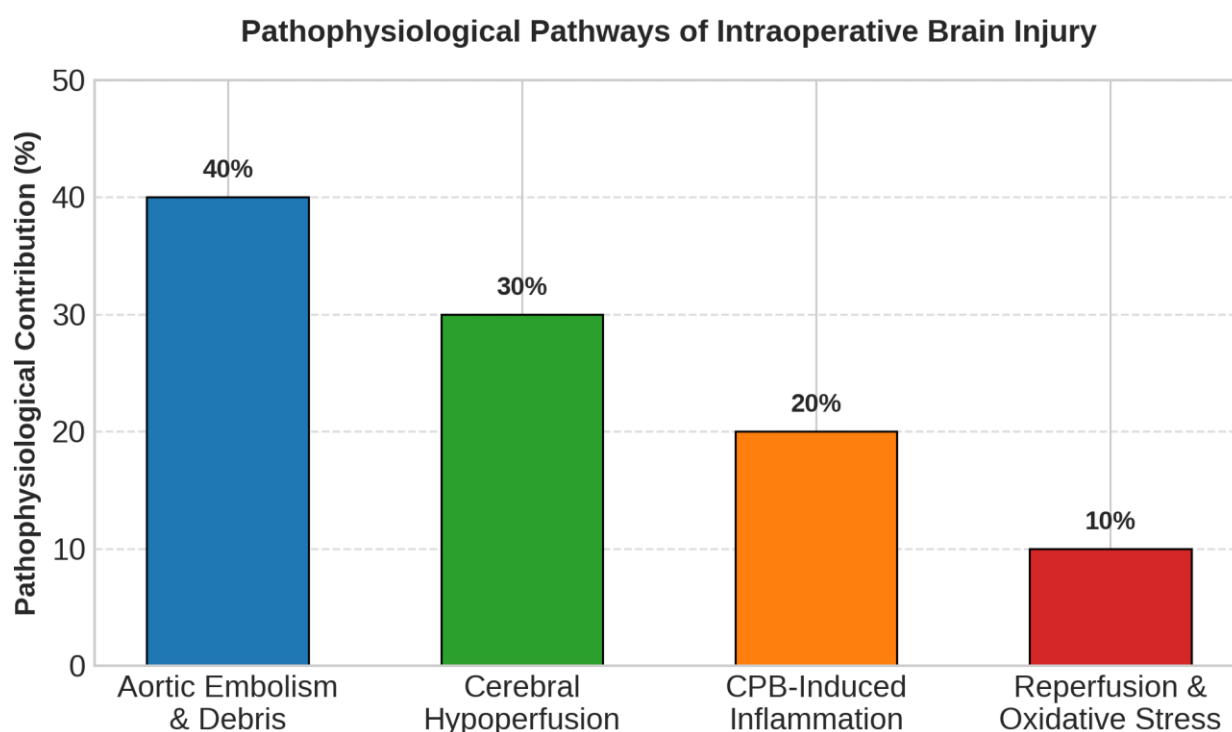


Figure 1. Relative pathophysiological contributions of key intraoperative mechanisms to perioperative brain injury.

Table 1. Major Mechanisms of Neurological Injury During Cardiac Surgery

Mechanism	Pathophysiology	Clinical Consequences	Prevention Strategy
Embolic Injury	Dislodgement of atheromatous debris and air microemboli	Focal cerebral ischemia, acute stroke, delirium	Epiaortic ultrasound screening, no-touch aortic techniques
Hypoperfusion	MAP falling below the lower limit of autoregulation	Watershed territory infarction, diffuse cognitive decline	Continuous autoregulation monitoring (COx), MAP titration
Inflammation	SIRS response triggered by extracorporeal blood-circuit contact	Blood-brain barrier breakdown, neuroinflammation	Biocompatible CPB circuits, anti-inflammatory protocols
Reperfusion Injury	Reactive oxygen species generation following ischemia restoration	Secondary apoptosis, microvascular dysfunction	Controlled rewarming rates, antioxidant maintenance

The clinical assessment of the intraoperative neuroprotective measures indicates different levels of efficacy in relation to particular procedural approaches. The epiaortic ultrasound is always found more accurate than palpation and transesophageal echocardiography (TEE) to detect ascending aorta atheroma that helps surgeons adjust their cannulation and cross-clamping

approaches to clear the tissue areas (Yousef et al., 2025).

