neurocritical care society Neurocrit Care (2017) 26:143–156
DOI 10.1007/s12028-016-0298-y

REVIEW ARTICLE

Brainstem Monitoring in the Neurocritical Care Unit: A Rationale for Real-Time, Automated Neurophysiological Monitoring

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Published online: 2 August 2016

Abstract Patients with severe traumatic brain injury or large intracranial space-occupying lesions (spontaneous cerebral hemorrhage, infarction, or tumor) commonly present to the neurocritical care unit with an altered mental status. Many experience progressive stupor and coma from mass effects and transtentorial brain herniation compromising the ascending arousal (reticular activating) system. Yet, little progress has been made in the practicality of bedside, noninvasive, real-time, automated, neurophysiological brainstem, or cerebral hemispheric monitoring. In this critical review, we discuss the ascending arousal system, brain herniation, and shortcomings of our current management including the neurological exam, intracranial pressure monitoring, and neuroimaging. We present a rationale for the development of nurse-friendly—continuous, automated, and alarmed—evoked potential monitoring, based upon the clinical and experimental literature, advances in the prognostication of cerebral anoxia, and intraoperative neurophysiological monitoring.

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Keywords Neurocritical care unit · Severe traumatic brain injury · Intracranial space-occupying lesions · Transtentorial herniation · Ascending arousal system · Intracranial pressure · Real-time, automated brainstem and cerebral monitoring · Somatosensory evoked potentials · Motor evoked potentials · Neuromonitoring

Abbreviations

AAS	Ascending arousal (reticular activating) system
BAEP	Brainstem auditory evoked potential
BR	Blink reflex
CPP	Cerebral perfusion pressure
CSF	Cerebrospinal fluid
CT	Computed tomography
EMG	Electromyography
EP	Evoked potential
ICP	Intracranial pressure
IONM	Intraoperative neurophysiological monitoring
MAP	Mean arterial pressure
MBAEP	Modified forms of the BAEP
MEP	Motor evoked potentials
NCCU	Neurocritical care unit
SOL	Space-occupying lesion
SSEP	Short latency somatosensory evoked potentials
sTBI	Severe traumatic brain injury
TcE-MEP	Transcranial electrical motor evoked potentials
TcM-MEP	Transcranial magnetic motor evoked potentials
TrSSEP	Trigeminal short latency somatosensory evoked potential
TTH	Transtentorial herniation

Introduction

Patients in the neurocritical care unit (NCCU) often have an altered level of consciousness and require sedation, analgesia, and muscle paralysis for restlessness, pain, intubation/airway management, facilitating radiological studies, and controlling intracranial pressure (ICP). The neurological examination to establish—level of consciousness, pupils, extraocular motility, and extremity responses—may be limited to brief periods of reduced or withheld medications. Often without apparent warning—or following carbon dioxide retention, a seizure, vigorous tracheal suctioning, diminished venous outflow, or ventricular system blockage—ominous findings occur such as onset of coma, pupillary changes, and motor posturing [1–6].

Lethargy, hypersomnolence, stupor, and coma secondary to space-occupying lesions (SOLs), usually indicate involvement of the ascending arousal (ascending reticular activating) system (AAS) [6–11]. SOLs are commonly associated with adjacent vasogenic edema, hyperemia, and ischemia. Compensation occurs by displacement of cerebrospinal fluid (CSF) and venous blood, and distortion of the brain parenchyma [12, 13]. As these mechanisms fail, precipitous brain tissue displacements, secondarily increased ICP, lateral midbrain shifts (uncal herniation) and/or downward herniation through the tentorial opening (transtentorial herniation, TTH) ensues. Without early detection, life threatening rostrocaudal deterioration and severe disability or death result from deep hemispheric shifts with ischemic injury, and/or secondary brainstem infarctions and hemorrhages [8–11]. Indeed, TTH is among the most emergent situations encountered in clinical medicine [4, 6, 8, 11, 14–16].

Various limitations and pitfalls exist in our present reliance on ICP, cerebral perfusion pressure (CPP), and neuroimaging [3, 6, 17, 18]. Reliable physiological or functional information is needed for more timely treatment. We advocate the use of short latency sensory and motor evoked potential modalities (EPs) in close proximity to the AAS in the upper pons, midbrain, and diencephalic region [19–22]. These monitoring tools, and possibly several others, can be automated for practical, real-time, nurse-friendly application within the NCCU.

'Real-time assessment of global or regional brain dysfunction could help clinicians recognize early worsening, prompt specific management changes, monitor response to therapy…(and)…used as surrogate endpoints in clinical trials [23].' Such monitoring would augment our present treatments and be utilized in patients not ordinarily considered for invasive ICP monitoring—such as somnolent patients with moderate head injuries, cerebral infarctions, and hemorrhages without rupture into the ventricle. This review is intended to stimulate development of bedside nurse-friendly, automated electrophysiological monitoring for these challenging patients.

The Ascending Arousal System and Transtentorial Herniation

Critical structures enclosed within the incisural plane or hiatus of the tentorium cerebelli are depicted in Fig. 1a–c [4, 14, 16]. These include the midbrain nuclei and fibers of the AAS which modulates cerebral cortical activity in the maintenance of vigilance and consciousness [9, 24]. Additional causes of coma consist of bilateral or central AAS lesions, or their thalamic targets, and portions of the hypothalamus and basal forebrain (Figs. 1c, 2) [7–11, 16, 19, 25]. Upward projecting AAS nuclei and major fiber bundles such as the central tegmental tract, being aligned parallel to the long axis of the brainstem (Fig. 2), may make the system particularly vulnerable to perpendicular or lateral bending forces.

