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Original Research

Non-invasive optical brain pulse monitoring: Experience from the first 195 patients

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Abstract

Purpose: Optical brain pulse monitoring (OBPM: Cyban Pty. Ltd) is an innovative neuromonitoring technology using near-infrared light to identify cerebrovascular changes in patients at risk of both primary and secondary brain injury. This review collates patient demographic data and user knowledge from our experience operating the device in the clinical research setting.

Patients and methods: We performed a retrospective review of data from patients who received non-invasive OBPM between October 2020 and August 2024.

Results: Five clinical studies conducted at six global sites used OBPM on 195 patients without any device-related adverse events. OBPM was used successfully in a wide-range of clinical environments including the intensive care unit, interventional radiology, emergency room, and both preoperative and operating room environments. Data were collected from patients with brain injuries such as subarachnoid haemorrhage (N=44), traumatic brain injury (N=23), intraparenchymal haemorrhage (N=19), and ischemic stroke (N=22). OBPM was effectively used in patients undergoing surgical procedures such as open heart surgery (N=22), and carotid endarterectomy (N=11) as well as to continuously monitor post-surgical patients at risk of neurological injury. Furthermore, OBPM was effectively used concurrently with existing invasive and non-invasive neuromonitoring systems such as electroencephalography and bispectral index, demonstrating safe and effective real-time multimodal assessment strategy of cerebral function throughout a clinical care environment.

Conclusion: OBPM experience in 195 patients has been shown to deliver consistent results with an unblemished safety record. Data drawn from the OBPM may improve clinical decision-making and bring significant clinical and economic value to healthcare stakeholders.

Keywords: Photoplethysmography, Neuromonitoring, Multimodal assessment, Near-infrared light, Brain monitoring

Introduction

Continuous, non-invasive optical brain pulse monitoring (OBPM; Cyban Pty. Ltd., Melbourne, Australia) represents a significant advancement in the field of neurological monitoring. OBPM uses red and infrared light sources to capture cardiac and respiratory waves from brain pulse waveforms, which reflect changes in both brain oxygen levels and brain movement. To date, clinical research demonstrates unique waveforms produced by the OBPM are correlated with changes in intracranial pressure and cerebral oxygen saturation, and may offer insights into cerebrospinal fluid dynamics, brain compliance, and electrophysiological events such as spreading cortical depressions [1-4]. Waveforms generated through non-invasive, bilateral and continuous responses can inform clinicians on underlying neuropathological phenomena in real-time, leading to the early detection and informed intervention of neurological decline. Traditional non-invasive brain assessment methods, such as

clinical assessment, electroencephalography (EEG), transcranial doppler (TCD) and near-infrared spectroscopy (NIRS), frequently lack the sensitivity and continuity required for the timely detection of neurological deterioration [5-9]. The unique sensor geometry of the OBPM sensors preferentially detects the oscillation of blood volumes in the pial venules, producing a complex and feature rich signal modulated by changes in respiratory and cardiac pressure gradients (**Figure 1A**). Its application spans intensive care units (ICU), operating rooms (OR), interventional radiology (IR), the ward, pre-operative areas, and the emergency department (ED).

The primary objective of this review was to evaluate the safety and utility of the OBPM across different clinical environments. We provide a comprehensive analysis of patient demographics and clinical outcomes associated with the use of the device and assess the integration and compatibility of the OBPM with existing neuromonitoring systems. The specific operator techniques that have been developed to adapt to various use environments are reported.

Material and methods

Study design

This present review involved the collation and analysis of data related to the use of the OBPM in hospitalized patients. Data were sourced by two reviewers independently (E.T, S.P.) from internal databases that included data from all clinical studies conducted by Cyban Pty. Ltd. from October 2020 to August 2024. No web search was performed as all relevant data were internal. No risk of bias assessment was required as this analysis did not compare outcome measures.

Data extraction

In August, 2024, variables including: study, site, age, sex, diagnosis/procedure, clinical environment, days in hospital, survival status, and concurrent neuromonitoring were extracted from the trial master databases across five clinical studies conducted at six clinical sites (**Table 1**). Data extraction was finalized on August 30th, 2024. Additionally, some data collected from the free text section of the clinical study case report forms were reviewed alongside detailed operator notes to identify key information related to operator insights. This was summarised to assist future researchers in the design and conduct of clinical studies with the OBPM device.

Database analysis

Data collation was performed using Google sheets. Descriptive statistics and visualisation were performed using R studio Version 2024.04.0+735.

Results

Overview of patient demographics and clinical settings

The internal trial master database search resulted in the collation of data from 195 patients (**Table 1**). The majority of included patients were male (102), with a median age of 59 years, hospital length of stay (LOS) 11 d, and survival rate was 66%. There were no OBPM device-related adverse event reported in any of the 195 patients. Studies using OBPM included the Transcutaneous Pulse OximeTry Brain Monitoring (T-POT) study, the Brain Pulse Monitoring (BPM) study, and the Idiopathic Intracranial Hypertension (IIH) study and were conducted across sites in Australia, the TPOT-UK and the TPOT-US **(Table 1)**.