When operating on aortic arch under circulatory arrest, the meta-analysis shows a reduced operative mortality (OR 0.64) and incidence of perioperative stroke (OR 0.62) by using selective antegrade cerebral perfusion (ACP) under moderate hypothermia (24.1–28.0°C) in comparison with deep hypothermic circulatory arrest (DHCA) only (Hameed et al., 2020; Belyaev et al., 2024).

Table 2. Comparative Evaluation of Intraoperative Neuroprotective Strategies

Strategy	Mechanism of Action	Clinical Advantages	Current Limitations
Epiaortic Ultrasound	Direct high-frequency ultrasound mapping of ascending aorta	Detects non-calcified plaques; alters cannulation/clamp sites	Requires sterile probe placement; operator skill dependency
Antegrade Cerebral Perfusion	Maintains oxygenated blood flow via carotid arteries during arrest	Markedly reduces stroke and mortality vs. DHCA	Debate over optimal perfusion pressures and unilateral vs. bilateral flow

Strategy		Mechanism of Action		Clinical Advantages	Current Limitations
NIRS Oximetry	Cerebral	Continuous non-invasive monitoring of frontal lobe rSO ₂		Provides real-time warning of cerebral desaturation	Prone to extracranial signal contamination and light interference
Transcranial Doppler (TCD)	Doppler	Ultrasonic velocity measurement in middle cerebral artery		Detects microembolic signals and cerebral blood flow velocity	Operator dependent; poor acoustic window in up to 15% of patients
Moderate Hypothermia		Reduces cerebral metabolic rate for oxygen (CMRO ₂)		Avoids deep hypothermia-induced coagulopathy and prolonged CPB	Optimal target temperature range continues to be refined
Controlled Rewarming	Slow	Gradual rewarming (<0.5°C/min) post-hypothermic CPB		Prevents jugular venous desaturation and electrocortical suppression	Extends overall cardiopulmonary bypass and operative duration

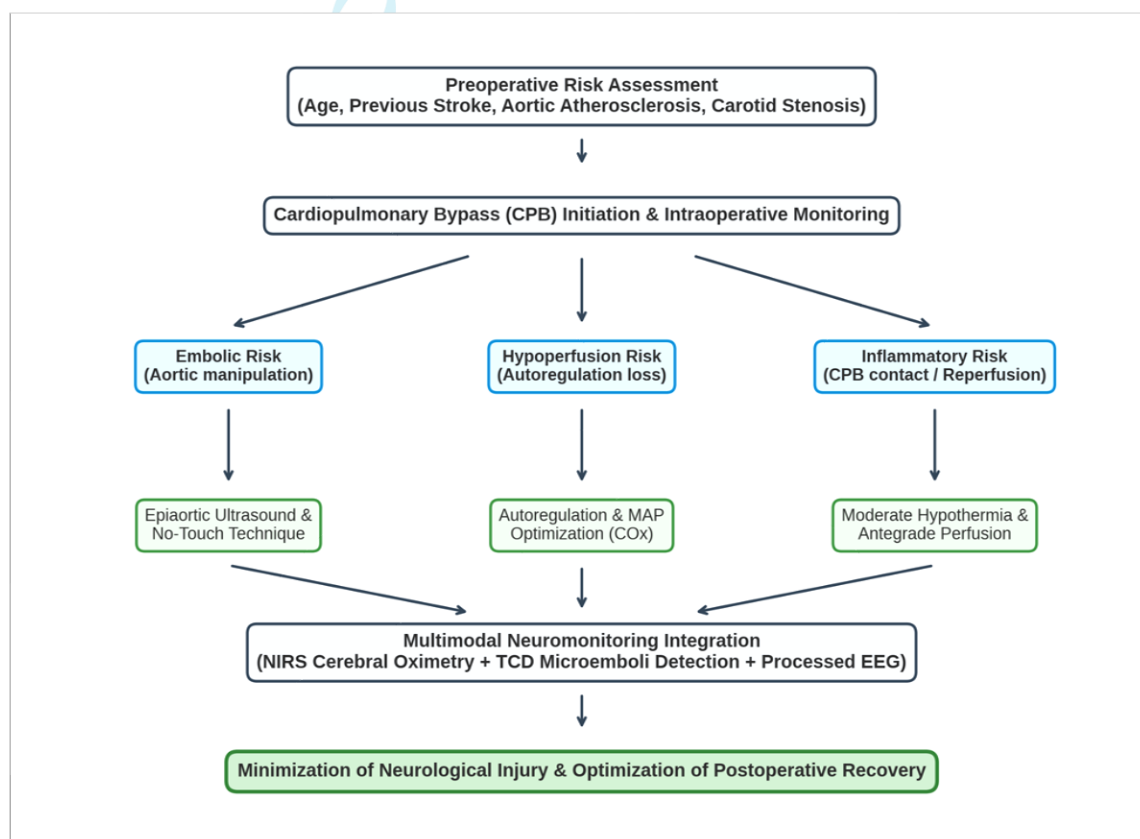


Figure 2. Integrated intraoperative neuroprotection pathway during cardiac surgical procedures.