TTH is dependent upon SOL volume, rate of radial expansion, vector force, and the presence or absence of cerebral atrophy [7, 8, 26–35]. Central herniation directs the mesodiencephalic region more caudally than laterally [7, 8, 10, 11, 36–39]. Earlier stages of TTH typically show mesial displacement of the basal hemisphere at or just above the tentorium, with widening of the ipsilateral ambient cistern (Figs. 3, 4) [36]. Accompanying this displacement is transposition of the attached midbrain, whose peduncle may become compressed or 'notched' against the contralateral rigid tentorial edge, causing hemiparesis ipsilateral to the SOL—the Kernohan-Woltman Phenomena (Figs. 3, 4, 5) [36, 40].

About half of SOL patients with TTH have only horizontal midbrain displacement and the other half downward shift of the midbrain tectum [4, 41–43]. Stupor and coma more closely correlate with a 6- to 13-mm midline hemispheric shift than vertical descent [44]. And effacement or closure of the perimesencephalic (ambient) cisterns a worsened outcome as well [45, 46]. At times, brainstem ischemia can be a significant factor without clear evidence of mechanical herniation or brainstem hemorrhage [36, 47–52].

The sudden and unpredictable nature of TTH is likely influenced by the extreme anatomic variability of the incisural length and width, midbrain proximity to the tentorial edge (0–7 mm), and oculomotor nerve distances [14, 16, 36, 53, 54]. Preferably, surgical decompressions should be performed at the early diencephalic (drowsy or stuporous) phase; but with loss of the neurological exam, and without a clear physiological indicator, much variability remains [46, 55–59].

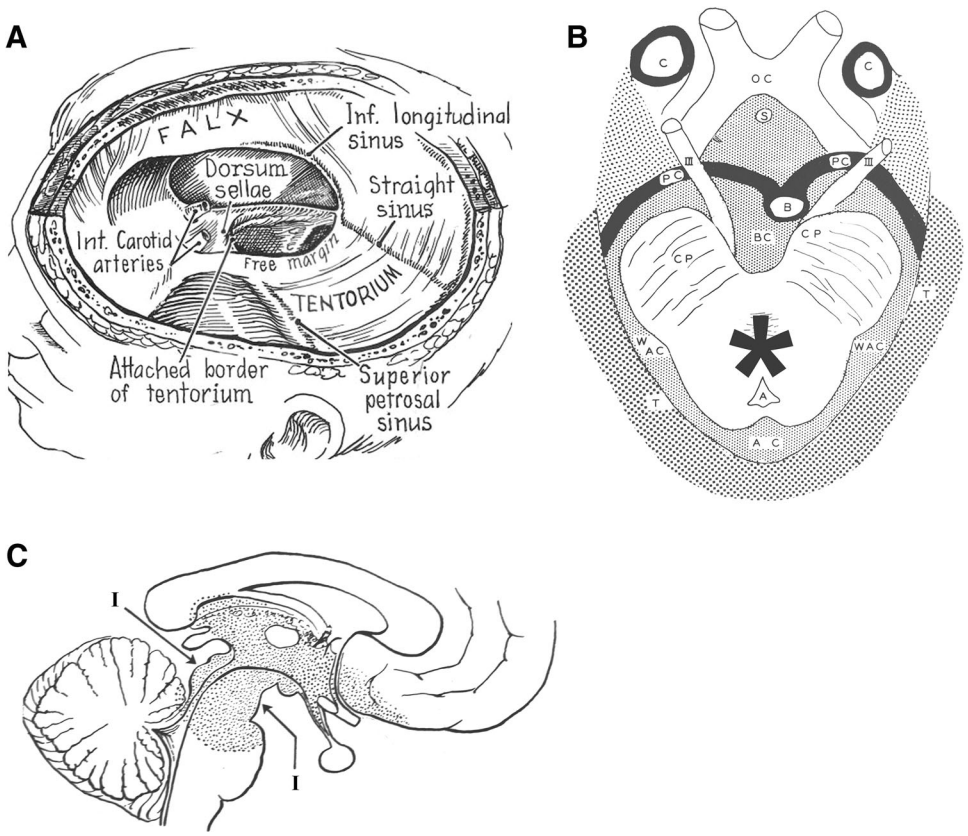

Fig. 1 **a** Drawing depicting the incisural opening of the tentorium cerebelli for passage of the midbrain. Note adjacent structures (from Finney and Walker 1962 with permission) [14]. **b** Cross section of the midbrain within the incisural plane as viewed from below. *A*—aqueduct of Sylvius, *B*—basilar artery, *BC*—basal cistern, *C*—internal carotid arteries, *CP*—cerebral peduncles, *OC*—optic chiasm, *PC*—posterior cerebral arteries, *S*—stalk of pituitary, *T*—tentorium cerebelli, *WAC*—wings of the ambient cistern. Large asterisk approximates the midbrain (reticular) ascending arousal system (AAS) (adapted from Walker 1969 with permission) [16]. **c** Sagittal section, stippling represents the predominant areas most related to preservation of consciousness. 'I'—approximates the incisural plane (from Jefferson 1958 with permission) [26]

Intracranial Pressure (ICP) and Related Issues

'The pathogenesis of signs and symptoms of an expanding mass lesion that causes coma is rarely a function of the increase in ICP itself, but usually results from imbalances of pressure between different (intradural) compartments leading to tissue herniation.' [8, p. 95].