Table 1. Summary of the OBPM studies. This table summarizes the studies included in the review, detailing their progress, ethics approvals, and the total number of participants involved. The table lists each study's title, site of conduct, current progress status, institutional review board or ethics committee responsible for approval, corresponding ethics approval number, and the total number of participants enrolled.

Study	Site	Progress	Institutional Review Board	Ethics Number	Total number of participants
T-POT AUS	St Vincent's Hospital, Melbourne	In Progress	St Vincent's Hospital (Melbourne, Australia) Human Research Ethics Committee (HREC)	HREC 160/20	124
T-POT AUS	Alfred Hospital, Melbourne	In Progress	St Vincent's Hospital (Melbourne, Australia) Human Research Ethics Committee (HREC)	HREC 160/20	11
T-POT AUS	Royal Melbourne Hospital, Melbourne	In Progress	St Vincent's Hospital (Melbourne, Australia) Human Research Ethics Committee (HREC)	HREC 160/20	11
T-POT UK	NHS Lothian, Scotland	Early Closure	NHS Lothian R&D Office	2022/0163C	2
T-POT US	Cleveland Clinic, Ohio	In Progress	Cleveland Clinic IRB & Human Research Protections	IRB 22-1286	11
BPM	St Vincent's Hospital, Melbourne	In Progress	St Vincent's Hospital (Melbourne, Australia) Human Research Ethics Committee (HREC)	HREC 231/22	34
BPM	Grampians Health Ballarat, Australia	In Progress	St Vincent's Hospital (Melbourne, Australia) Human Research Ethics Committee (HREC)	HREC 231/22	1
IIH	St. Vincent's Hospital, Melbourne	Early Closure	St Vincent's Hospital (Melbourne, Australia) Human Research Ethics Committee (HREC)	HREC 022/22	1

Abbreviations: T-POT: The Transcutaneous Pulse OximeTry Brain Monitoring; BPM: Brain Pulse Monitoring; IIH: Idiopathic Intracranial Hypertension

Across these sites, the OBPM was undertaken in various clinical environments. These included the Intensive Care Unit (ICU) (n = 142), Interventional Radiology (IR) (n = 30), the Ward (n = 22), the Operating Room (OR) (n = 19), pre-operative areas (pre-OP) (n = 15) and Emergency Department (ED) (n = 6). One hundred and thirteen patients underwent OBPM episodes in multiple clinical settings, and this is reflected in the corresponding total count (n). Age, length of stay (LOS), survival rate, and total recording duration were reported for each clinical setting in **Table 2**. The individual recordings were variable in duration, ranging from 1M 14S to 1d 15H 37M 0S. A representative brain pulsatile waveform collated from these patients is depicted in **(Figure 1B)**.

At the time of monitoring, many patients were mechanically ventilated (n = 148). Some critically ill patients had undergone surgical interventions including decompressive craniectomy (n=11) and VA-ECMO (n=4). One patient underwent 3 episodes of cardiopulmonary resuscitation (CPR) and one patient underwent cardiac massage for approximately 10 minutes whilst undergoing OBPM. These procedures did not hinder the collection of OBPM data. **Table 3** details the frequency of recording episodes for patients who underwent these interventions. Further examination of these cohorts was undertaken with respect to their clinical environment and are described below.

Table 2. Demographic and Clinical Outcomes by Clinical Environment. This table presents the demographic and clinical outcomes of patients monitored with the OBPM across six clinical environments. The metrics include median age, length of stay (LOS), survival rate, and patient count. Median Age (Range): Indicates the median age of patients along with the range of ages in each clinical environment. Median LOS (Range): Represents the median length of stay in days, with the range of LOS for each environment. Survival Rate (%): The percentage of patients who survived in each clinical setting. Patient Count: The total number of patients monitored in each clinical environment.

Clinical Environment	Median Age (range)	Median LOS (range)	Survival rate (%)	Total duration (DD:HH:MM:SS)
ICU	58 (18-83)	19 (1-82)	69.4	36:12:28:28
IR	54 (19-86)	4 (0-55)	90.3	0:19:05:51
Ward	45 (21-88)	3 (0-24)	97.5	0:05:00:29
OR	68 (58-84)	5 (2-21)	84.2	2:12:10:33
Pre-OP	69 (60-84)	7 (2-21)	88.9	02:31:52
ED	69.5 (48-88)	3.5 (1-14)	83.3	0:2:33:28

Abbreviations: LOS: Length of Stay; ICU: Intensive Care Unit; IR: Interventional Radiology; OR: Operating Room; Pre-OP: Pre-Operative areas; ED: Emergency Department

