Cerebral monitoring in surgical ICU patients

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Purpose of review
To give an overview of cerebral monitoring techniques for surgical ICU patients.

Recent findings
As the burden of postsurgical neurological and neurocognitive complications becomes increasingly recognized, cerebral monitoring in the surgical ICU might gain a relevant role in detecting and possibly preventing adverse outcomes. However, identifying neurological alterations in surgical ICU patients, who are often sedated and mechanically ventilated, can be challenging. Various noninvasive and invasive techniques are available for cerebral monitoring, providing an assessment of cortical electrical activity, cerebral oxygenation, blood flow autoregulation, intracranial pressure, and cerebral metabolism. These techniques can be used for the diagnosis of subclinical seizures, the assessment of sedation depth and delirium, the detection of an impaired cerebral blood flow, and the diagnosis of neurosurgical complications.

Summary
Cerebral monitoring can be a valuable tool in the early detection of adverse outcomes in surgical ICU patients, but the evidence is limited, and clear clinical indications are still lacking.

Keywords
cerebral autoregulation, cerebral monitoring, cerebral oxygenation, electroencephalography, intracranial pressure

INTRODUCTION

The purpose of monitoring vital signs in critically ill patients is to timely detect signs of deterioration in organ functions and take appropriate corrective interventions to guarantee the best outcome. Many intensive care providers will recognize that monitoring in the ICU is focused on respiratory and cardiovascular functions, whereas cerebral monitoring is not consistently applied as a standard of care [1▪]. This discrepancy is probably even wider in the surgical ICU setting, where patients are often admitted only for a few hours after surgery to ensure stable vital signs before discharge to the normal ward. The postoperative course can be complicated by neurocognitive alterations, but these disorders go often underdiagnosed, especially when presenting with subtle signs such as hypoactivity or somnolence. Perioperative neurocognitive disorders include postoperative delirium (POD), manifesting within a few days after surgery, and postoperative neurocognitive disorders, persisting for 1 up to 12 months after surgery [2]. The incidence of POD can exceed 30% in elderly patients, and postoperative neurocognitive disorders can be detected in up to 30% of elderly patients 3 months after surgery [3]. Are we as clinicians doing enough to monitor the brain? The answer would probably be yes in most instances as the clinical assessment of consciousness and the neurologic examination represent the most immediate and arguably the most important tools for an adequate cerebral monitoring. However, as ICU patients are often sedated and mechanically ventilated after surgery, the neurological examination might be impaired and neurological findings might be masked. Furthermore, subtle alterations in brain function may go undetected to the clinical assessment [e.g., subclinical seizures, or an altered cerebral blood flow (CBF) autoregulation], but still have a negative impact on the outcome [4▪,5▪]. Under these circumstances, various monitoring techniques allow a more focused cerebral monitoring, providing an assessment of cortical electrical activity, cerebral oxygenation, and blood flow

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KEY POINTS

- Continuous electroencephalography monitoring can promptly diagnose subclinical seizures, but it is resource-consuming and should be targeted to patients at high risk for postsurgical seizures.
- Processed electroencephalography monitoring can be used to optimize sedation and pain assessment in surgical ICU patients, in particular during deep sedation and invasive ventilation.
- The evidence for monitoring cerebral oxygenation postoperatively is limited and has yet to be proven to improve postoperative (neurological) outcomes.
- Bedside monitoring of cerebral autoregulation is feasible, although it still needs to be assessed if individualized blood pressure targets will improve neurological outcomes postoperatively.
- The methods for monitoring intracranial pressure and cerebral metabolism remain very invasive so that their use should be limited to neurosurgical patients with high risk of complications.

autoregulation or – mainly in the neurosurgical setting – intracranial pressure (ICP) and cerebral metabolism. An overview can be found in Fig. 1. The aim of this review is to summarize the latest evidence about the role of cerebral monitoring in the surgical ICU patient. We sought to present the main monitoring techniques and to provide an overview of the key advantages they can offer when applied in the appropriate clinical context.

Cortical electrical brain activity

Monitoring of cortical electrical brain activity is traditionally performed by raw electroencephalography (EEG), usually requiring an experienced clinician for the interpretation of EEG readings. Processed EEG devices provide an easier interpretation of the cortical electrical activity with the main purpose of monitoring the depth of sedation or anesthesia.

