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REVIEW ARTICLE

Complications of Intracranial Multimodal Monitoring for Neurocritical Care: A Systematic Review and Meta-Analysis

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Abstract

Intracranial multimodal monitoring (iMMM) is increasingly used for neurocritical care. However, concerns arise regarding iMMM invasiveness considering limited evidence in its clinical significance and safety profile. We conducted a synthesis of evidence regarding complications associated with iMMM to delineate its safety profile. We performed a systematic review and meta-analysis (PROSPERO Registration Number: CRD42021225951) according to the Preferred Reporting Items for Systematic Review and Meta-Analysis and Peer Review of Electronic Search Strategies guidelines to retrieve evidence from studies reporting iMMM use in humans that mention related complications. We assessed risk of bias using the Newcastle–Ottawa Scale and funnel plots. The primary outcomes were iMMM complications. The secondary outcomes were putative risk factors. Of the 366 screened articles, 60 met the initial criteria and were further assessed by full-text reading. We included 22 studies involving 1206 patients and 1434 iMMM placements. Most investigators used a bolt system (85.9%) and a three-lumen device (68.8%), mainly inserting iMMM into the most injured hemisphere (77.9%). A total of 54 postoperative intracranial hemorrhages (pooled rate of 4%; 95% confidence interval [CI] 0–10%; I^2 86%, $p < 0.01$ [random-effects model]) was reported, along with 46 misplacements (pooled rate of 6%; 95% CI 1–12%; I^2 78%, $p < 0.01$) and 16 central nervous system infections (pooled rate of 0.43%; 95% CI 0–2%; I^2 64%, $p < 0.01$). We found 6 system breakings, 18 intracranial bone fragments, and 5 cases of pneumocephalus. Currently, iMMM systems present a similar safety profile as intracranial devices commonly used in neurocritical care. Long-term outcomes of prospective studies will complete the benefit-risk assessment of iMMM in neurocritical care. Consensus-based reporting guidelines on iMMM use are needed to bolster future collaborative efforts.

Keywords: Intracranial multimodal monitoring, Complications, Brain tissue oxygen, Microdialysis, Intracranial electroencephalography

Introduction

Acute brain injuries (ABIs), for example, traumatic brain injury (TBI), subarachnoid hemorrhage (SAH), and stroke, are a leading cause of disability and death worldwide [1, 2]. Neurocritical caregivers aim to diagnose and treat the underlying causes of primary brain injury while preventing secondary insults. Physiological monitors of brain function may identify these insults early to prevent irreversible neurological disorders. Intracranial pressure (ICP) is widely used as a unique intracranial modality for neuromonitoring [3]. Yet this single parameter may be insufficient to understand the pathophysiology of secondary brain injuries fully. Therefore, intracranial multimodality monitoring (iMMM) has been implemented in multiple neurocritical care units using various intraparenchymal monitors, for example, brain

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tissue oxygenation ($PbtO_2$), microdialysis, regional cerebral blood flow, and intracranial electroencephalography electrodes [4–6]. However, concerns may arise regarding iMMM invasiveness, particularly as most literature draws from retrospective single-center studies on small adult cohorts with specific ABI conditions, underlining the limited evidence about its clinical significance and safety profile [7, 8].

Methods

We conducted this study according to the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) (PROSPERO Registration Number: CRD42021225951) [9]. This study did not involve new data collection from patients and, as such, was deemed exempt from ethical approval.

Eligibility Criteria

The working definition of iMMM refers to any additional intracranial modality to the ICP in patients with ABI. For the systematic review, we included all screened articles reporting iMMM use in humans mentioning related complications (i.e., absence or presence) with no restrictions regarding date, language, types, or publication status. For the meta-analysis, we imposed additional eligibility criteria to conduct specific subgroup analyses as follows: (1) a cohort of at least ten unselected patients, (2) common criterion standards defining complications and putative risk factors of interest, and (3) computable rates and ratios based on data reported.

Information Sources and Search Strategy

On January 10, 2022, we searched three major bibliographic sources: MEDLINE, Scopus, and the Cochrane Central Registry of Controlled Trials. Under the Peer Review of Electronic Search Strategies 2015 guidelines [10], we used combinations of free-text and Medical Subject Headings terms with Boolean operators and database-specific syntax (Supplemental File 1).

Study Selection and Data Collection

We managed the review process on Covidence (Veritas Health Innovation, Melbourne, Australia). We sought to characterize iMMM reported by clinical, technical, and surgical features (Supplemental File 2). The iMMM complications were defined as surgical complications or adverse events and described as significant when a subsequent change of management was reported. We defined surgical complications as postoperative intracranial hemorrhages (PIHs), probe misplacements, central nervous system (CNS) infections, intracranial bone fragments, and pneumocephalus. Probe misplacements were defined on postplacement imaging (1) as extra-axial, aberrant intra-axial (e.g., deep grey matter or within a lesion), and intraventricular locations due to putative increased postoperative neurological sequelae or infectious risks they might induce and/or (2) as nonoptimally located probes (i.e., not placed in intended location) due to risk of irrelevant measures. Hence, the final determination of a probe being misplaced rested with the original study investigators, provided they explicitly stated it.

Adverse events comprised accidental dislodgement or breaking of any probe or fixation device requiring iMMM replacement or withdrawal and inadvertent monitoring discontinuation. For the meta-analysis, we chose criterion standards based on their prevalence across studies, considering both the number of studies adopting them and the cohort sizes of these studies.

Risk of Bias and Between-Study Heterogeneity

Two independent reviewers performed quality and risk of bias analysis using the Newcastle–Ottawa Scale, a validated tool for assessing the quality of nonrandomized studies across three parameters: the selection of the study groups, their comparability, and the ascertainment of exposure or outcome [11]. Heterogeneity among included studies was assessed via the chi-squared test (significance level < 0.1) and homogeneity level (I^2 statistic). An I^2 less than 40% was considered as not significant, an I^2 of 40–70% was considered as substantial, and an I^2 above 80% was considered as considerable heterogeneity. We generated funnel plots to detect bias or systematic heterogeneity between included studies visually; however, their use has significant limitations [12].

Effect Measures and Synthesis of Results

We performed a meta-analysis of single proportions to determine pooled complication rates and ratios of putative risk factors using the '*meta*' package in RStudio (version 1.3.1093), using the default significance level (0.05) and reporting two-tailed p values. We used an arcsine transformation to prevent overestimation of this incidence in low-occurrence-rate conditions, and the script accounted for zero events with the increment function.