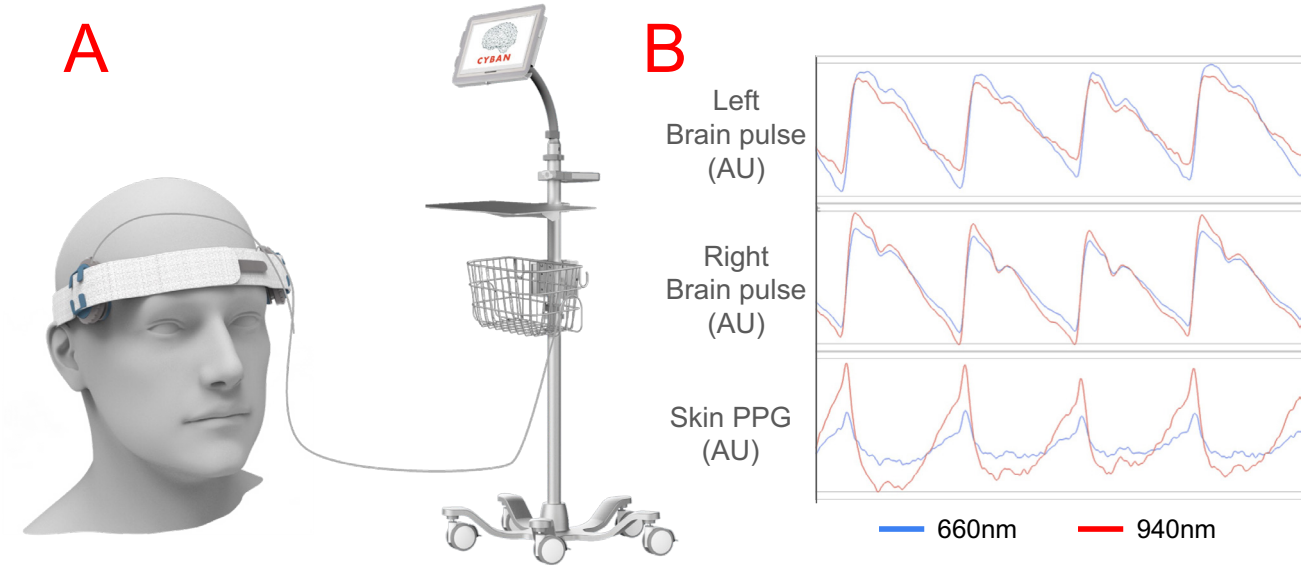

Figure 1. Cyban's optical brain pulse monitor (OBPM) and associated photoplethysmography output.

Table 3. Count of Monitoring Recordings for Patients Undergoing Serious Medical Interventions. This table presents the number of OBPM recordings made in patients who underwent medical interventions including VA-ECMO, craniectomy, ventilation and CPR.

Medical intervention	Count
VA-ECMO	11
Mechanical Ventilation	359
Craniectomy	37
CPR	3
Cardiac massage	1

Abbreviations: VA-ECMO: Venoarterial Extracorporeal Membrane Oxygenation; CPR: Cardiopulmonary Resuscitation

Intensive care unit (ICU)

OBPM data was collected in 144 patients in the ICU. Seven of these patients also underwent OBPM within the OR (n=11) or IR (n=12). The median age of ICU patients was 57 and their median LOS 20 d. These patients were predominantly male (62.1%), had the largest LOS range (1 - 82d), and the poorest survival rate (71.2%) of all clinical environments in this review. **Figure 2A** illustrates the OBPM in situ on an ICU patient with subarachnoid haemorrhage (SAH). This highlights the site of neuromonitoring in this setting and user navigation of obstacles such as an external ventricular drain (EVD), intubation, surgical dressings and long thick hair.

Frequencies of the primary diagnoses among patients in the ICU are reported in **(Figure 2B)**. Although many of these patients had multiple complex diagnoses, only the primary diagnosis is reflected. The highest frequency of diagnosis reported was for SAH (n=48), open heart surgery which encompasses coronary artery bypass graft, heart valve, and aortic root procedures (n=21), followed by traumatic brain injury (TBI; n=21) and intraparenchymal haemorrhage (IPH; n=14). Less frequently reported diagnoses included ischemic stroke (n=9) occurring in both the middle and anterior cerebral artery regions; anoxic/hypoxic brain injury (n=9) including both out-of-hospital cardiac arrests and out-of-hospital pulseless electrical activity arrest; and a variety of other diagnoses (n=25) including seizure, encephalitis, post neurosurgery, hydrocephalus, encephalitis.

Some patients in the ICU had OBPM performed concurrently with invasive methods, such as an EVD (n=59), CODMAN ICP monitor (n=33) or Licox brain oxygen monitoring probe (n=8). One patient also had a subdural drain in situ during OBPM. Another patient had an EEG monitoring episode alongside OBPM. A subset of these ICU patients was reported to use 2–3 of these neuromonitoring systems simultaneously with the OBPM (n=21). **Table 4** indicates the frequency of monitoring recordings for patients who were subject to existing neuromonitoring methods.