Raw electroencephalography

Recording of raw EEG signals is the gold standard to detect and diagnose (nonconvulsive) seizures. Seizures can complicate the postoperative course of patients undergoing neurosurgery [6] and cardiac surgery [7], in both cases with an association with adverse outcome. The raw EEG is an intermittent diagnostic technique and covers a limited time frame (usually around 30 min), with the drawback of missing many episodes of nonconvulsive seizures. Conversely, continuous EEG monitoring has a higher sensitivity in critically ill patients, in whom nonconvulsive seizures are frequent and are often detected after hours of monitoring [8].

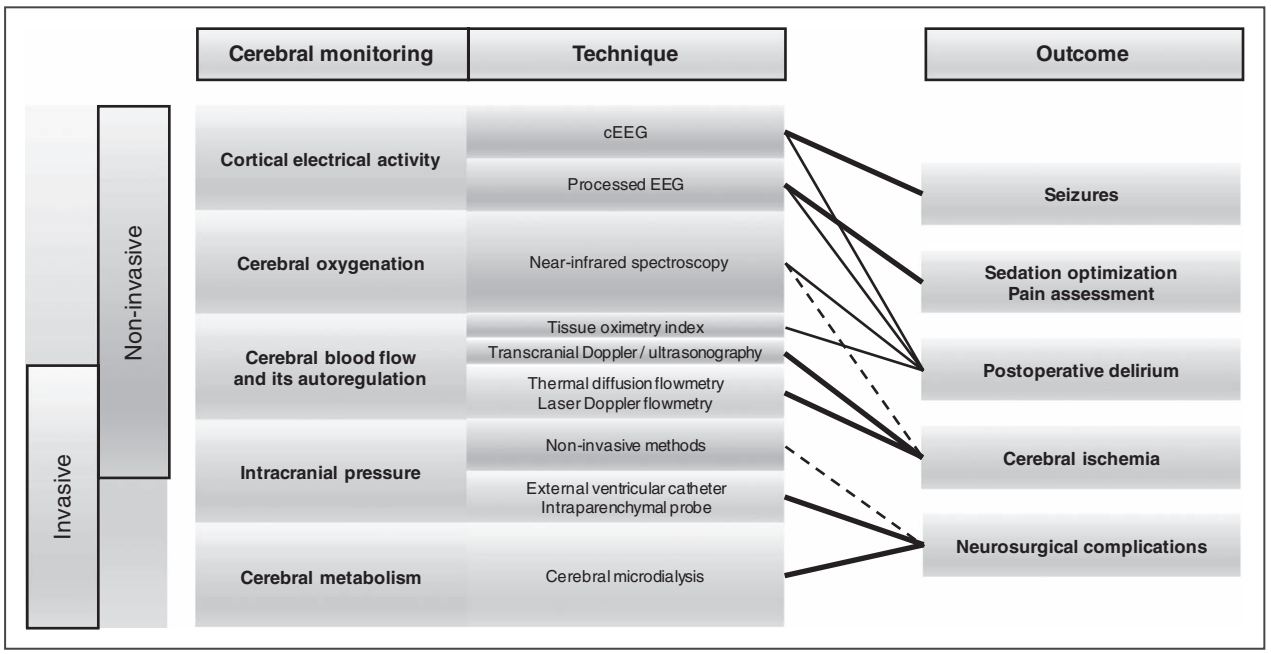

FIGURE 1. Cerebral monitoring techniques and associated outcomes. Bold lines indicate an established association with the respective outcome, solid lines indicate that there is evidence for an association, dashed lines indicate that there is limited evidence for an association with the outcome. cEEG, continuous electroencephalography.

The incidence of postneurosurgical seizures is thought to be highest in the immediate postoperative period when sedative medication may interfere with the interpretation of neurological signs. In patients admitted to the ICU after neurosurgery, a 29% incidence of clinical or electrographic seizures was found by continuous EEG monitoring within 72 h after surgery, without any clinical signs in over two thirds of cases (subclinical seizures) [9▪]. The mortality at discharge was similar in patients with and without seizures, but outcomes in a longer timeframe were not investigated [9▪]. Another prospective study found a lower incidence (10%) of electrographic seizures in neurosurgical patients with clinical suspicion of nonconvulsive status epilepticus [10], even though the incidence was likely underestimated as antiepileptic medications had already been started in one third of patients. Factors associated with a higher risk of seizures after neurosurgery include a history of epilepsy, subdural hematoma, perioperative subarachnoid hemorrhage, and lobar tumor [9▪,11].