Results

We initially identified 676 articles. After removing 310 duplicates, we selected 366 articles for screening; 60 were screened via full-text reading, among which, 20 with inconsistent iMMM definitions and 18 animal studies were excluded. Therefore, 22 articles were included: 16 experience series, three research studies, and three case reports (Table 1). Figure 1 depicts the PRISMA flow diagram. Concerning bias assessment, four studies presented a low bias risk, seven presented a medium bias risk, and eight presented a high bias

Table 1 Main features of included studies

References	Type	Number of eligible patients	Number of insertions	Routine postplacement CT	Placement settings	Targeting strategy	ABI	PIH, *n* (%)	Significant PIH, *n* (%)	Misplacement, *n* (%)	Dislodgement, *n* (%)	CNS infections, *n* (%)	EVD, *n* (%)
Guan et al. [39]	Case report	1	1	N/A	N/A	Bilateral	TBI	N/A	N/A	N/A	N/A	N/A	1 (100)
Stuart et al. [14]	Case report	1	1	N/A	N/A	Nondominant	SAH	N/A	N/A	N/A	N/A	N/A	1 (100)
Foreman et al. [7]	Experience series	43	43	Yes	Bedside	Most injured	TBI	16 (37.2)	1 (2.3)	6 (13.9)	N/A	0 (0)	N/A
Bailey et al. [8]	Experience series	501	696	Yes	Bedside	Most injured	TBI	19 (2.7)	4 (0.6)	22 (3.2)	N/A	1 (0.1)	N/A
Stewart et al. [25]	Experience series	34	34	No	Bedside	Least injured	TBI	N/A	N/A	N/A	N/A	0 (0)	N/A
Steiner et al. [40]	Experience series	21	27	No	OR/bedside	Least injured or bilateral	Stroke	N/A	N/A	N/A	N/A	N/A	N/A
Waziri et al. [41]	Experience series	16	16	Yes	OR/bedside	At risk of ischemia	Mixed	0 (0)	0 (0)	0 (0)	N/A	N/A	10 (62.5)
Van Santbrink et al. [42]	Research series	22	22	No	N/A	Right	TBI	N/A	N/A	N/A	N/A	N/A	N/A
Al-Rawi et al. [43]	Experience series	40	40	Yes	N/A	N/A	TBI	0 (0)	0 (0)	N/A	N/A	0 (0)	N/A
Kiening et al. [44]	Experience series	15	15	Yes	N/A	Least injured	TBI	0 (0)	0 (0)	N/A	N/A	0 (0)	N/A
Forsse et al. [45]	Research series	12	12	Yes	N/A	Nondominant	aSAH	1 (8.3)	0 (0)	N/A	N/A	N/A	–[a]
Seule et al. [46]	Experience series	10	11	No	N/A	Most injured	aSAH	N/A	N/A	N/A	N/A	N/A	10 (100)
Sekhon et al. [47]	Research series	10	10	No	N/A	Nondominant	TBI	N/A	N/A	N/A	N/A	N/A	N/A
Sioutos et al. [13]	Experience series	56	56	No	N/A	N/A	TBI	N/A	N/A	N/A	N/A	3 (5.4)	Unspecified
Stuart et al. [14]	Experience series	61	61	Yes	OR	Most injured	Mixed	2 (3.3)	1 (1.6)	2 (3.3)	26 (42.6)	3 (4.9)	N/A
Simonin et al. [48]	Case report	2	2	N/A	OR	Right	CVT	N/A	N/A	N/A	N/A	N/A	N/A
Idris et al. [49]	Experience series	26	26	No	OR	N/A	TBI	1 (3.8)	1 (3.8)	N/A	N/A	N/A	Unspecified
Sarrafzadeh et al. [15]	Experience series	97	97	No	OR	Most injured	aSAH	0 (0)	0 (0)	N/A	N/A	9 (9.3)	–[b]
Vajkoczy et al. [50]	Experience series	14	28	No	OR	At risk of ischemia	aSAH	N/A	N/A	N/A	N/A	0 (0)	14 (100)

Table 1 (continued)

References	Type	Number of eligible patients	Number of insertions	Routine postplacement CT	Placement settings	Targeting strategy	ABI	PIH, *n* (%)	Significant PIH, *n* (%)	Misplacement, *n* (%)	Dislodgement, *n* (%)	CNS infections, *n* (%)	EVD, *n* (%)
Staub et al. [51]	Experience series	10	10	Yes	OR	N/A	SAH	0 (0)	0 (0)	N/A	N/A	N/A	10 (100)
Al Barajraji et al. [16]	Experience series	113	123	Yes	OR	Most injured	Mixed	14 (11.4)	1 (0.8)	16 (13)	7 (5.7)	0 (0)	Unspecified
Dings et al. [24]	Experience series	101	103	Yes	OR/bedside	Bilateral/most injured	Mixed	2 (1.9)	0 (0)	N/A	8 (7.8)	0 (0)	N/A

ABI acute brain injury, *aSAH aneurysmal subarachnoid hemorrhage*, *CNS* central nervous system, *CT* computed tomography, *CVT* central venous thrombosis, *EVD* external ventricular drain, *N/A* not applicable, *OR* operating room, *PIH* postoperative intracranial hemorrhage, *SAH* subarachnoid hemorrhage, *TBI* traumatic brain injury

[a] Forsse et al. reported 9 of 12 patients with ventricular or lumbar drain without more specification

[b] Sarrafzadeh et al. reported systematic use of ventricular or lumbar drain without more specification