The intracranial contents largely consist of inhomogeneous brain tissue, liquid blood, and CSF [60–63]. The largest component—brain is a deformable viscoelastic structure, which exhibits properties characteristic of a solid as well as a fluid [12, 13, 61, 64–71]. This property predisposes to 'shear stresses' resulting in 'pressure differentials' or 'gradients' between regions of increased and decreased tension within the brain. Gradients are frequent in the vicinity of compressed or deformed brain tissue but also occur contralateral and across compartments predisposed to TTH and foramen magnum herniation [61, 64–66]. Experimental intracranial mass expansion results in the immediate appearance and elevation of such gradients, with quick reversal by decompression [28, 30–32, 34, 64, 65, 72–74]. Gradients have also been detected in SOL patients with multiple ICP monitors [17, 29, 75–82].

Due to the risk of causing clinical deterioration and TTH, ICP devices are customarily placed contralateral to the SOL. Thus, ICP underestimates distant gradient effects, but also the effects of brain turgor and compliance adjacent to the mass lesion or deeper, or how fast deadly processes may be occurring [60, 67, 70, 71, 82–84]. Consequently, ICP devices must be suspect of measuring a local as opposed to a generalized, broadly applied value like systemic arterial pressure. In addition, midline shifts may lead to falsely low ICP values by narrowing third ventricular width, impeding CSF egress, thus transmission of ICP to the contralateral ventricular monitor [72]. Acute mass lesions in the temporal or posterior fossa have progressed to somnolence and herniation even with ICP levels recorded at 20 mm Hg [18].

Cerebral perfusion pressure (CCP) has been helpful in management of patients with increased ICP to avert hypotension [62, 84]. Either hypotension—reduced mean arterial pressure (MAP) or increased ICP (without an associated increase in MAP)—results in decreased cerebral perfusion pressure (CPP = MAP minus ICP) [83–86]. However, the CPP is critically dependent upon the ICP value and, like ICP, only can be relied upon to reflect the value near the monitor's tip [18].

There is certainty that refractory ICP is detrimental, and an initial ICP value greater than 20 mm Hg is associated with poor outcome after severe traumatic brain injury (sTBI, Glasgow Coma Score $\leq$8) [18, 46, 62, 84]. In

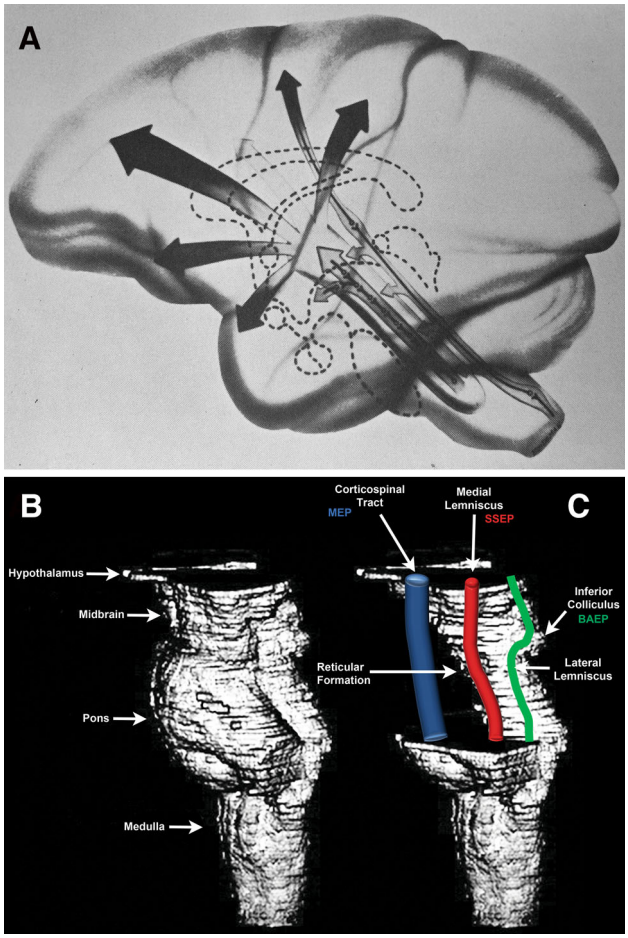

Fig. 2 **a** Classic depiction of the brainstem ascending (reticular) arousal system (AAS) activating higher central nervous system centers resulting in arousal (from Magoun 1954 with permission) [25]. **b** Model of the brainstem and hypothalamus prepared from thinly cut human material, and sub-millimeter MRI images from a number of patients with brainstem coma. **c** A 'cutaway model' depicting the volume of the midbrain and pons that constitutes the reticular formation of the AAS (designated with *long horizontal arrow*). Superimposed in proximity are the corticospinal tract, medial lemniscus, and lateral lemniscus/inferior colliculus—responsible for the respective evoked potential responses—MEP, SSEP, and BAEP (adapted from Parvizi and Damasio 2004 with permission) [9]

addition, ICP per se is not a useful indicator for a functional outcome [6, 62, 86]. Recent consensus holds that ICP/CPP-directed monitoring and adherence to guidelines leads to overall improved attention and management of the sTBI patient (efficiency of care). However, due to a number of factors such as a baseline high mortality, variability in ICP devices, a lack of standards for recording ICP values, uncertainty of individual ICP threshold values, as well as the ability to effectively control ICP, outcome remains similar to those managed without ICP monitoring [17, 62, 85–94].