After cardiac surgery, continuous subhairline EEG started at ICU admission evidenced a 3% incidence of seizures [12], but when considering patients undergoing open-heart valve surgery with a complete continuous EEG monitoring the seizure incidence increased to 9%, with abnormal EEG patterns in as much as 33% of patients [13▪▪]. Electrographic seizures were also associated with POD on the first postoperative day [13▪▪]. Significantly, POD is also characterized by alterations in functional neural interactions [14] and other typical EEG features (e.g., a shift of EEG power to lower frequencies) [15] – some of which have been associated with mortality in delirious critically ill patients [16] – making continuous EEG monitoring a promising tool to assess POD development and severity [15]. An ongoing study aims to determine whether perioperative (from 2 days before surgery until up to 7 days after) EEG patterns during sleep and wakefulness can predict POD in cardiac surgery patients [17]. These findings elucidate the organic cause of POD in surgical ICU patients and should stimulate its diagnosis and prevention to improve the outcome.

Finally, in surgical ICU patients undergoing continuous EEG for an altered mental status the incidence of nonconvulsive seizures was 16%, with a strong association with a composite poor outcome (death, vegetative state, or severe disability) [18]. Moreover, periodic epileptiform discharges were identified in 29% of patients [18]. The cost-effectiveness of continuous EEG monitoring in surgical ICU patients remains to be determined. First, its application should be targeted to patients with identifiable risk factors for subclinical seizures such as a history of epilepsy or neurosurgery for a lobar tumor. Second, some drawbacks regarding its usefulness should be considered, including the high demand in terms of human and technical resources and the artifacts in continuous EEG readings that are frequently generated in the ICU environment [19].

Processed electroencephalography

Processed EEG devices are commonly used in the operating room for monitoring the depth of anesthesia. There is also increasing evidence for its role in the ICU, where monitoring of sedation is a relevant issue, especially in light of the association between (too) deep sedation and adverse outcomes [20]. Commonly, clinical scales are applied in the ICU to assess the level of sedation. In postsurgical ICU patients, some studies found a good correlation between Bispectral index (BIS) [21,22], entropy [21] or Narcotrend index [23] values and the Richmond Agitation Sedation Scale, and between BIS [24,25] or patient state index (PSI) [26] values and the Ramsay sedation scale [24,25]. However, other studies found a poor correlation between BIS or PSI values and the Ramsay sedation scale [27], and between BIS values and the Riker Agitation Sedation Scale [28]. The majority of the studies concluded that processed EEG devices do not perform adequately enough to substitute clinical scales, but they might be a useful adjunct to clinical assessment. Guidelines suggest that BIS monitoring might be best suited for titrating sedation during deep sedation or neuromuscular blockade, when clinical assessment is less sensitive [29]. In addition, sedation scales are commonly evaluated intermittently and the patient has to be stimulated to assess the level of sedation, whereas processed EEG monitoring is continuous and does not require a modification of the sedation state [30]. Furthermore, as already mentioned for continuous EEG, processed EEG devices might also have a role in the diagnostic workup of perioperative neurocognitive disorders: on the first postoperative day after cardiac surgery, low BIS values showed high specificity but low sensitivity in identifying delirious patients [31].

Besides sedation assessment, BIS monitoring has also been implemented in closed-loop target-controlled infusion systems for sedation in the surgical ICU providing a tight and reliable sedation control [32▪], even though the choice of the sedation level should always take into account adverse hemodynamic effects [33▪].

Finally, an interesting application of BIS monitoring involves the assessment of pain in patients undergoing invasive ventilation. BIS values were positively correlated with critical-care pain observation tool after cardiac surgery [34], and appeared to

be more suitable for pain assessment in unconscious patients after neurosurgery compared with critical-care pain observation tool [35]. Furthermore, BIS was more sensitive than hemodynamic changes in assessing pain [34].

In conclusion, processed EEG devices can help optimizing the sedation and the assessment of pain in surgical ICU patients, in particular during deep sedation and invasive ventilation.