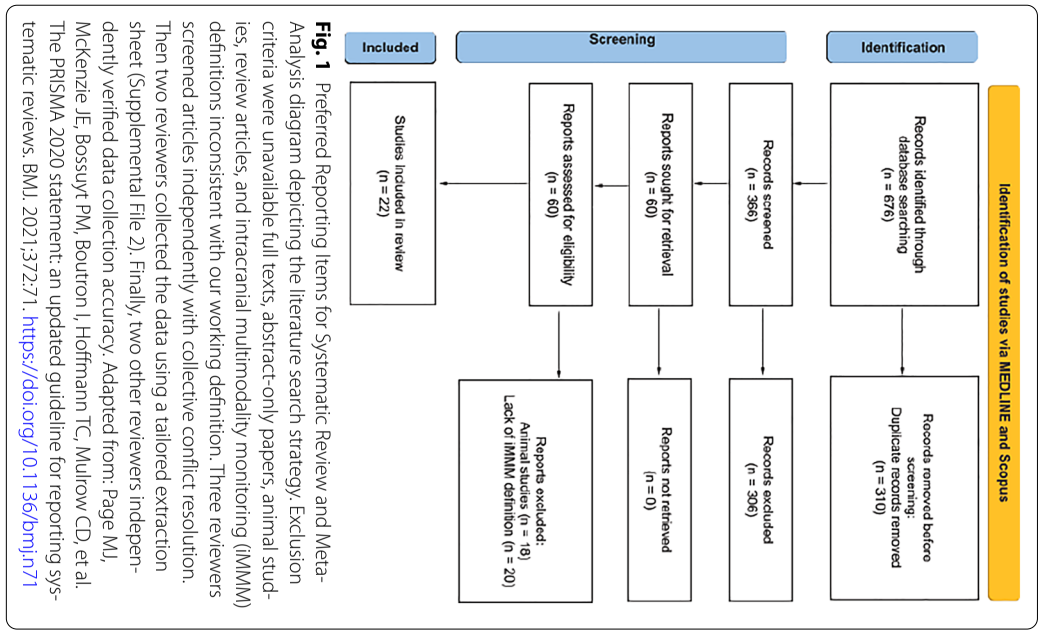

Fig. 1 Preferred Reporting Items for Systematic Review and Meta-Analysis diagram depicting the literature search strategy. Exclusion criteria were unavailable full texts, abstract-only papers, animal studies, review articles, and intracranial multimodality monitoring (iMMM) definitions inconsistent with our working definition. Three reviewers screened articles independently with collective conflict resolution. Then two reviewers collected the data using a tailored extraction sheet (Supplemental File 2). Finally, two other reviewers independently verified data collection accuracy. Adapted from: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021;372:71. https://doi.org/10.1136/bmj.n71

risk (Table 2). The supplemental files provide funnel plots for each measured outcome for publication bias assessment. The oldest article was published in 1995 [13]. Accordingly, 1206 patients (range 1–501) who underwent 1434 iMMM placements (range 1–696) were included in the qualitative synthesis. The reported indications of iMMM were TBI for 61.2% (738 patients in nine series), stroke for 14.68% (177 patients in nine series, mainly SAH), and mixed ABI etiologies for 24.13% (291 patients in four series) of the study population. Due to wide variation in reporting of iMMM durations (47 h to 14 days), no summary measures were derived. Single burr hole was routinely performed for 66.34% of iMMM placements retrieved (952 placements in seven series). Concerning the iMMM targeting strategy, investigators opted for the most injured hemisphere for 77.94% (940 patients in eight series), the least injured hemisphere for 4.06% (49 patients in two series), the so-called nondominant or right

Table 2 Risk of bias of included studies

References	Selection ****	Comparability *	Outcome ***				Total
			PIH ***	Misplacement ***	Dislodgement ***	CNS infections ***	
Foreman et al. [7]	**	*	***	***	***	–	6
Bailey et al. [8]	***	*	***	***	–	***	7
Stuart et al. [14]	***	*	***	***	***	***	7
Dings et al. [14]	*	*	***	–	***	***	5
Van Santbrink et al. [42]	*	*	*	–	–	–	3
Stewart et al. [25]	*	*	*	–	–	*	3
Steiner et al. [40]	*	*	*	*	–	–	3
Al-Rawi et al. [43]	**	*	***	–	–	**	3
Kiening et al. [44]	**	*	***	–	–	**	6
Forsse et al. [45]	*	–	–	–	–	–	1
Idris et al. [49]	**	–	*	–	–	–	3
Seule et al. [46]	**	*	*	–	–	–	4
Sekhon et al. [47]	*	-	–	–	–	–	1
Sarrafzadeh et al. [15]	**	*	**	–	–	**	5
Vajkoczy et al. [50]	**	*	*	–	–	–	4
Sioutos et al. [13]	**	–	–	–	–	*	3
Staub et al. [51]	**	*	*	–	–	–	4
Waziri et al. [41]	****	*	***	***	–	–	8
Al Barajraji et al. [16]	***	*	***	***	***	***	7

In the Newcastle-Ottawa Scale star system, each '*' symbol denotes a quality criterion met by the study, indicating lower risk of bias

Studies that scored 7–9 points were considered to have a low risk of bias, studies that scored 4–6 points were considered to have a medium risk of bias, and studies that scored 3 points or less were considered to have a high risk of bias

CNS central nervous system, *PIH* postoperative intracranial hemorrhage

hemisphere for 3.90% (47 patients in five series), and both hemispheres for 1.82% (22 patients in two series) of the cases; laterality was unspecified for 12.27% (148 patients in five series). The iMMM reported was fixed using bolt systems in 85.98% (1233 placements in 18 series) and the tunneling method in 11.16% (160 placements in three series) of cases; an unspecified fixation method was used in 2.93% (42 placements in two series). The bolt systems reported were single lumen in 10.53% (151 placements in three series), double lumen in 2.23% (32 placements in three series), triple lumen in 68.83% (987 placements in ten series), quadruple lumen in 3% (43 placements in one series), or unspecified in 15.48% (222 placements in six series). Besides ICP, intracranial modalities studied included $PbtO_2$ in 18 series, microdialysis in ten series, brain temperature in nine series, regional cerebral blood flow in six series, and intracranial electroencephalography in three series. The iMMM placement was performed at the bedside in 53.91% (773 placements in three series), in the operating room in 23.22% (333 placements in seven series), and in an unspecified location in 22.94% (329 placements in 12 series) of cases. Complications are diagrammed in Fig. 2.

PIHs

Fifty-four PIHs comprising seven significant 'ones' (four requiring surgical intervention) were retrieved from eleven series. PIH rates reported ranged from 0 to 40.5%. For the meta-analysis, ten studies accounting for 921 patients and 1118 iMMM placements complied with eligibility criteria. Routine postplacement computed tomography was the criterion standard used to define PIH. We found an overall PIH pooled rate of 4% (95% confidence interval [CI] 0–10%; I^2 86%, $p<0.01$ with random-effects model), and there was a 1% pooled rate for significant PIH if we only considered the four series reporting PIH (95% CI 0–1%; I^2 0%, $p=0.68$ with random-effects model). Forest plots depict these findings in Fig. 3. Putative risk factors investigable were iMMM placement location (bedside vs. operating room) and ABI etiology (TBI vs. stroke). Placement location and ABI etiology were not significant determinants, with risk ratios of 0.54 (0.30–1.04) and 1.30 (0.19–55.31), respectively.