A large, prospective, double-blind, sTBI study analyzed secondary pupillary or motor score deterioration and argued a critical need to identify patients at particular risk [46]. Another prospective study examined patients with a large-volume cerebral hemispheric infarction who underwent decompressive hemicraniectomy [55]. This study made a strong case that ICP monitoring was unreliable, thalamic/brainstem shift on imaging studies held more importance, and earlier recognition was essential to preserve life and a functional recovery [55]. Perhaps more reliable or different information is needed than can be presently obtained from ICP monitoring [17, 95, 96].

Neuroimaging

Neuroimaging provides essential structural-anatomic detail for acute diagnosis and emergency medical and surgical treatments of hemorrhages, hydrocephalus, tumors, and infarctions [6]. However, clear imaging of brain tissue impacted by deep mass effects and the propensity for identifying early TTH is limited (see above 'The Ascending Arousal System and Transtentorial Herniation' section). In patients without pupillary findings or motor posturing, the ICP value usually carries more importance than the significance of nonhemorrhagic CT findings such as increased edema, midline shift, or basal cistern obliteration. In stable patients, MRI may be performed and coronal images are particularly revealing (Fig. 5b) compared to axial CT and coronal reconstructions. Unfortunately, these patients are often unstable and transporting them may be problematic [6]. Laying these patients flat and moving them into and out of scanners not infrequently leads to stubborn increases in ICP and monitor malfunction or dislodgement, including other mounted monitoring devices. We believe functional or physiological bedside information is necessary for more timely treatment of TTH.

Neurophysiological Monitoring at the Incisural Plane: A Review of Related Clinical and Experimental Research

Neurophysiological monitoring 'allows for real-time assessment of neurologic integrity, signal transmission, and secondary processing of sensory information… Signal changes can be measured over time…to detect responses to therapeutic interventions, recovery of brain function, or progression of injury' [97]. For decades, somatosensory evoked potentials (EPs) have been used as indicators to assess stroke and sTBI patients [98–104]. Positive clinical correlations were found, and advantages of serial EP recordings were realized [98, 103–106]. Reviews were optimistic regarding the future use of somatosensory EPs in

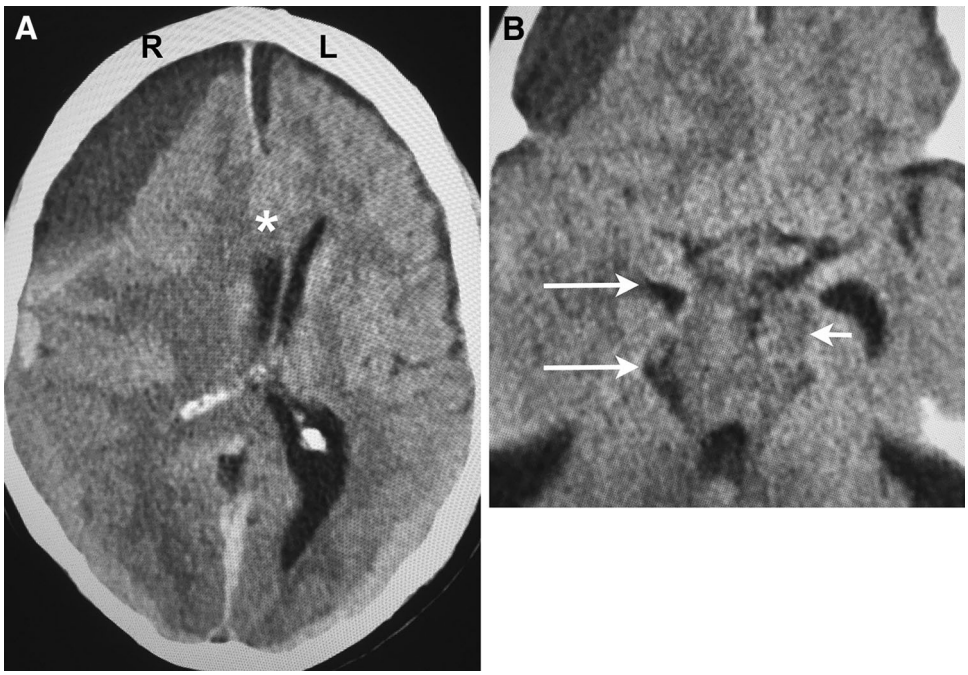

Fig. 3 Eighty-three-year-old male with dementia and falls presented with extreme lethargy and right-sided weakness. **a** Plain CT scan of the brain showed a large right, mixed-density, chronic, subdural hematoma with marked subfalcine herniation (*asterisk*) and pronounced *right to left* midline shift. **b** Basal image of the CT scan shows medial displacement of the right temporal horn (*upper arrow*) and widening of the right ambient cistern (*lower arrow*). The left midbrain cerebral peduncle appears compressed (*short arrow*) and the adjacent left temporal horn dilated. Despite timely surgical decompression, the patient later expired from medical complications