Over the course of the included studies, there were important device experiences encountered prompting solutions to maintain the integrity of the collected OBPM data. One significant learning was identification and management of respiratory artifacts generated by the oscillations of mechanical ventilators. This was addressed by ensuring the sensors were securely placed and that the cables were not under tension and positioned well clear of any moving objects, such as the bed. Another learning for the operator was positioning the device in patients with a craniectomy. While the headband

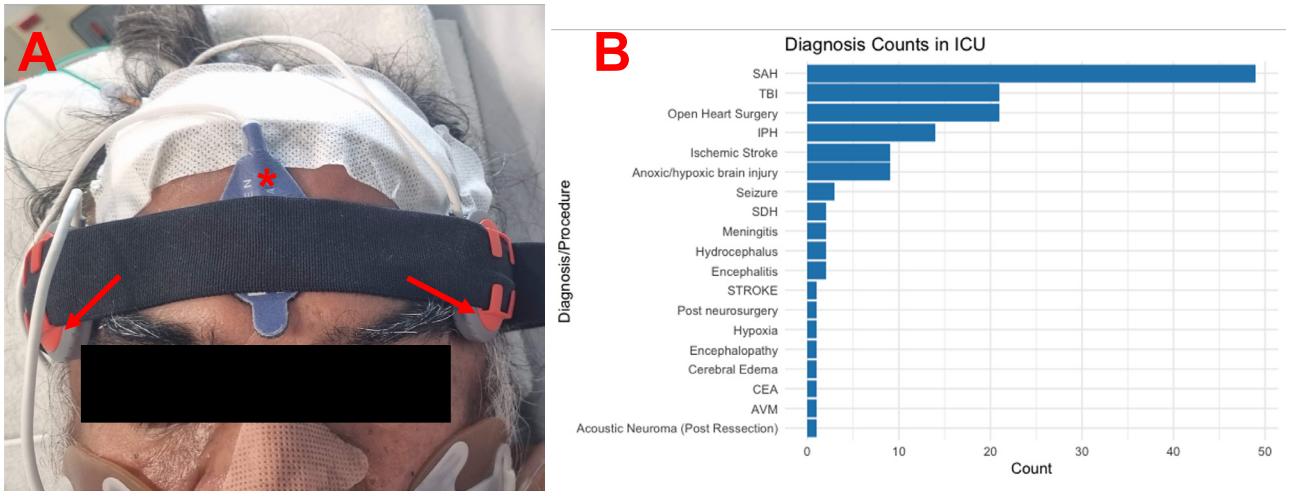

Figure 2. OBPM in the intensive care unit (ICU). **A)** Photograph of the OBPM sensors in situ indicated with the red arrows on a patient with subarachnoid haemorrhage. **B)** Indicates the counts for each diagnosis/procedure.

Table 4. Count of Monitoring Recordings for Patients Receiving Concurrent Invasive and/or Non-Invasive Neuromonitoring. This table displays the number of neuromonitoring methods undertaken simultaneously with the OBPM in patients. Invasive devices and methods include EVD, CODMAN, Licox, Lumbar drain and Subdural drain. Non-invasive include the BIS. Combinations of monitoring devices and interventions in the included patients are indicated under multimodal assessment.

Neuromonitoring method	Count
EVD	145
CODMAN	76
Lumbar Pressure	9
Licox	10
BIS	22
Subdural drain	2
Multimodal assessment	20
EVD, CODMAN	12
CODMAN, Licox	5
EVD, CODMAN, Licox	3

Abbreviations: EVD: External Ventricular Drain; BIS: Bispectral Index

could be placed over craniectomy without issue, positioning the sensor too close to the site often resulted in artefactual signals from the movement of the underlying tissue due to the absence of bone. Additionally, during patient repositioning, such as turning, there was a possibility of the sensors being pressed into the pillow or other surfaces. This not only affected signal quality but also introduced risk of a pressure injury. Any breakages in the skin were meticulously avoided to prevent contamination of both the sensors and the site. Careful attention to sensor placement, skin integrity, and secure cable management were critical in mitigating these issues and ensuring consistent, reliable data collection throughout the study.

Four patients received VA-ECMO in the ICU for cardiac support. Patients receiving ECMO are at high risk of neurological complications arising from the precipitant, such as cardiac arrest, or due to stroke risks associated with the circuit. OBPM was able of successfully identify these oscillations in all patients ECMO despite the low contribution of the heart to cardiac output.

Interventional radiology (IR)

Thirty patients underwent OBPM whilst undergoing treatment in IR. In this cohort, there was a skew towards female patients (67.7%), the median age was 54, and the survival rate (90.3%). Median LOS for IR patients was 4 d.

Reasons for enrolment of patients who were monitored in the IR are summarized in **Figure 3**. These included undergoing a CT-guided lumbar puncture for suspected idiopathic intracranial hypertension (IIH; n=15) and undergoing mechanical thrombectomy for the treatment of acute ischemic stroke (n=11). Four patients with SAH complicated by vasospasm, all of whom had an EVD in situ, were monitored during their spasmolysis treatment (n=4).