Cerebral oxygenation monitoring

Cerebral oxygenation (ScO_2) can be continuously and noninvasively monitored by means of near-infrared spectroscopy (NIRS), a monitoring technique that is widely used in the intraoperative care of cardiac surgery patients. In this population, intraoperative cerebral desaturations occur frequently and are associated with adverse outcomes such as postoperative neurocognitive disorders, prolonged hospital stay and increased mortality [36▪]. Current guidelines recommend pre- and intraoperative cerebral oximetry monitoring to identify patients at increased risk of such adverse outcomes [37▪▪]. Notably, cerebral desaturations continue to occur during the postoperative ICU stay in a large subset of patients [38,39]. A recent study showed prolonged postoperative cerebral desaturation after cardiac surgery with cardiopulmonary bypass (CPB), but not after noncardiac surgery [40]. Therefore, there is a need and growing interest in extending the monitoring of ScO_2 to the postoperative phase, even though the evidence is still limited [41] and insufficient to recommend postoperative monitoring [37▪▪]. However, some recent studies provided interesting insights into the relationship between postoperative NIRS monitoring and outcomes. In cardiac surgery ICU patients with POD, low ScO_2 values were associated with the severity of delirium, and started to increase as delirium resorbed [42]. In addition, in older patients undergoing cardiac surgery, ScO_2 values were lower in patients who developed POD, and larger postoperative decreases in ScO_2 were associated with POD independently of other confounding factors such as advanced age and high EuroSCORE II [43▪]. However, a perioperative therapy aimed at reversing cerebral desaturations either during surgery or within the first 24 postoperative hours had no effect in preventing POD in a cohort of 249 cardiac surgery patients [44].

A cerebrovascular accident (e.g. ischemic stroke) is a devastating complication after cardiac surgery. There was no difference in the incidence of postoperative cerebrovascular events in patients with and without carotid stenosis undergoing coronary artery bypass grafting, and no difference in cerebral oxygenation was found [45▪]. However, patients with carotid stenosis had higher mean arterial pressure (MAP), which might have guaranteed an adequate cerebral perfusion in this group of patients. This raises the hypothesis that cerebral oxygenation monitoring might have a role in the prevention of cerebrovascular events by optimization of MAP and CBF (for more details see below paragraph).

Cerebral blood flow and its autoregulation

CBF is regulated by complex myogenic, neurogenic, metabolic, and endothelial mechanisms [46▪▪]. CBF can be monitored invasively using thermal diffusion flowmetry and noninvasively by transcranial Doppler (TCD) or laser Doppler flowmetry [47▪,48]. Thermal diffusion flowmetry uses the temperature difference between a thermistor and a detector to estimate CBF, TCD uses ultrasound to assess blood flow, and with laser Doppler flowmetry erythrocyte flux is assessed directly [47▪,48]. TCD is the primary (noninvasive) tool for monitoring CBF [47▪,48]. Improvements in the TCD led to the development of transcranial color-coded duplex ultrasonography which has a color Doppler mode that can be used to easily detect vessels and assess flow [49]. The use of thermal diffusion flowmetry is recommended for patients at risk for focal cerebral ischemia [50], although the applicability of this tool in a surgical ICU might be limited due to the invasiveness of the method. TCD and transcranial color-coded duplex ultrasonography might be used in patients at risk of postoperative cerebral ischemia in a surgical ICU, although no official recommendation has been made regarding surgical ICU patients.

Cerebral autoregulation means that despite variations in cerebral perfusion pressure, CBF will be kept constant by automatic adjustment of the diameter of the arteries and veins [51], although this is limited to a certain blood pressure (BP) range (the autoregulation range) (Fig. 2). Cerebral perfusion pressure is determined by the MAP minus the ICP. CBF is the resultant when cerebral perfusion pressure is dived by cerebral vascular resistance. For a long time it was thought that a MAP between 50 and 150 mmHg was the range in which autoregulation could ensure constant CBF [52]. However, some studies found individual lower limits ranging from 40 to 91 mmHg [53–56] and increased lower limits of autoregulation within hypertensive or elderly patients (Fig. 2) [51]. In addition, BPs exceeding the upper limits of autoregulation during CPB were associated with POD as was shown in 491 cardiac surgery patients [57]. It was also shown in patients having surgery with CPB that interindividual