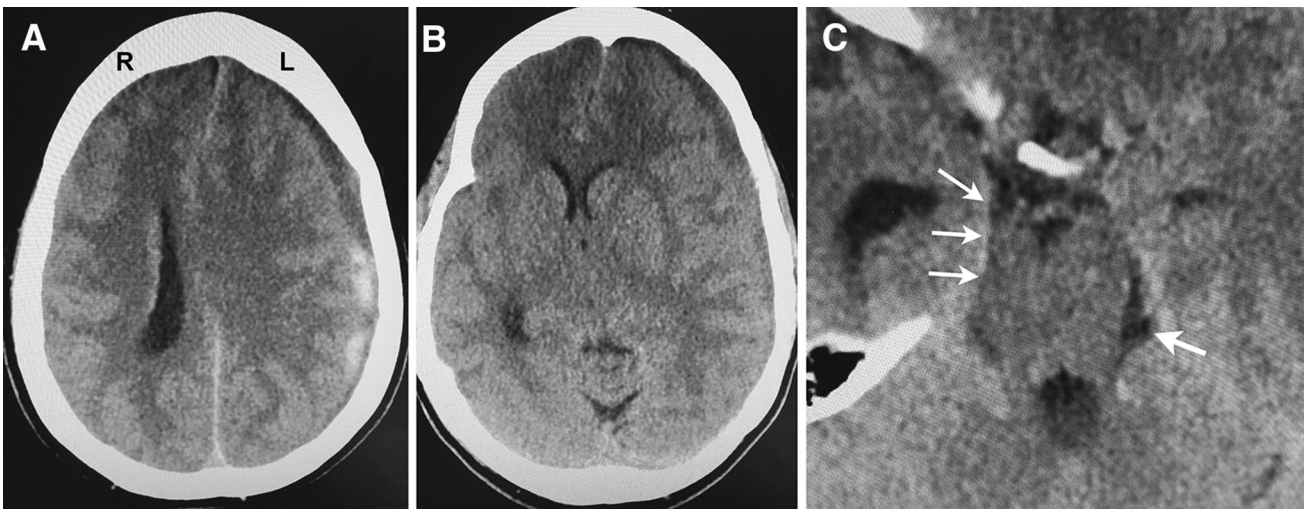

Fig. 4 Fifty-one-year-old nurse with progressive headaches requiring aspirin, recent vomiting, and lethargy. She slept when left alone (somnolent), opened her eyes (but not fully) after moderate stimuli, was oriented to person, place and time, and followed commands. Glasgow Coma Score was deceptive at 14. She had drift of the left outstretched arm and a right Babinski sign. **a** Plain CT scan showed a large left subacute-appearing subdural hematoma, obliteration of much of the left lateral ventricle, and approximately 1.5-cm midline shift. **b**, **c** A trapped, dilated right temporal horn was present; and the right midbrain cerebral peduncle appeared effaced by the right tentorial edge (*arrows*). The left ambient cistern was enlarged (*left arrow*). Due to the alteration in consciousness, mass effect, and radiographic appearance of incipient TTH, she was given mannitol and platelets, promptly taken to the operating room for intubation, and a left frontotemporoparietal craniotomy was performed. Neurological deficits resolved and she returned to work as a nurse about 6 months later

coma and TTH, but advances in neuroimaging and adoption of ICP/CPP-directed care led to less use of EPs in the NCCU [86, 97–99, 101, 107]. More recent NCCU studies and improved EP technology have significantly confirmed and extended the usefulness of EPs in these patients [97, 100, 108–118].

In accordance with recent literature on neurocritical care, the ideal monitor provides bedside, noninvasive, real-time, user-friendly advanced data analysis to improve treatment [86, 97, 118]. We believe some of the neurophysiological modalities described in this section could be adapted to fulfill this present void in our NCCU care.