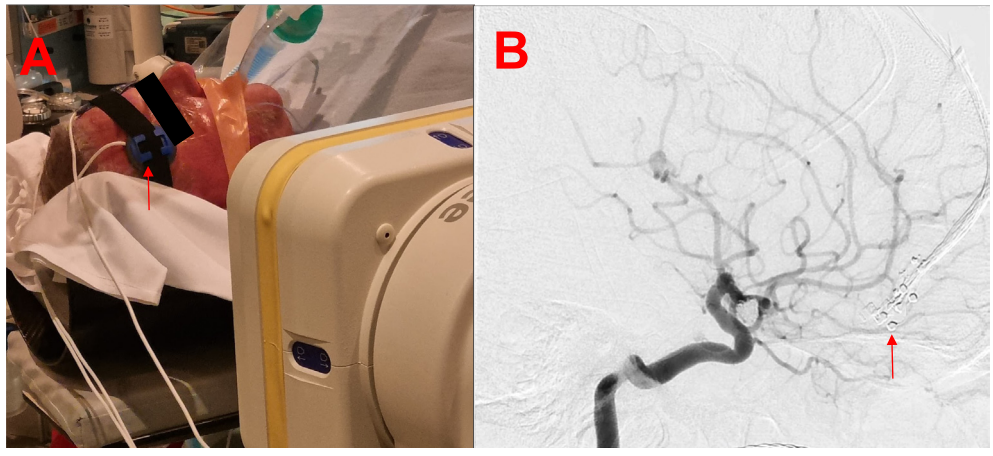

Figure 3. OBPM in interventional radiology (IR). **A)** Photograph of the OBPM sensors in situ indicated with the red arrows on a patient undergoing thrombectomy. **B)** Digital subtraction angiography image demonstrating sensor positioning (red arrow).

OBPM operators in this clinical environment reported challenges that were unique to coordinating with IR procedures, particularly during mechanical thrombectomy. Specifically, given that expediency in the IR is crucial, the window for applying the sensors without interference is highly limited. Once the patient's head is positioned within the frame used to secure and limit movement, the sensors must be deployed swiftly and efficiently to establish a suitable signal. Only then should the sensors be secured in place and the cables supported to prevent disturbance of the procedure. A key learning in these procedures was the risk of the cables becoming tangled or interfering with the robotic X-ray arm. Additionally, the weight of the sensor connectors was noted as a potential risk, as significant patient movement could dislodge the sensors. Lastly, although the sensors were radiolucent, which was highly advantageous in this imaging environment, it was vital to ensure that they were not positioned too posteriorly. Improper positioning could obscure visualisation of critical vascular structures such as the middle cerebral artery, the circle of Willis, and the internal carotid artery. These considerations were critical in ensuring the smooth integration of the OBPM system into the fast-paced environment of IR.

Further technical learnings were gained in the context of IR during CT-guided lumbar punctures, where patients were monitored both in the lateral and prone positions. When patients were positioned laterally, the lower sensor, typically on the right side, often became pressed into the pillow, disrupting the signal. Additionally, due to the painful nature of the procedure, patients frequently grimaced, which further affected sensor stability and signal integrity. Given these challenges, monitoring ICP during this procedure proved to be technically difficult. From an operator's perspective, it was found to be significantly more practical and less problematic to measure ICP pre- and post-operatively. Conducting these measurements under controlled conditions, with patients lying flat, offered a better cost-benefit ratio, provided more reliable data, and allowed for the control of blood pressure, an important factor that is not conventionally measured during intraprocedurally in this patient group.

Operating room (OR) and pre-operative setting (Pre-OP)

OBPM data was collected from 19 patients in the OR across two procedure groups, the first group undergoing carotid endarterectomy (CEA) (n=11), and the second undergoing open heart surgery (n=8) (**Figure 4**). The median age was 68, median LOS was 5 d and the survival rate was 84.2%. 78% of these OR patients were male. Within the OR cohort, 9 patients underwent a local anaesthetic only and 10 patients underwent a general anaesthetic with mechanical ventilation. Ten patients underwent concurrent Bispectral Index (BIS) monitoring throughout their surgical procedures.

Nine of the patients who underwent surgical procedures had OBPM data collected pre-operatively. This included 5 patients undergoing open heart surgery and 4 CEA patients. The median age of this patient subset was 69, LOS 7 d and survival rate 88.9%.

Contemporaneous cerebral oximetry was attempted in pre-op on one patient using an INVOS 7100. However, placing the INVOS 7100 in proximity to the OBPM caused high-frequency interference in the OBPM waveform signal, and the INVOS 7100 StO_2 value increased from approximately 71 to 85. Both device signals returned to baseline if the other was removed.

In cardiac surgery, the accurate and stable placement of sensors was a critical step that occurred in the pre-operative holding bay, following the placement of the central venous catheter. Sensors were positioned and secured before intubation, as intubation often involved significant head movement, which could compromise sensor placement if not properly secured. Some signal interference was also observed. The sensors detected vibrations from the sternotomy saw, as well as a very small artifact from the electrocautery machine. Cardiopulmonary bypass also significantly augmented the waveform, with distinct differences observed between pulsatile and non-pulsatile bypass, similar to the variations seen in arterial blood pressure. Despite these challenges, the OBPM sensors were defibrillator-safe, successfully withstanding several defibrillations during cardiac procedures without any compromise to their functionality or the quality of the signal beyond an isolated, abrupt increase in voltage.