DISCUSSION:

Mechanisms of Embolic Injury and Aortic Management Strategies

Aortic athero-embolism is still the leading cause of ischemic stroke in patients undergoing cardiac surgery. Manipulations with the ascending aorta, in particular cannulation, clamping and unclamping and creating proximal anastomoses with coronary vein grafts causes fragmentation of calcified or friable atherosclerotic plaques into the cerebrovascular system (Ikram et al., 2018; Yousef et al., 2025). Transesophageal echocardiography is utilized as an intraoperative cardiac evaluation tool; however, this procedure has a proven 'blind spot' in the distal part of the ascending aorta and proximal aortic arch due to the presence of air in the left main bronchus. Moreover, manual palpation by the operating surgeon does not identify half of the atheromatous plaques because of the lack of tactile sensation provided by soft non-calcified plaques.

The epi-aortic ultrasound technique involves the use of a high-frequency linear probe applied directly to the exposed ascending aorta in a sterile sheath. From clinical studies, routine epi-aortic ultrasound is shown to offer better spatial resolution with respect to the detection of plaque thickness, mobile debris, and calcification (Yousef et al., 2025). The presence of significant aortic disease leads to the change in surgical approach, including the use of other arterial cannulation sites (e.g., axillary and femoral artery), single cross-clamp technique, OPCAB surgery, or 'no touch' approach on the aorta with arterial grafts. According to clinical registry results, the ultrasound-guided approach reduces the risk of stroke in at-risk patients undergoing coronary bypass surgery (Yousef et al., 2025).

Cerebral Autoregulation and Hemodynamic Optimization

The primary clinical outcomes evaluated across the included literature include blood flow. Cerebral blood flow is tightly regulated across a range of blood pressures under normal physiological conditions. This regulation is known as autoregulation. However during bypass cerebral autoregulation is frequently impaired or

completely lost. This happens because of hypothermia -pulsatile blood flow, hemodilution, systemic inflammatory mediators and exposure to microemboli. When mean arterial pressure falls below the limit of autoregulation cerebral blood flow becomes entirely pressure-dependent. This means the brain can no longer maintain its blood supply. As a result the brain becomes vulnerable, to hypoperfusion watershed tissue ischemia and diffuse ischemic injury. The primary clinical outcomes evaluated across the included literature include:

Conventional CPB practice relies on a MAP target that is not tailored to each patient. For instance many surgeons set MAP between 50 and 70 mmHg. Yet new studies show that the lowest level that keeps the brain protected - the LLA - is different for every heart-surgery patient. Some LLA values are as low as 40 mmHg; others are above 85 mmHg. The wide range is driven by conditions such as blood pressure, past stroke or blood vessel problems and diabetes (Pezzato et al. 2025).

I have found that we can watch the brain's blood flow in time by using the cerebral oximetry index, COx. COx is a number that compares MAP with the oxygen level in the brain measured by NIRS, the cerebral oxygen saturation (SrSO₂). When COx gets close, to +1 the brain cannot regulate its blood flow; when COx stays around zero or below the brain's regulation works well. By keeping MAP than the patient's own LLA during CPB we cut down how long and how deep the brain gets low blood flow. This simple trick is linked to cases of delirium after surgery and less brain dysfunction (Pezzato et al. 2025).