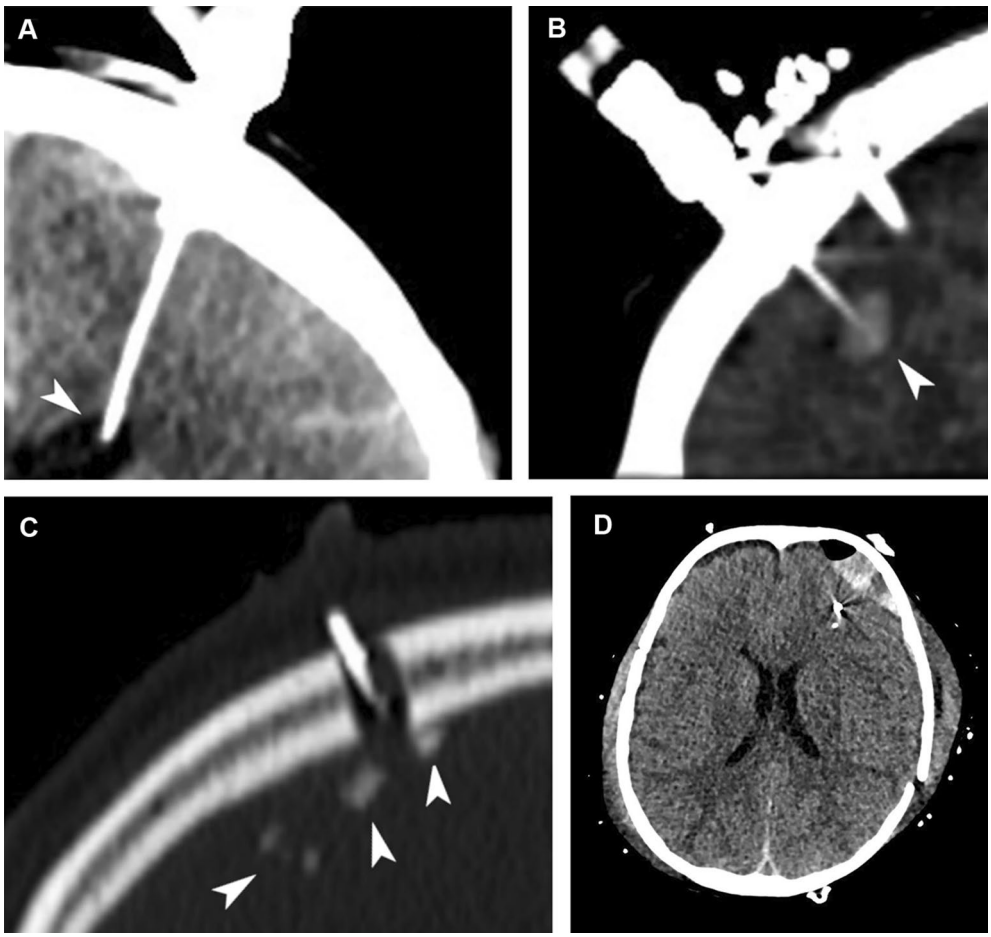

Fig. 2 Illustration of intracranial multimodality monitoring complications with arrowheads pointing at misplacement (**a**), i.e., an intraventricular probe, postoperative intracranial hemorrhage (**b**), i.e., a tract hemorrhage, bone fragments on computed tomography imaging (**c**), and extradural hematoma associated with pneumocephalus (**d**)

Misplacements

Forty-six iMMM misplacements (i.e., aberrant anatomical location and/or failure of placement in the intended location defined by postplacement imaging) were retrieved from five studies. Misplacement rates ranged from 0 to 13.9%. For the meta-analysis, these five studies, accounting for 742 patients and 938 iMMM placements, complied with eligibility criteria. Our criterion standard for defining misplacement was a description of an intended optimal placement with routine postplacement computed tomography. We found a misplacement pooled risk rate of 6% (95% CI 1–12%; I^2 83%, $p < 0.01$, random-effects model). A forest plot depicts these findings in Fig. 4.

CNS Infections

Sixteen CNS infections were retrieved from sixteen studies. CNS infection rates ranged from 0 to 9%. Two of the three cases reported by Stuart et al. [14] and all nine reported by Sarrafzadeh et al. [15] had a concurrent external ventricular drain (EVD). For the meta-analysis, eight studies accounting for 921 patients and 1118 iMMM placements complied with our eligibility criteria. For confounding factors (e.g., open-head injury or EVD), our criterion standard was the clear incrimination of iMMM as the primary source of CNS infections. We found a pooled risk of 0.43% (95% CI 0–2%; I^2 64%, $p < 0.01$, random-effects model). A forest plot depicts these findings in Fig. 5.

Adverse Events

Forty-one iMMM dislodgements with rates of 5.7% and 7.8% and six breakings with rates of 1.62% and 3.88% were retrieved from series by Al Barajraji et al. [16] and Dings et al. [17]. Stuart et al. [14] and Foreman et al. [7] reported that inadvertent monitoring discontinuation occurred for 43% and 58% of their patients, respectively.