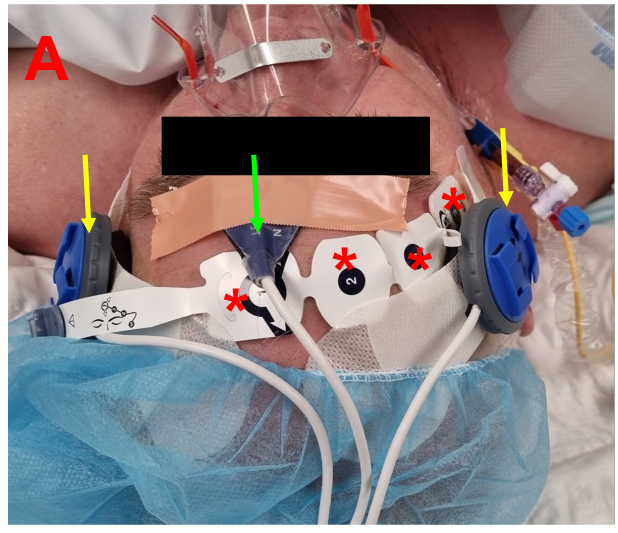

Figure 4. OBPM in the operating room (OR). **A)** Photograph of the OBPM sensors in situ indicated with the red arrows on a patient undergoing coronary artery bypass graft surgery. Yellow arrows indicate OBPM sensors. Green arrow indicates skin pulse oximeter. Asterisk indicates BIS monitor electrodes.

Additional operator considerations in the OR setting were acknowledged in CEA procedures. Firstly, it is essential to secure the sensors at the very beginning of the operation. Replacing the sensors once the procedure has commenced is technically challenging due to the limited motion allowed in the neck, which must remain still to maintain a stable operating field. Further, patients who are awake during the procedure often move or grimace, which can introduce significant motion artifacts that complicates interpretation of the signal, making it difficult to obtain accurate and reliable readings over long periods of time. Therefore, ensuring that the sensors are securely placed from the start is critical in minimizing these issues and maintaining the integrity of the monitoring process throughout the procedure.

Ward

OBPM episodes were undertaken on 22 patients in the ward. Of these patients, 7 had additional OBPM episodes collected at other clinical environments, including the ED (n=2), IR (n=3) and OR (n=2). Six out of the nine were female, with a median age of 45, LOS 3 d and 97.5% survival rate. Patients monitored in the ward had been diagnosed with IIH (n=1), ischemic stroke (n=9) or arteriovenous malformation (AVM) (n=1). Two patients had undergone CEA, and one open heart surgery. The IIH patient had a lumbar drain in situ during OBPM episodes.

OBPM in the ward setting was technically straightforward, with minimal challenges in patients who were conscious and cooperative. The cooperation of the patients facilitated operators in securing the sensors and maintaining stable readings. As a result, the data collected from these patients were often simple to interpret, providing clear and reliable results. This underscores the effectiveness of the monitoring system in a controlled environment where patients are compliant.

Emergency department (ED)

OBPM was undertaken in 6 patients whilst in the ED. All ED patients had been diagnosed with an acute ischemic stroke, the median age was 69.5, LOS was 3.5 d, and survival rate 83.3%. Two patients were undergoing thrombolysis treatment for stroke throughout the OBPM episode. In the emergency department, the OBPM proved to be technically challenging, largely due the patients being agitated or confused.

Discussion

This review showcases the application of the OBPM in 195 hospital patients. We report on the data derived from these patients, which spans five clinical studies across six global sites. Crucially, we identified no reports of device-related adverse events. As this review examined patients at heightened risk of primary or secondary brain injury, this indicates that implementation of OBPM is a safe strategy in the management of diagnosed and potential brain injuries. Examination of this cohort highlights that this device has been successfully used in six clinical environments, on patients admitted for a diverse range of diagnoses or procedures. Device-related technical considerations and recommendations specific to each environment were collated and reported in the interest of facilitating future clinical studies.

Clinical impact and utility

The interval proceeding an acute brain injury is critical as numerous pathomorphic processes can worsen or enlarge the neurological insult. Consequently, early detection of edema, hypoxia, ischemia, and seizures is vital to inform appropriate, timely therapeutic interventions; therefore preventing deleterious secondary injury and augmenting patient outcomes [9-11]. However, there is a deficit of suitable, non-invasive neuromonitoring techniques that provide continuous surveillance of these variables in neurocritical populations. The OBPM provides continuous, sensitive data from which essential pathophysiological information can be deduced in real-time. This capability aligns with the emphasis placed by clinical recommendations for bedside monitoring and promotes its utility in managing neurocritical patients.