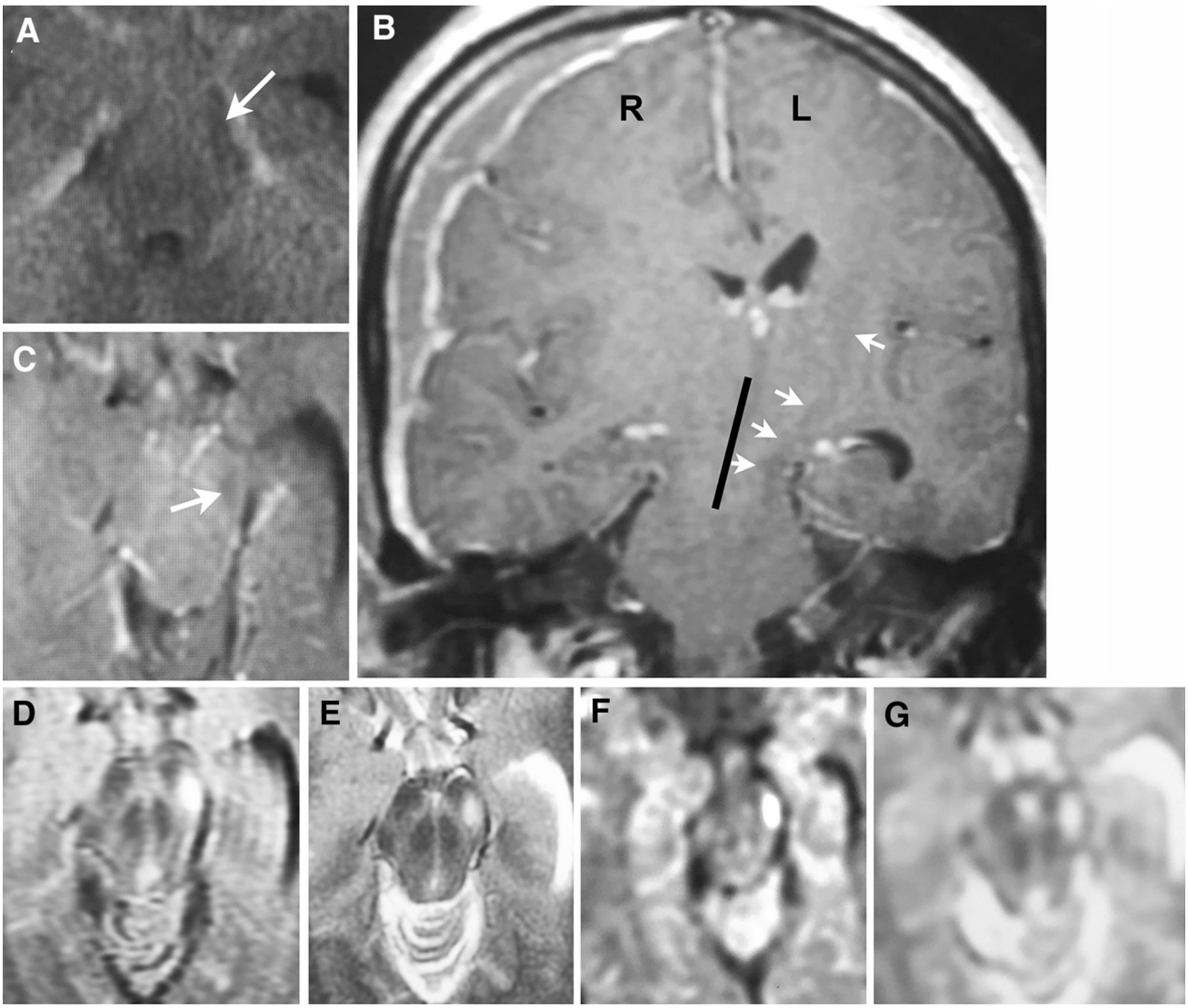

Fig. 5 Thirty-six-year-old male was beaten up, found moderately lethargic (stuporous), only intermittently followed commands, and Glasgow Coma Score was 10. A right hemiparesis was present. **a** CT scan of the brain disclosed a large right-sided subdural hematoma with midline shift, a right basifrontal hemorrhagic contusion, and smaller bitemporal contusions. The basal cisterns showed an abundance of subarachnoid hemorrhage and a possible area of low density in the left midbrain cerebral peduncle (*arrow*). Due to the prominent subarachnoid hemorrhage as well as weakness ipsilateral to the subdural, MRI/MRA of the brain was obtained and no vascular lesions were detected. **b** MRA—*coronal view* shows the large subdural, and right to left shift with angulation of the diencephalic–midbrain region (*solid line*). An altered signal intensity (*white arrows*) believed to represent insult to the left corticospinal (*pyramidal*) tract was evident in the hemisphere and upper brainstem. The midbrain was well visualized and T1 axial (MRA) image (**c**) showed a faint low density within the left midbrain peduncle (*arrow*). A very bright, white signal was noted in the axial left midbrain peduncle on Flair (**d**), T2 (**e**), DWI (**f**), and ADC (**g**) images. The findings are not considered compatible with an ischemic event but rather a non-hemorrhagic bruise or damage to the densely packed motor fibers of the corticospinal (*pyramidal*) tract. Increased lethargy and slight right arm extensor posturing prompted emergent right-sided craniotomy for evacuation of the subdural and basifrontal hematoma. After extensive rehabilitation, he remained moderately disabled due to right-sided weakness and cognitive problems

The Blink Reflex (BR)

The blink reflex (BR), used to indicate facial nerve integrity, is largely a pontine reflex resulting in momentary, bilateral eye closure (orbicularis oculi muscles) [119, 120]. A brief stimulus applied to the supraorbital branch of the trigeminal nerve results in an early ipsilateral oligosynaptic orbicularis oculi muscle action potential (R1-10 ms), and a later bilateral multisynaptic response (R2-20 ms) interfaces with the pontine reticular formation before synapsing in bilateral facial motor nuclei [120, 121]. In patients with sTBI or cerebrovascular lesions affecting the cerebral

cortex, basal ganglia, and deep cerebral regions, R2 is absent or suppressed in the early days after the insult [119, 122–125]. Perhaps the polysynaptic connections of R2 make this waveform of increased sensitivity to cephalad or mesodiencephalic reticular influences. A study in cats of increased ICP, which led to mesodiencephalic ischemia, was associated with the disappearance of R2 and preservation of R1 [126]. Although known to be suppressed by sleep and sedatives, the BR can now be recorded under general anesthesia [127–130]. Less-studied reflexes utilize the jaw jerk (masseteric reflex) believed to invoke the mesencephalic trigeminal nucleus and could have future clinical applications [120, 128].

Upper Extremity Short Latency Somatosensory Evoked Potentials (SSEP)

The SSEP provides an 'objective test for cortical reactivity to external stimulation—a measure of responsiveness to the outside world and *sine qua non* of consciousness' [97]. The upper extremity SSEP is derived secondary to median nerve stimulation in the upper extremity. The signal is recorded at the brachial plexus (Erb's point), carried in the ipsilateral posterior column, and a cervical electrode (N13) indicates spinal cord entry or the cervicomedullary region. After a synapse in the cuneatus nucleus, the tract crosses to become the contralateral medial lemniscus, which ascends the medulla, pons, and midbrain before a synapse in the ventroposterolateral nucleus of the thalamus with relay to the postcentral gyrus. Here, the major cortically generated peak is N20, recorded from the central regions of the scalp C3′ and C4′ (Fig. 2c) [99, 131–138].

SSEP responses are durable, and widely used in continuous intraoperative neurophysiological monitoring (IONM), where an N20 latency increase of 10 %, or 50 % diminished amplitude from the patient's presurgical baseline is considered a significant change and the surgical team notified [131, 132, 139, 140]. Recently, SSEPs have become very useful in the NCCU as an important prognostic indicator after cerebral anoxia. Bilateral absence of N20 after cardiac arrest is associated with persistent vegetative state or death in all patients [112, 113, 118, 138, 141–143]. In a meta-analysis, SSEP as a single prognostic marker of both good and bad outcomes after sTBI performed better than pupillary response, Glasgow Coma Scale, CT findings, and EEG [113]. Recent work suggests amplitude values of a preserved N20 and later cortical N35 peak may relate to outcome quality, further increasing prognostic accuracy [144].