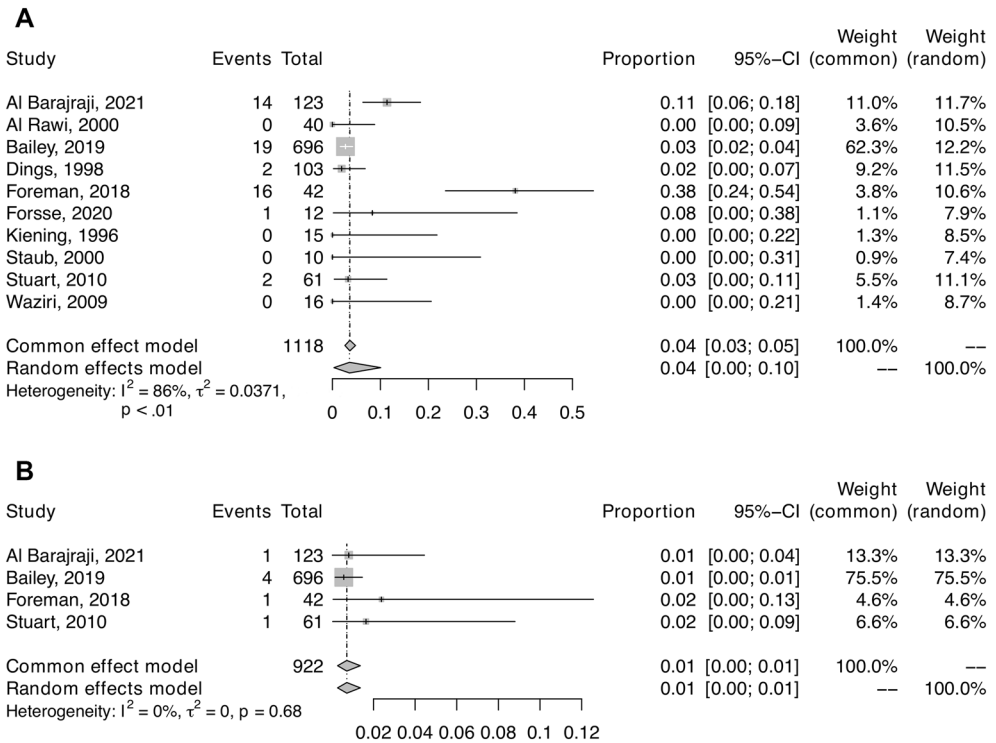

Fig. 3 **a** Forest plot of overall postoperative intracranial hemorrhage (PIH) (across all eligible studies). **b** Forest plot of significant PIH (only in eligible studies reporting PIH). CI confidence interval

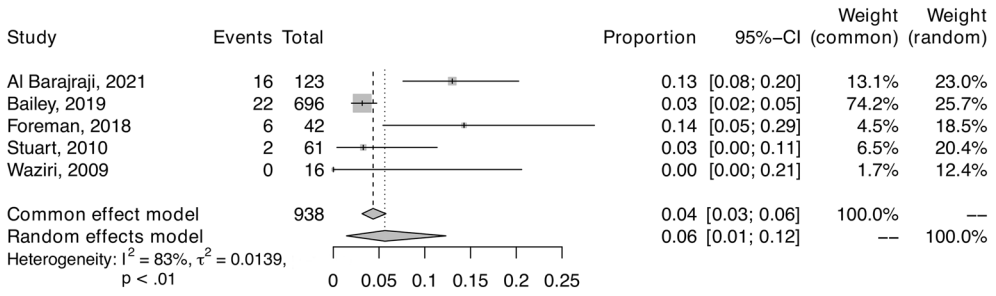

Fig. 4 Forest plot of misplacement rates. CI confidence interval

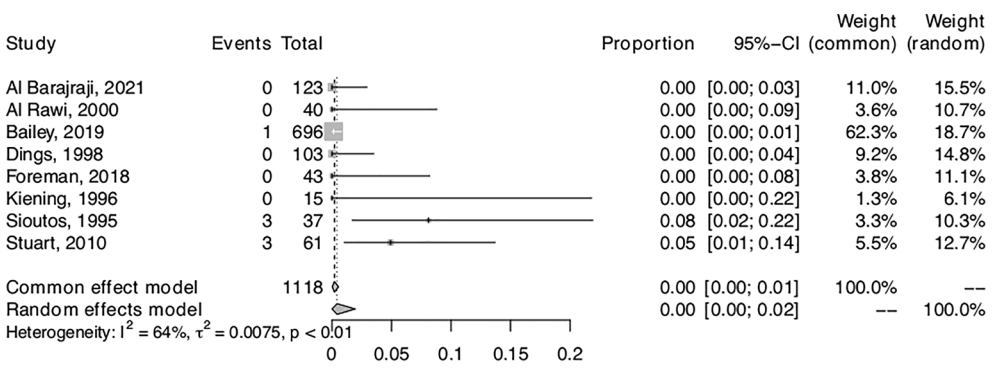

Fig. 5 Forest plot of central nervous system infection rates. CI confidence interval

Other Complications

Eighteen cases of intracranial bone fragments associated with iMMM placement were retrieved from two studies with rates of 3.2% and 70%. Only one series reported five patients with postoperative pneumocephalus associated with iMMM implantation (rate of 5%).

Discussion

Our systematic review retrieved 22 articles reporting 1206 patients who underwent 1,434 iMMM placements. The first reported indication of iMMM was TBI (61.19%). Most investigators used a bolt system (85.92%) and a three-lumen device (68.78%) and mainly targeted the most injured hemisphere (77.94%). Our meta-analysis found a PIH rate of 4%, a probe misplacement rate of 6%, and a CNS infection rate of 0.43%.

PIH

The PIH rates due to iMMM placement varied widely, ranging from 0 to 40.5%. However, an imaging review and a definition of PIH were often not specified in the studies investigated, potentially leading to detection and selection biases. Our meta-analysis found an overall pooled PIH rate of 4% (1% for significant PIH); however, this rate of rare events derived from a random-effects model should be considered cautiously. In comparison, the associated PIH rate with ventriculostomy is currently estimated between 5.7 and 7% (less than 1% for significant PIH) according to two meta-analyses and is reported below 1–2.5% for intraparenchymal fiberoptic probes [18–21]. A meta-analysis on stereoelectroencephalography found a PIH pooled prevalence of 1% [22]. Interestingly, these meta-analyses were questioned by extensive single-center series [23, 24], exemplifying the challenge of pooled estimation based on heterogeneous data with potential reporting bias, as encountered here. Current data are scarce concerning putative PIH risk factors, particularly for preoperative antithrombotic regimens or bleeding disorders. Furthermore, surgical procedure details (e.g., type of cranial drill used, craniotomy diameter), iMMM technical features (e.g., bolt specifications, number and concentration of inserted probes in close vicinity imposed by multi-lumen devices, implantation depth), or repeated insertions were not consistently reported or investigated. Only Al Barajraji et al. [16] performed risk factor analyses, investigating the underlying ABI etiology (e.g., TBI and potential diffuse axonal injury) and the number of probes inserted through the three-lumen bolt as determinants for PIH without finding significant associations. As stated, most iMMM reported in the literature used a three-lumen bolt device requiring a relatively large burr hole to insert up to three probes. Anecdotally, Dings et al. [17] shifted after their first 15 iMMM placements from a single three-lumen bolt to two one-lumen bolts to insert $PbtO_2$ and ICP probes separately, requiring smaller burr holes (ø 6 vs. ø 2.7 mm), and reported no other PIH for the following 103 placements. The experience gained and the separate probe insertion through smaller bolts may explain the reduced complication rate. Probe insertion systems featuring a longer plastic sheath allowing penetration through the pia mater were also previously implicated [25]. Based on the data reported, we were able to a perform pooled risk analysis for two potential determinants: iMMM placement location (bedside vs. operating room) and ABI etiology (TBI vs. stroke).