Current clinical guidelines stress the importance of neuromonitoring to identify variations in key physiological parameters in the management of acute brain injury. The purpose of monitoring is to detect worsening prior to irreparable secondary injury, individualise patient care, monitor response to treatment and adverse effects, and to overall improve patient outcome and quality of life. There is a plethora of physiological processes that are relevant in neurocritical care, including ICP and CPP, cerebrovascular autoregulation, systemic and cerebral oxygenation, electrophysiology and metabolism [11,12]. More and more, multimodal assessment is being heralded as the optimal strategy in individualised precision medicine [9,10,12,13]. The OBPM represents a significant advancement in neuromonitoring technology by providing a brain pulse waveform, allowing for the inference of a range of physiological data continuously and in real-time. Preliminary work indicates that the device can provide information regarding cerebral vascular pressure gradients, cerebral oxygen saturation, cerebrospinal fluid dynamics, brain compliance, and electrophysiological occurrences like seizures and spreading cortical depressions [1-4]. Further, as this device is non-invasive, it presents a highly advantageous alternative in patients where the procurement of ICP and oxygenation data does not justify the risk of more invasive methods, increasing the pool of individuals who can be monitored. Thus, the device has the potential to identify key pathomorphic changes in many neurocritical individuals to complement, or, in place of, existing neuromonitoring techniques.

Safety and cost-benefit

No device-related adverse events were reported in the 195 patients who used the OBPM. The included studies comprised a cohort of individuals in highly critical condition, all with heightened risk for brain injury or surgical complication. Even implementation of non-invasive neuromonitoring methods increases risk to these patients by introducing additional personnel and potential physical interference with the injury site, catheters/drains, or procedures being undertaken in the IR or OR. The identification of no device-related adverse events in these studies can reassure clinicians that implementing this neuromonitoring device is safe and beneficial in the management of ongoing and possible brain injuries.

The OBPM has a clear advantage in safety relative to more invasive monitoring methods. ICP and partial pressure of brain tissue oxygenation ($PbtO_2$) monitors are the most common invasive techniques, and are widely used in combination in the management of severe, acute brain injury [9]. Both Invasive brain oxygen monitoring and invasive ICP monitoring is accompanied by risk for complications including infections and bleeding, and technical obstructions or failure; including plugging [11], misplaced transducers,

clots, and ventricular collapse caused by edema [14]. Reported ICP monitor-related adverse events are highly variable in meta-analysis, from 0 – 32% for CSF infections, and 0 – 41% for haemorrhage (although this typically has limited clinical significance) [15]. Risk of haemorrhage and difficulty with insertion is elevated in paediatric cases [16,17]. Frequency of EVD infections is also compounded by factors associated with neurocritical care patients. This includes the presence of additional systemic infections, extended duration of monitoring, SAH or intraventricular haemorrhage and skull fracture [16]. As a result, prior to the insertion of an ICP monitor physicians typically administer prophylactic antibiotics and assess coagulation status [15,18]. Intraparenchymal type monitors are less prone to these complications, however they lack sensitivity and measure only local pressure [17]. Further, invasive neuromonitoring lacks long-term utility, and is restricted to use in the critical care unit [8,19]. These shortcomings alongside the associated technical and economic difficulties preclude their use in all but the most severe cases [3]. Typically, ICP monitors are used in half of TBI incidence, and brain $pbtO_2$ probes in 10% [20]. Therefore, OBPM presents a suitable alternative in patients where the potential clinical insights do not sufficiently outweigh the risk of invasive neuromonitoring, allowing a more diverse range of medically compromised individuals across different parts of the hospital to be observed.

Use of the OBPM may furthermore lead to improved patient outcomes compared to reliance solely on traditional non-invasive monitoring methods. These techniques, including EEG, TCD and NIRS, frequently lack continuity and are technically challenging [5,9]; and neurological exams and imaging provide predominantly post-hoc information [9]. As the OBPM has the potential to provide sensitive, continuous, real-time data, this device may in future offer an improved cost-benefit ratio. Clinicians could use OBPM data to complement existing multi-modal technologies to gauge mechanism of injury, detect pathology earlier and improve patient outcomes. Currently, while there is evidence that the waveform derived from the OBPM is comparable with more invasive methods, this has been explicitly examined in limited number of patients [2]. Further studies are necessitated to validate its equivalency with existing neuromonitoring methods in a range of diagnoses prior to its implementation in isolation.

Integration with existing neuromonitoring systems

Typically, a single neuromonitoring device in isolation is insufficient to indicate the extent of underlying pathophysiological processes in acute brain injury. As such, emerging consensus in the literature advocates the employment of multimodal assessment strategies [5,9,10,12,13,21]. This involves the concurrent use of multiple complementary neuromonitoring methods to derive more information. The advantage of this approach is that it can integrate complex multidimensional physiological parameters and therefore guide individualized patient management [9,12]. Many acute brain injury patients characterised in this present review were indicated to use multiple invasive, and non-invasive neuromonitoring techniques to accurately and in real-time track variation in ICP, brain oxygenation, and sedation, therefore enhancing diagnostic accuracy. Similarly, although non-invasive tools cannot yet substitute invasive neuromonitoring, multimodal assessments provide essential physiologic data to inform clinical decisions. For instance, in a paediatric case of hypoxic brain ischemia, the detection of generalised periodic discharges via EEG, correlated with mean arterial blood pressure and unchanged neurologic exams collectively prompted the escalation of treatment with antiseizure medication [13]. The compatibility of the OBPM with concurrent neuromonitoring systems highlights its amenability to being bundled with other diagnostic/prognostic techniques to improve clinician decision making.