Trigeminal Short Latency Somatosensory Evoked Potentials (TrSSEPs)

Of possible interest in regard to NCCU monitoring are the TrSSEPs [145, 146]. Electrical stimulation is applied to the lower lip, and scalp recording of a potential at 20 ms is obtained from positions just lateral to those used for upper extremity SSEPs (C5′, C6′) [147, 148]. A latency difference between sides of greater than 1 ms or diminished amplitude greater than 50 % is considered abnormal [149]. Having been used largely in the dental/maxillofacial fields under general anesthesia, TrSSEPs may prove of value in NCCU monitoring [148, 150].

Brainstem Auditory Evoked Potentials (BAEP)

The BAEP is a subcortical response generated by the cochlear and brainstem auditory pathways. Each ear is stimulated separately in response to moderately loud, short-duration click stimuli delivered thru soft insert earphones. The waveform response is recorded from the vertex (Cz) or frontal scalp (Fz) and generally appears within 10 ms after stimulation. Wave I—Auditory nerve, Wave III—Superior olivary nucleus (pons), and Waves V and Vn—Inferior colliculus (midbrain, tentorial incisura) are measured for their latency and amplitude [151–155]. This robust response is refractory to level of consciousness, medications, general anesthesia, or muscle paralyzing agents [98, 139, 152–155]. Like the SSEP, threshold abnormalities of the major peaks during IONM are a 10 % latency increase or 50 % amplitude decrease from baseline [131, 135, 139, 152, 154, 156]. Nurse-friendly neonatal hearing screening with rapid automated interpretation utilizing BAEP Wave V is at present extensively performed [152, 157].

BAEP studies in patients with herniation syndromes have shown correlations with ICP, pupillary changes, TTH, and outcome. Timely decompressive treatments in a number of these studies resulted in rapid clinical and electrophysiological improvement [115–117, 158–168].

Faster rates of BAEP stimulation worsen BAEP abnormalities, and modified forms of the BAEP (MBAEP) may increase the diagnostic utility of the test [98, 155, 169, 170]. Notable MBAEP changes were found in normal volunteers placed in a 10°–15° downward head position to simulate increased ICP [155] and patients symptomatic of mild to moderately increased ICP with mass effects and shifts from large, slow-growing cerebral SOLs (mostly tumors) [171, 172]. In the patients, significant MBAEP changes normalized when re-tested after surgical excision [171, 172].

Upper Extremity Motor Evoked Potentials (MEP)

Upper extremity MEPs are obtained during IONM in neurosurgical patients undergoing operations under general anesthesia, or on awake patients, in response to respective transcranial electrical (TcE-MEP) or transcranial magnetic (TcM-MEP) stimulation over the central regions (C3, C4) [173, 174]. Following such pyramidal/corticospinal tract stimulation, the signal is recorded from extremity muscles by needle or surface EMG. Although the responses are more variable than the sensory EPs, a 50 % or greater loss of amplitude is concerning [173–175]. In conscious patients, TcM-MEP has found much interest in clinical neurology to assess central motor pathways [176, 177]. TcM-MEP is delivered by a very well tolerated, locally applied cap-like coil MEP [176, 177]. Repetitive TcM-MEP techniques lead to intracortical motor facilitation and have improved the motor response [178–180].

Recent clinical reports on the Kernohan notch syndrome (Figs. 3, 4, 5) have included MEP studies on patients with cerebral mass lesions and TTH [181–190]. Upper extremity TcM-MEP was performed in a small group of patients with intracerebral hematomas, altered mental status, and pyramidal tract involvement [190]. The presence of any MEP response indicated a compressed but not destroyed pyramidal tract with propensity for recovery [190].

Herniation Research Using Multiple Modalities

A number of years ago our group studied anatomically confirmed TTH in the cat and monkey—indicated by sudden pupillary dilatation or midposition fixation—secondary to an expanding temporal extradural balloon. TTH in the cat over a 2-h period was monitored with ICP, BAEP, upper extremity SSEP, and in some MEP [191–193]. Cats showed significant BAEP/SSEP abnormalities from baseline, and the prominent warning sign just before TTH was a 30 % drop in BAEP Wave V amplitude. Complete Wave V flattening, caudal displacement of the inferior colliculus [191, 192], and a marked drop in inferior colliculus blood flow were tightly correlated with TTH [193]. A unilateral MEP loss was considered hemispheric compression, whereas bilateral MEP loss, especially if associated with significant changes in BAEP Wave V, heralded the beginning of TTH [194].

A 4-h primate model of TTH [195] was patterned after classic studies decades earlier [27, 28, 33]. Four hours was chosen to simulate the frequently encountered SOL, acute subdural hematoma with a similar delay allowing some compensatory mechanisms to occur [196]. Twelve macaque monkeys underwent gradual expansion of an extradural balloon, which at 10 % of brain volume led to the precipitous onset of bilaterally dilated or less often midposition fixed pupils (Fig. 6a, b) [195]. Two hours before TTH, a transient rise in ICP followed each inflation, as did systolic hypertension and bradycardia (Cushing reflex). ICP gave significant forewarning of TTH 1 h before (16 mm Hg, $p < 0.05$), one-half hour before (23 mmHg, $p < 0.01$), and at TBH (44 mm Hg, $p < 0.001$). Compared to ICP, Wave V of the BAEP gave an identically significant warning (25 % amplitude depression) 1 h before TTH, further Wave V amplitude depression being a more statistically significant warning than the ICP one-half hour before ($p < .001$), and a similarly significant severe Wave V flattening or loss at TTH ($p < .001$) [195]. Upper extremity SSEP showed depressed amplitude one-half hour before TTH ($p < .05$) and near loss or absence of SSEP at TTH ($p < .01$) [195].