Monitoring Placement

No consensus exists regarding the optimal iMMM probe placement considering injured brain tissue, even for the most used $PbtO_2$ modality [26, 27]. Several placement strategies targeting the presumed nondominant hemisphere, the normal-appearing brain representative of putative uninjured parenchyma, or potentially at-risk perilesional parenchyma were reported. Hence, optimal placement and misplacement definitions were inconsistent between series. Therefore, precise descriptions of intended placement may be associated with higher misplacement rates. In those strategies, failure of placement in the intended location or probes within an eloquent area, a lesion, or a ventricle may yield irrelevant measures and hold a higher complication risk and thus may be considered as misplacement after imaging confirmation. Accordingly, misplacement rates ranged from 0 to 14.3%. Dings et al. [17] and Stewart et al. [25] always targeted the right frontal region and reported no misplacement. Stuart et al. [14] targeted some probes in perilesional tissue, with 2 of 61 (3%) misplacements: one case involving the intraventricular depth electrode and one with the probe located within the infarction. Foreman et al. [7] had the highest misplacement rate, as 6 of 43 (14.3%) devices were outside the expected location (frontal subcortical white matter, most injured hemisphere). Our meta-analysis found an iMMM misplacement pooled rate of 6%. In comparison, the rate of free-hand optimal EVD placement, a more challenging surgical procedure, widely varied in the literature between 55 and 95% without considering the number of attempts [28].

CNS Infections

Neurocritical patients have an intrinsic risk for CNS infections, as a primary ABI etiology or secondarily (e.g., due to open-head TBI, postoperative neurosurgical status, or EVD). These conditions and interventions are confounding factors in formally identifying CNS infections attributed to iMMM. For instance, [14] reported three

cases of CNS infections (i.e., positive cerebrospinal fluid culture) among 61 patients (5%), and two had concurrent EVD. In the most extensive series (501 patients), Bailey et al. [8] reported only one infection due to an improper bolt placement technique with a faulty seal causing a CSF leak and potentially bacterial meningitis. Al Barajraji et al. [16] reported that nine (8%) of their patients developed CNS infections. However, despite a relatively high mean monitoring time, they did not attribute it to iMMM; no intraventricular misplacement was associated with CNS infections [16]. Our meta-analysis found a pooled rate of CNS infection associated with iMMM placement of 0.43%. Similarly, CNS infection incidence for ICP intraparenchymal monitors was reported as 0.6–2.1% [18, 29], lower than the EVD-related rate (5% to over 20%) [30].

Other Complications

Three series mentioned bone fragments as an iMMM placement complication. González et al. [31] were the first to report 14 cases with a high complication rate (70%). Foreman et al. [7] mentioned "small bone chips" within the device path without further detail. Recently, Al Barajraji et al. [16] reported four patients with clinically insignificant intracranial bone fragments following iMMM placement (complication rate 3.2%). The long-term evolution of these bone fragments has yet to be assessed. Pneumocephalus as an individualized iMMM surgical complication was only reported by Al Barajraji et al. [16], without reporting any clinical significance.

Adverse Events

Bolts anchored in the skull ensure probe fixation, often using Luer locks to prevent probes' dislodgement or breaking during conducive situations (i.e., head manipulations, patient transport). The tunnelization technique, while potentially less obtrusive than bulky bolt devices, may pose a challenge concerning its stability with the risk of the device sliding. Still, the current literature lacks any comparative review or comparable data to investigate this hypothesis. Once again, the definitions may have varied widely with poor descriptions. For instance, the highest probe dislodgement rate (43%), reported by Stuart et al. [14], is explained by the authors' inclusive definition based on unintentional monitoring interruption comprising probe dislodgement and hardware malfunction. Interestingly, Foreman et al. [7] time-tracked data recording stops as discontinuations (i.e., either from dislodgement or unplugging) by one-off events rather than reporting their overall occurrence: 58% of patients were concerned with 4.2% of data unusable. The technical reliability of iMMM was beyond our scope. Nonetheless, we note that dedicated investigations are rare, although they are essential to ascertain iMMM contribution to neurocritical care.

Pediatric Considerations

Al Barajraji et al. [16] reported three pediatric cases, of which one concerned their only revision surgery. Based on this limited experience, they raised concerns about relatively large multi-lumen bolt devices unsuited for pediatric indications. Furthermore, we found no other reports of iMMM complications in children. Specific technical notes by seasoned pediatric neurocritical teams would be of interest [32–34].

Limitations

High-level evidence about the relevant literature is lacking. To our knowledge, no previous systematic review or meta-analysis is available. Our literature review found significant heterogeneity mainly due to a lack of standardization in definitions used to report iMMM experience. For the meta-analysis, we mitigated this data heterogeneity by constraining eligibility criteria. Consequently, we only performed a rigorous risk factor analysis for PIH for a limited subset of two determinants.

Future Directions

Consensus-based reporting guidelines for iMMM experience are needed to provide high-level evidence by limiting the current literature heterogeneity. Moreover, experience-sharing initiatives, such as technical notes, are scarce [35]. These collaborative efforts are crucial for disseminating best practices. On another note, we believe that accessible technology may improve current practice. Hybrid approaches between bolt and tunneled methods merit consideration to combine their advantages, ensuring reliable iMMM probe fixation while minimizing device bulkiness, potentially reducing adverse events and infection risk and improving imaging compatibility. Multimodality single probes and one-lumen minimally invasive anchor bolts (e.g., as used in stereoelectroencephalography) may reduce iMMM invasiveness while enhancing implantation strategy versatility. Furthermore, iMMM placement accuracy could be improved by the increasing availability and future development of stereotactic neuronavigation, robot-assisted methods, and intraoperative real-time recordings. Finally, recent progress (e.g., endovascular neural recording [36, 37]) and industry interest in minimally invasive brain-machine interfaces may enhance technology transfer for iMMM development [38].

Conclusions

Currently, iMMM systems present a safety profile with complication rates consistent with intracranial devices

commonly used in the neurocritical setting, i.e., intraparenchymal and intraventricular probes. However, available data were insufficient to perform extensive risk factor analysis. Multicenter prospective studies providing long-term outcomes (e.g., complication follow-up) are lacking. Consequently, the benefit-risk assessment of iMMM for neurocritical care remains inchoate. Likewise, consensus-based reporting guidelines are needed to efficiently mount high-level evidence. These collaborative efforts would support best practices and innovation for future iMMM development.

Supplementary Information
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Data Availability
All data and code used are available on request.

Conflict of interest
The authors have no conflicts of interest to declare.

Ethical Approval/Informed Consent
This study was performed in compliance with all ethical guidelines and specifically according to the Preferred Reporting Items for Systematic Review and Meta-Analysis and Peer Review of Electronic Search Strategies guidelines.