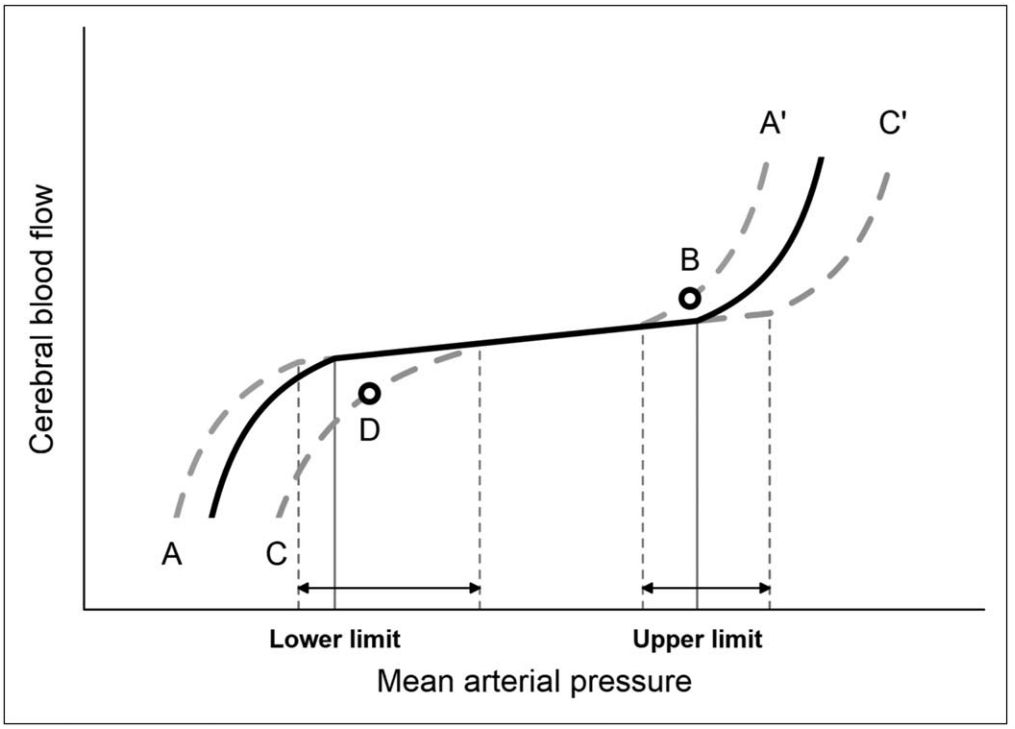

FIGURE 2. Autoregulation of cerebral blood flow. Cerebral blood flow is kept constant when the mean arterial pressure is within the upper and lower limits of cerebral autoregulation. Such limits are classically assumed within the range of 50–150 mmHg, but can differ in both directions on an individual basis (as indicated by the arrows), for example due to chronic hypertension. The normal cerebral autoregulation curve is represented by the continuous curve. If the curve is left-shifted (*A–A′* dashed curve), a mean arterial pressure close to the 'classical' upper limit of cerebral autoregulation will result in an increased cerebral blood flow (*B* circle). If the cerebral autoregulation curve is right-shifted (*C–C′* dashed curve), for example in a hypertensive patient, a mean arterial pressure close to the 'classical' lower limit of cerebral autoregulation will be insufficient to provide an adequate cerebral blood flow (*D* circle).

variability was high and could not be predicted by demographic and disease specific factors [56]. Therefore, it is important to assess the autoregulation limits on an individual basis. The autoregulation system is not able to compensate for MAP excursions outside of the individual autoregulation range, resulting in increased or decreased CBF, possibly causing cerebral ischemia or edema and neurological complications. Cerebral autoregulation can be assessed by the following factors: an estimate of CBF, measurement of (changes in) cerebral perfusion pressure, and assessment of the relation between cerebral perfusion pressure and CBF [58▪▪].