Temperature Management and Cerebral Perfusion Protocols

The main results looked at in the studies include: Today aortic surgery is mostly done using hypothermic circulatory arrest (MHCA, 24.1°C to 28.0°C) along with antegrade cerebral perfusion (ACP). This approach is supported by research from Hameed et al. In 2020. Belyaev et al. In 2024. ACP means inserting tubes into the artery and/or the left common carotid artery. This lets oxygen-rich blood flow directly to the brain at a steady rate

(8 to 12 mL/kg/min) while the rest of the body's circulation is stopped. Studies that compare methods show that MHCA with ACP gives the same or better brain protection than deep hypothermic circulatory arrest (DHCA) alone. It also cuts down how the heart-lung machine runs, lowers the need for blood transfusions and reduces death within 30 days and stroke rates. This is based on Hameed et al., 2020. There's still debate over whether using one side or both sides for ACP is better.. Now most experts agree that using just one side (unilateral ACP) is safe and works well if the time without blood flow is under 30 to 40 minutes. For complex surgeries where the time without blood flow goes, over 40 minutes using both sides (bilateral ACP) is the preferred choice.

Multimodal Neuromonitoring Integration

The main clinical results looked at in the studies include:

Single-modality monitoring is not enough to see the changing conditions inside the nervous system when someone has complex heart surgery. Multimodal neuromonitoring uses methods like Near-Infrared Spectroscopy (NIRS) Transcranial Doppler (TCD) and processed Electroencephalography (EEG) to give a full view of brain oxygen levels, blood flow, small blockages and brain activity (Jarry et al., 2024; Patel et al. 2025).

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Near-Infrared Spectroscopy (NIRS) checks how much oxygen is in the part of the brain by looking at how much light is taken in by oxygen-rich and oxygen-poor blood. When NIRS shows a drop in oxygen levels (when the number goes below 50 or drops than 20% from normal) it means the brain is not getting enough oxygen. Quick steps like raising blood pressure increasing the heart-lung

machine flow improving oxygen in the blood making sure the blood has red cells or adjusting the tube in the aorta can often fix the drop in oxygen and reduce the chance of serious problems, with other organs (Patel et al. 2025). Transcranial Doppler (TCD) ultrasonography monitors blood flow velocity in the middle cerebral artery and detects high-intensity transient signals (HITS), which correspond to gaseous microemboli or solid atheromatous particulate debris.

Processed Electroencephalography (EEG) tracks cortical electrical activity, enabling anesthesiologists to assess hypnotic depth, prevent intraoperative awareness, detect subclinical seizure activity during rewarming, and confirm metabolic burst suppression prior to deep hypothermic circulatory arrest or targeted pharmacological neuroprotection.

Pharmacological Neuroprotection and Delirium Prevention Protocols

There is a vast amount of research conducted on the effectiveness of pharmacologic neuroprotectants such as N-methyl-D-aspartate (NMDA) receptor blockers, free radical scavengers, calcium channel blockers, and anti-inflammatory agents in preclinical studies, yet the results of clinical trials in human cardiac surgery are rather inconsistent and inconclusive. Volatile halogenated agents like sevoflurane and isoflurane show evidence of their myocardial ischemic preconditioning effect but cannot be proven superior to propofol-based TIVA in terms of neuroprotection. While high doses of corticosteroids such as methylprednisolone and dexamethasone decrease the level of systemic inflammation in CPB, there are randomized controlled trials that found no significant decrease in mortality rate and risk of neurological dysfunction (SIRS trial, DECS trial).

Nonetheless, non-pharmacological approaches for delirium prevention proved clinically effective. In multimodal delirium management, it is emphasized that intraoperative cerebral saturation should be optimized; long-acting benzodiazepines should be avoided; opioids should be used cautiously; extubation in the operating room should be done early; reorientation and

maintenance of sleep hygiene should be ensured; early physical activity should be encouraged (de la Varga-Martínez et al., 2023; Saczynski et al., 2012).

Conclusion

The main clinical results looked at in the studies include: Neurological injury is still a problem after heart surgery. It leads to sickness, higher death rates and long-term problems with how the body works. To cut down on brain and nerve damage during and after surgery doctors need to understand all the ways it can happen. These include clots from the aorta, the brain losing its ability to control blood flow, body-wide inflammation and damage from cutting off and then restoring blood flow.

Today's best way to protect the brain during surgery is an approach that fits each patient. It includes using ultrasound to get clear pictures of the aorta setting blood pressure goals based on how well the brain is regulating its own blood flow using mild cooling along with selective antegrade cerebral perfusion for aortic repairs and watching the brain with several tools, like NIRS, TCD and EEG.

While these intraoperative strategies have reduced neurological morbidity, further progress is essential. Priorities for future clinical research include conducting large-scale multicenter prospective trials with standardized neurological endpoints, refining real-time autoregulation monitoring platforms, prospective validation of machine-learning risk prediction tools, and developing targeted pharmacoprotective interventions.

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