Clinical Trial Registration
This study has been registered with PROSPERO (CRD42021225951).

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References

1. Chin JH, Vora N. The global burden of neurologic diseases. Neurology. 2014;83(4):349–51. https://doi.org/10.1212/WNL.0000000000000610.
2. Dewan MC, Rattani A, Gupta S, et al. Estimating the global incidence of traumatic brain injury. J Neurosurg. 2018;130(4):1080–97. https://doi.org/10.3171/2017.10.JNS17352.
3. Hawryluk GWJ, Aguilera S, Buki A, et al. A management algorithm for patients with intracranial pressure monitoring: the Seattle International Severe Traumatic Brain Injury Consensus Conference (SIBICC). Intensive Care Med. 2019;45(12):1783–94. https://doi.org/10.1007/s00134-019-05805-9.
4. Le Roux P, Menon DK, Citerio G, et al. Consensus summary statement of the international multidisciplinary consensus conference on multimodality monitoring in neurocritical care: a statement for healthcare professionals from the neurocritical care society and the European Society of Intensive Care Medicine. Intensive Care Med. 2014;40(9):1189–209. https://doi.org/10.1007/s00134-014-3369-6.
5. Citerio G, Oddo M, Taccone FS. Recommendations for the use of multimodal monitoring in the neurointensive care unit. Curr Opin Crit Care. 2015;21(2):113–9. https://doi.org/10.1097/MCC.0000000000000179.
6. Roh D, Park S. Brain multimodality monitoring: updated perspectives. Curr Neurol Neurosci Rep. 2016;16(6):56. https://doi.org/10.1007/s11910-016-0659-0.
7. Foreman B, Ngwenya LB, Stoddard E, Hinzman JM, Andaluz N, Hartings JA. Safety and reliability of bedside, single burr hole technique for intracranial multimodality monitoring in severe traumatic brain injury. Neurocrit Care. 2018;29(3):469–80. https://doi.org/10.1007/s12028-018-0551-7.
8. Bailey RL, Quattrone F, Curtin C, et al. The safety of multimodality monitoring using a triple-lumen bolt in severe acute brain injury. World Neurosurg. 2019;130:e62–7. https://doi.org/10.1016/j.wneu.2019.05.195.
9. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Syst Rev. 2021;10(1):89. https://doi.org/10.1186/s13643-021-01626-4.
10. McGowan J, Sampson M, Salzwedel DM, Cogo E, Foerster V, Lefebvre C. PRESS peer review of electronic search strategies: 2015 guideline statement. J Clin Epidemiol. 2016;75:40–6. https://doi.org/10.1016/j.jclinepi.2016.01.021.
11. Wells G, Shea B, O'Connell D, et al. The Newcastle-Ottawa Scale (NOS) for assessing the quality of nonrandomized studies in meta-analysis. Ott Ott Hosp Res Inst. 2011;2:1–12.
12. Ioannidis JPA. Interpretation of tests of heterogeneity and bias in meta-analysis. J Eval Clin Pract. 2008;14(5):951–7. https://doi.org/10.1111/j.1365-2753.2008.00986.x.
13. Sioutos PJ, Orozco JA, Carter LP, Weinand ME, Hamilton AJ, Williams FC. Continuous regional cerebral cortical blood flow monitoring in head-injured patients. Neurosurgery. 1995;36(5):943–50. https://doi.org/10.1227/00006123-199505000-00009.
14. Stuart RM, Schmidt M, Kurtz P, et al. Intracranial multimodal monitoring for acute brain injury: a single institution review of current practices. Neurocrit Care. 2010;12(2):188–98. https://doi.org/10.1007/s12028-010-9330-9.
15. Sarrafzadeh AS, Sakowitz OW, Kiening KL, Benndorf G, Lanksch WR, Unterberg AW. Bedside microdialysis: a tool to monitor cerebral metabolism in subarachnoid hemorrhage patients? Crit Care Med. 2002;30(5):1062–70. https://doi.org/10.1097/00003246-200205000-00018.
16. Al Barajraji M, Bogossian E, Dewitte O, et al. Safety profile of an intracranial multimodal monitoring bolt system for neurocritical care: a single-center experience. Acta Neurochir (Wien). 2021;163(12):3259–66. https://doi.org/10.1007/s00701-021-04992-z.