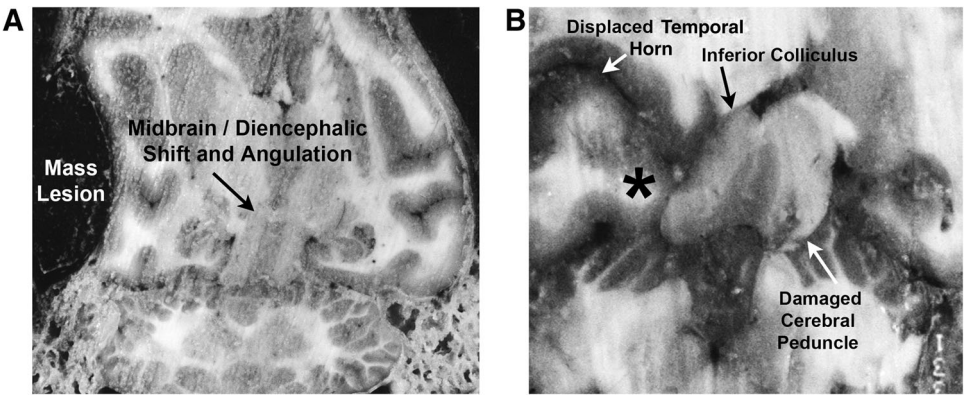

Fig. 6 **a** Frontal/coronal section of the non-human primate experimental TTH study depicting the right-sided (*balloon*) mass and its effect on the hemisphere at the time of TTH. Note the diencephalic/midbrain angulation. **b** Magnified view of the displaced temporal horn and herniated right temporal lobe (*asterisk*) at the time of TTH. Note the displaced inferior colliculus and damage to the contralateral cerebral peduncle. This overall appearance closely models the TTH situation in patients (adapted from Stone et al. 1990 with permission) [195]

The Future

Monitoring in the NCCU (SSEP, BAEP, TcM-MEP) must be nurse friendly, preferably continuous (or nearly so), with automation of threshold breaches (similar to those used in IONM) leading to alarms. Nurses, residents, fellows, or technicians are easily taught scalp surface electrode placement for stimulation and recording (International 10-20 system). Technical requirements such as adequate noninvasive afferent signal delivery, grounding, electrode impedance, artifact rejection, advanced filtering, and other concerns have much improved in recent decades [97, 109–111, 115].

Conclusion

This focused review of the neurocritical care and related literature has emphasized a number of shortcomings in our current ICP/neuroimaging-directed management of patients with an altered level of consciousness secondary to intracranial mass lesions. We elected to concentrate on noninvasive bedside electrophysiological monitoring tools that we believe could substantially improve patient management.

Data collected over decades on stuporous or comatose NCCU patients is highly supportive of the continuous monitoring of sensory and motor EPs, as well as the development of nurse-friendly, automated devices to monitor brain function. Structured clinical trials correlating neurophysiological changes in the early and later phases of TTH would appear to be a fertile field to investigate and develop. Improving the neurological and neurosurgical care of these challenging conditions by more timely recognition and intervention is of obvious importance, and technology to do so may well be at hand.

Acknowledgments This work is dedicated to Dr. Robert A. Moody, a modern pioneer in the aggressive approach to cerebral decompression and ICP monitoring. In 1975, Dr. Moody established an experimental brain herniation laboratory at Chicago's Cook County Hospital Hektoen Laboratory with the foresight to utilize the recently developed evoked potential responses. There, the senior author was stimulated to conduct experimental work. Special thanks to Dr. Jerome B. Posner of New York City, noted authority on 'Stupor and Coma' who graciously reviewed a draft of the manuscript, which he found of much interest, and met with the senior author to review the figures. We remain particularly grateful to Dr. John R. Hughes, our longtime mentor in clinical neurophysiology at the University of Illinois in Chicago (UIC). Dr. Gleb Gorelick, neuroradiologist at Advocate Illinois Masonic Hospital in Chicago assisted in interpretation of the MRI images, and Dr. Ankit Mehta, from the UIC Department of Neurosurgery, reviewed the manuscript and provided input. Finally, we thank our active clinical neurophysiology and intraoperative monitoring teams at both the UIC and Evanston/North Shore University Hospital for their continued enthusiasm and support.

Compliance with Ethical Standards

Conflict of interest James L. Stone: Natus/Biologic provided evoked potential instrumentation and some technical support of work presented in this review. Patent issued to inventor JLS on 01/12/2014 and assigned and owned by the University of Illinois. Title: NonInvasive, Bedside Intra-Cranial Pressure And Brain Shift/Herniation Monitoring Unit Utilizing Early OnSet Auditory Evoked Responses. A University of Illinois start-up cooperation (Remote Vital Monitoring) has been formed and is in the early stages of development. Outside funding has not been obtained. JLS has 53 % stock ownership in this corporation. John Fino: A University of Illinois start-up corporation (Remote Vital Monitoring) has been formed and is in the early stages of development. Outside funding has not been secured. JF is a minor shareholder (5 % stock) in this corporation. Julian E. Bailes, Ahmed N. Hassan, Brian Sindelar, and Vimal Patel declare that they have no conflict of interest.

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