Technical considerations and performance in specific contexts

Several device-related technical considerations and issues were raised by operators over the course of these studies, and their notes reveal recommendations and limitations for deployment of the OBPM across the 6 clinical settings. Firstly, sources of disturbances to the waveform were identified through user experience. This included artifacts generated by oscillations in mechanical ventilators, or signal noise induced by the sternotomy saw, electrocautery machine or cardiopulmonary bypass. Ensuring the sensors are secured and that connecting cables are not obstructed will minimise this interference wherever feasible. Further, manual repositioning of the patient, movement of proximal exposed tissue in craniectomy patients and even facial expressions during a painful procedure were also indicated to result in signal disruptions. These reports corroborate an existing publication detailing how continuous OBPM recordings are distorted by mechanical disturbances, including shivering, swallowing, seizures, or contraction of the temple or other areas where the sensors sit [4]. Although these occurrences may briefly interfere with the signal, the stabilisation of the sensors with the adhesives and headband ensure that the device will promptly resume functioning.

These reports additionally emphasize the importance of swiftly, accurately and securely positioning the sensors and cables in order to efficiently integrate the OBPM with IR procedures, including mechanical thrombectomy. Inadequate stabilisation of the OBPM sensors and attached cables may not only result in loss of quality signal, but it may also physically impede operations of the IR equipment. Further, pre-operative placement was repeatedly indicated, as adjustment during certain procedures was not possible once underway. Longer recording durations furthermore have the benefit of collecting more data, to minimise effects associated with unavoidable motion artifacts.

Overall, use of the OBPM in the ward for short recordings (less than 30 minutes) was revealed by operators to be the most efficient, as many patients were conscious and cooperative, leading to swift OPBM installation and good signal quality. This indicates that patients in the Ward represent a favourable niche for future studies collecting short duration monitoring data with minimal technical limitations. On the other hand, the disorderly and frantic environment innate to the ED hindered the operators in integrating the OBPM stably in these patients.

Moreover, certain technical challenges have been identified that limit its use in specific scenarios. Firstly, the sensors cannot be placed over a skin or bone trauma, or over a wound dressing. This may exclude some TBI patients, however the flexibility in sensor placement makes alternative placement of sensors possible. Secondly, given that the OBPM utilizes NIR technology, it cannot be used in direct proximity with another NIR device. This limitation was observed in one patient in the OR. Contemporaneous cerebral oximetry was attempted simultaneously with the OBPM, resulting

in an interference in frequency and StO_2 recording. This was resolved when one device was used in isolation. Therefore, the OBPM should be applied in the absence of NIRS. Lastly, the assorted technical difficulties raised during CT-guided lumbar puncture caused by patient positioning and movement indicate that this may be one procedure in which OPBM data collection is not feasible. These technical considerations will inform future troubleshooting and improve future researcher design and conduct of clinical studies utilising the OBPM.

Economic considerations

The OBPM serves as an example of a cost-effective neuromonitoring technique. It can be deployed quickly, does not require complex training of staff and does not require regular monitoring to detect adverse safety effects. Although the skin requires checking every 8 hours, this interruption is minimally impactful on the signal. In fact, one recording session collected from an ICU patient had a duration over 1d 15 h, highlighting its long-term use. When used prophylactically this would save hospitals substantially in in staff hours and resources. Further, OBPM data can provide physiologic assessment of patients admitted for medium risk procedures/diagnoses to effectively detect the occurrence of secondary injury, potentially reducing the risk of complications, and shortening hospital LOS. Preliminary cost-consequence modelling of continuous OBPM in middle cerebral artery infarct patients reveals a significant economic benefit compared with standard care. This monitoring could hypothetically facilitate early detection of indications for decompressive hemicraniectomy, saving 220,000 USD annually. In doing so, this will reduce hospital LOS and unnecessary procedures, whilst increasing prophylactic interventions to reduce secondary or long-term injury [22].

Conclusion

This analysis illustrates the breadth of clinicopathological contexts in which the OBPM has been deployed, emphasizing its safety and versatility in a wide variety of neurocritical patients. Successful recording episodes were obtained from patients in the ICU, IR, OR, Pre-OP, ward and ED spanning five clinical studies and six global hospital sites. No device-related adverse events were reported in any patient, highlighting the suitability of this device even in highly compromised patients. OBPM was also undertaken in patients who were already being evaluated via invasive and non-invasive neuromonitoring methods, indicating synergy, with the exception of a NIRS device. Technical factors and challenges associated with the device's use were reported to aid future research applications. The OBPM offers substantial clinical and economic value to healthcare stakeholders, by providing real-time multifaceted physiological information to improve prognostic and diagnostic patient management.

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Disclosure

B.D. is the founder and Chief Scientific Officer of Cyban, Pty Ltd and reports grants and personal fees from Cyban, during the conduct of the study; In addition, B.D. has patents US9717446B2 and WO2008134813A1 issued to Cyban. E.J.T. is a shareholder of Cyban Pty. Ltd. EJT and S.P. are paid employees of Cyban. F.I was under contract at the time of conducting the research.

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