17. Dings J, Meixensberger J, Jäger A, Roosen K. Clinical experience with 118 brain tissue oxygen partial pressure catheter probes. Neurosurgery. 1998;43(5):1082–94. https://doi.org/10.1097/00006123-199811000-00045.
18. Bauer DF, Razdan SN, Bartolucci AA, Markert JM. Meta-analysis of hemorrhagic complications from ventriculostomy placement by neurosurgeons. Neurosurgery. 2011;69:255–60.
19. Binz DD, Toussaint LG, Friedman JA. Hemorrhagic complications of ventriculostomy placement: a meta-analysis. Neurocrit Care. 2009;10:253–6.
20. Bekar A, Doğan Ş, Abaş F, et al. Risk factors and complications of intracranial pressure monitoring with a fiberoptic device. J Clin Neurosci. 2009;16(2):236–40. https://doi.org/10.1016/j.jocn.2008.02.008.
21. Gelabert-González M, Ginesta-Galan V, Sernamito-García R, Allut AG, Bandin-Diéguez J, Rumbo RM. The Camino intracranial pressure device in clinical practice. Assessment in a 1000 cases. Acta Neurochir (Wien). 2006;148(4):435–41. https://doi.org/10.1007/s00701-005-0683-3.
22. Mullin JP, Shriver M, Alomar S, et al. Is SEEG safe? A systematic review and meta-analysis of stereo-electroencephalography-related complications. Epilepsia. 2016;57(3):386–401. https://doi.org/10.1111/epi.13298.
23. McGovern RA, Ruggieri P, Bulacio J, Najm I, Bingaman WE, Gonzalez-Martinez JA. Risk analysis of hemorrhage in stereo-electroencephalography procedures. Epilepsia. 2019;60(3):571–80. https://doi.org/10.1111/epi.14668.
24. Gardner PA, Engh J, Atteberry D, Moossy JJ. Hemorrhage rates after external ventricular drain placement. J Neurosurg. 2009;110:1021–5.
25. Stewart C, Haitsma I, Zador Z, et al. The new Licox combined brain tissue oxygen and brain temperature monitor: assessment of in vitro accuracy and clinical experience in severe traumatic brain injury. Neurosurgery. 2008;63(6):1159–65. https://doi.org/10.1227/01.NEU.0000333265.19131.7C.
26. Ponce LL, Pillai S, Cruz J, et al. Position of probe determines prognostic information of brain tissue PO2 in severe traumatic brain injury. Neurosurgery. 2012;70(6):1492–502. https://doi.org/10.1227/NEU.0b013e31824ce933.
27. Lindner A, Rass V, Ianosi BA, et al. The importance of PbtO2 probe location for data interpretation in patients with intracerebral hemorrhage. Neurocrit Care. 2021;34(3):804–13. https://doi.org/10.1007/s12028-020-01089-w.
28. Stuart MJ, Antony J, Withers TK, Ng W. Systematic review and meta-analysis of external ventricular drain placement accuracy and narrative review of guidance devices. J Clin Neurosci. 2021;94:140–51. https://doi.org/10.1016/j.jocn.2021.10.014.
29. Lozier AP, Sciacca RR, Romagnoli MF, Connolly ES. Ventriculostomy-related infections: a critical review of the literature. Neurosurgery. 2002;51(1):170–82. https://doi.org/10.1097/00006123-200207000-00024.
30. Beer R, Lackner P, Pfausler B, Schmutzhard E. Nosocomial ventriculitis and meningitis in neurocritical care patients. J Neurol. 2008;255(11):1617–24. https://doi.org/10.1007/s00415-008-0059-8.
31. González I, Santamarta D. Multimodal neuromonitoring catheter insertion: secondary complications. ICU Manag Pract. 2018;18(4):266–7.
32. Figaji AA, Fieggen AG, Argent AC, Leroux PD, Peter JC. Does adherence to treatment targets in children with severe traumatic brain injury avoid brain hypoxia? A brain tissue oxygenation study. Neurosurgery. 2008;63(1):83–92. https://doi.org/10.1227/01.NEU.0000335074.39728.00.
33. Goodman G, Palmer S, Bader MK. Cerebral tissue oxygen saturation (PbtO2) in pediatrics—experience with the Licox catheter in 13 patients: 10. Pediatr Crit Care Med. 2005;6(1):105.
34. Rohlwink UK, Zwane E, Fieggen AG, Argent AC, le Roux PD, Figaji AA. The relationship between intracranial pressure and brain oxygenation in children with severe traumatic brain injury. Neurosurgery. 2012;70(5):1220–31. https://doi.org/10.1227/NEU.0b013e318243fc59.
35. Pinggera D, Petr O, Putzer G, Thomé C. Adjustable and rigid fixation of brain tissue oxygenation probe (Licox) in neurosurgery: from bench to bedside. World Neurosurg. 2018;117:62–4. https://doi.org/10.1016/j.wneu.2018.05.154.
36. Fan JZ, Lopez-Rivera V, Sheth SA. Over the horizon: the present and future of endovascular neural recording and stimulation. Front Neurosci. 2020;14:432. https://doi.org/10.3389/fnins.2020.00432.
37. Sefcik RK, Opie NL, John SE, Kellner CP, Mocco J, Oxley TJ. The evolution of endovascular electroencephalography: historical perspective and future applications. Neurosurg Focus. 2016;40(5):E7. https://doi.org/10.3171/2016.3.FOCUS15635.
38. Musk E. An integrated brain-machine interface platform with thousands of channels. J Med Internet Res. 2019;21(10):e16194. https://doi.org/10.1101/703801.
39. Guan J, Spivak ES, Wilkerson C, Park MS. Subdural empyema in the setting of multimodal intracranial monitoring. World Neurosurg. 2017;97:749.e1-749.e6.
40. Steiner T, Pilz J, Schellinger P, Wirtz R, Friederichs V, Aschoff A, et al. Multimodal online monitoring in middle cerebral artery territory stroke. Stroke. 2001;32:2500–6.
41. Waziri A, Claassen J, Stuart RM, Arif H, Schmidt JM, Mayer SA, et al. Intracortical electroencephalography in acute brain injury. Ann Neurol. 2009;66:366–77.
42. van Santbrink H, Maas AIR, Avezaat CJJ. Continuous monitoring of partial pressure of brain tissue oxygen in patients with severe head injury. Neurosurgery. 1996;38:21–31.
43. Al-Rawi PG, Hutchinson PJA, Gupta AK, Piechnik SK, Pickard JD, Kirkpatrick PJ. Multiparameter brain tissue monitoring: correlation between parameters and identification of CPP thresholds. Zentralbl Neurochir. 2000;61:74–9.
44. Kiening KL, Unterberg AW, Bardt TF, Schneider G-H, Lanksch WR. Monitoring of cerebral oxygenation in patients with severe head injuries: brain tissue PO2 versus jugular vein oxygen saturation. J Neurosurg. 1996;85:751–7.
45. Forsse A, Nielsen TH, Mølstrøm S, Hjelmborg J, Nielsen KS, Nygaard KH, et al. A prospective observational feasibility study of jugular bulb microdialysis in subarachnoid hemorrhage. Neurocrit Care. 2020;33:241–55.
46. Seule M, Sikorski C, Sakowitz O, von Campe G, Santos E, Orakcioglu B, et al. Evaluation of a new brain tissue probe for intracranial pressure, temperature, and cerebral blood flow monitoring in patients with aneurysmal subarachnoid hemorrhage. Neurocrit Care. 2016;25:193–200.
47. Sekhon MS, Gooderham P, Menon DK, Brasher PMA, Foster D, Cardim D, et al. The burden of brain hypoxia and optimal mean arterial pressure in patients with hypoxic ischemic brain injury after cardiac arrest*. Crit Care Med. 2019;47:960–9.
48. Simonin A, Rusca M, Saliou G, Levivier M, Daniel RT, Oddo M. Multimodal regional brain monitoring of tissue ischemia in severe cerebral venous sinus thrombosis. Neurocrit Care. 2019;31:297–303.
49. Idris Z, Ghani RI, Musa KI, Ibrahim MI, Abdullah M, Nyi NN, et al. Prognostic study of using different monitoring modalities in treating severe traumatic brain injury. Asian J Surg. 2007;30:200–8.
50. Vajkoczy P, Horn P, Thome C, Munch E, Schmiedek P. Regional cerebral blood flow monitoring in the diagnosis of delayed ischemia following aneurysmal subarachnoid hemorrhage. J Neurosurg. 2003;98:1227–34.
51. Staub F, Graf R, Gabel P, Köchling M, Klug N, Heiss W-D. Multiple interstitial substances measured by microdialysis in patients with subarachnoid hemorrhage. Neurosurgery. 2000;47:1106–16.