So far, assessing cerebral autoregulation has been limited to specific fields with high incidence of cerebral injury, for example during cardiac and noncardiac surgery, in neonatology, septic shock, out of hospital cardiac arrest, and in the neurocritical care [58▪▪]. There is a paucity of data regarding the monitoring of CBF and autoregulation in patients admitted postoperatively on a routine basis to the surgical ICU, with studies only conducted in patients after cardiac surgery measuring tissue oximetry index [4▪]. This is a NIRS-derived variable that can range from −1 to 1, with values between −1 and 0 indicating intact autoregulation and values from 0 to 1 indicating impaired autoregulation. Patients with POD compared with those without POD had a higher mean tissue oximetry index (0.270 ± 0.199 vs. 0.180 ± 0.142, $P = 0.044$) on postoperative day 0 and tissue oximetry index was independently associated with POD on day 0 [odds ratio (OR) 1.05, 95% confidence interval 1.01–1.10, $P = 0.043$]. Another study assessed cerebral autoregulation in 67 patients scheduled for cardiac surgery with CPB [59]. Impaired cerebral autoregulation was found in 55% of patients 24 h postoperatively and in 20% of patients 7 days postoperatively. In addition, a lower autoregulation index preoperatively and 24 h postoperatively predicted POD. The last study consisted of 134 cardiac surgery patients, in whom cerebral oxygenation and arterial BP were monitored from the start of surgery until the next morning in the ICU [5▪]. The prevalence of impaired autoregulation was higher in the OR than in the ICU (40 vs. 13%, $P < 0.001$) and in an exploratory

analysis it was found that impaired autoregulation in the ICU was associated with POD [5▪]. In conclusion, the field of assessing cerebral autoregulation in postsurgical ICU patients is slowly expanding. In patients with traumatic brain injury or subarachnoidal hemorrhage, bedside assessment of cerebral autoregulation seemed feasible [60]. However, before monitoring cerebral autoregulation becomes routine clinical practice, it first needs to be assessed if individualized BP targets will actually improve postoperative neurological outcomes.

Intracranial pressure monitoring

Monitoring ICP is limited to patients with cerebral disease affecting ICP and to certain neurosurgical patients [50]. The external ventricular catheter is currently the gold standard and can even be used for therapeutic intervention in patients with hydrocephalus [48,61]. The intraparenchymal pressure monitor can be used in patients without hydrocephalus, where no drainage is needed [48]. Other invasive methods, for example subdural, epidural, and subarachnoidal bolts are less accurate [48]. Hemorrhage, infection, and local lesions in the brain tissue are risks of invasive ICP monitoring, and thus its use should be restricted to a very select patient population [48]. A multitude of noninvasive methods is available, although none of them is currently accurate enough for clinical use [48,61]. The noninvasive methods are all based on measuring a variable that is related to ICP, the broad categories are flow, otic, ophthalmic, electrophysiologic, and others, an overview can be found here [61]. An improvement in accuracy of noninvasive methods will allow ICP monitoring in a broader patient population at risk for increased ICP.

Cerebral metabolism monitoring

For cerebral microdialysis, a microdialysis catheter is placed near the cerebral region of interest and dialysate samples can be taken to evaluate concentrations of metabolites. Cerebral microdialysis is recommended in patients at risk for oxygen or energy deprivation [50]. Commonly studied metabolites are lactate and pyruvate for cerebral ischemia, glutamate for excitotoxicity, glycerol for cell death, and glucose [48,62]. A microdialysis catheter is very small and flexible and these properties make its use relatively safe, yet it remains a very invasive method. No infection or hemorrhage was associated with placement of microdialysis catheters during open craniotomy in a cohort of 174 patients [63]. However, a major limitation is that monitoring is limited to a very specific area of the brain. Other limitations of cerebral microdialysis are that it is time consuming, can only be performed intermittently, and that clinical reference values for different disease states are lacking [48]. Therefore, it is recommended to combine cerebral microdialysis with other monitoring tools for prognostic purposes and guiding treatment [50]. An overview of treatment considerations can be found here [62].

CONCLUSION

There is a paucity of data regarding cerebral monitoring in a postsurgical ICU. Subclinical seizures, cerebral desaturations, and alterations of the cerebral autoregulation and metabolism can only be detected with the appropriate monitoring technique. Hence, cerebral monitoring in the ICU can contribute to the prompt identification of patients at risk for adverse outcomes. Invasive cerebral monitoring is mainly indicated after neurosurgery. Noninvasive monitoring techniques such as continuous (processed) EEG, NIRS, and TCD can be applied to a broad subset of surgical ICU patients, but the cost-effectiveness and the most appropriate target populations have yet to be determined. Future studies will also elucidate if cerebral monitoring in the ICU might have a role in improving the neurological outcome of surgical patients.

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Conflicts of interest

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