Brain and Spine 4 (2024) 102859

Contents lists available at ScienceDirect

Brain and Spine

journal homepage: www.journals.elsevier.com/brain-and-spine

A clinical evaluation of variation in paediatric intracranial pressure waveforms

Amarah Saeed [a,*], Richard Boulton [b], Roddy O'Kane [c], Martin Shaw [b], Laura Moss [b]

[a] School of Medicine, University of Glasgow, Scotland, United Kingdom
[b] Department of Clinical Physics and Bioengineering, NHS Greater Glasgow and Clyde, Scotland, United Kingdom
[c] Royal Hospital for Children & Institute of Neurological Sciences, 1345 Govan Road, Glasgow, Scotland, United Kingdom

ARTICLE INFO

Handling Editor: Dr W Peul

Keywords:
Intracranial pressure
Intracranial pressure monitoring
Paediatric intracranial pressure waveforms
Paediatric hydrocephalus
Paediatric craniosynostosis
Plateau waves

ABSTRACT

Introduction: Intracranial pressure (ICP) monitoring is commonly used in investigating the aetiology of chronic paediatric neurological conditions. A series of high-amplitude spikes has been observed in overnight ICP recordings of some children, many of whom have hydrocephalus or craniosynostosis.
Research question: This clinical evaluation aimed to define the spike pattern, describe the patient group in which it is most likely to occur, and conduct high-resolution waveform analysis.
Material and methods: ICP waveforms from 40 patients aged 0–5 years (inclusive), recorded between 2017 and 2021 at the Royal Hospital for Children Glasgow, were retrospectively analysed. The pattern was defined through visual inspection of regions of interest by two reviewers. Patients were stratified using demographic and clinical data. R software was used to perform regression and high-resolution waveform analyses.
Results: The spike pattern was defined as the presence of 2 consecutive spikes with an amplitude of at least 8 mmHg, with a gap of at least 30 min between spikes. In the adjusted Poisson regression, age was significantly associated with the number of spikes (IRR 0.8, 95% CI 0.70 to 0.92, p-value 0.001).
Discussion and conclusion: Younger age was significantly associated with an increased number of spikes in this cohort. Investigation of clinical consequences of the spikes is warranted.

1. Introduction

1.1. Background

Raised ICP in children can have serious neurological complications (Dunn, 2002; Raboel et al., 2012; Tamburrini et al., 2005). There is a lack of consensus over interpretation of ICP values and waveform changes in paediatric hydrocephalus and craniosynostosis. A higher average/baseline ICP may be accepted as normal, however this value is not a representative depiction of the data and does not account for postural changes, such as the increase in ICP upon lying flat. Identification of Lundberg A ('plateau') and B waves, originally described in adults, facilitates advanced analysis, but universal definitions and clinical significance are not established (Raboel et al., 2012; Tamburrini et al., 2005; Sæhle and Eide, 2015; Eide et al., 2002; Renier et al., 1982).

ICP increases during sleep, hypothesised to be associated with cerebral vasodilation due to increased cerebral metabolic rate, particularly during the rapid eye movement (REM) stage of sleep (Barritault et al., 1980; Cooper & Hulme, 1966; Raboel et al., 2012). Obstructive sleep apnoea (which is common in syndromic craniosynostosis) may further contribute to this phenomenon, possibly due to hypercapnia (Raboel et al., 2012; Driessen et al., 2013; Hanigan and Zallek, 2004). The percentage of sleep spent in the REM stage decreases with age (Pierre-Kahn et al., 1976).

Interventions used in hydrocephalus and craniosynostosis can be highly invasive - these structural deformations can also lead to altered ICP. Surgical techniques such as modified (open) strip craniectomy have been associated with postoperative raised ICP (though confounded by age, due to its role in determining procedure) (Thomas et al., 2015). Postoperative raised ICP is also established in syndromic craniosynostosis (Tamburrini et al., 2005; Thomas et al., 2015; Christian et al., 2015; Langvatn et al., 2019; Zipfel et al., 2020).

* Corresponding author. School of Medicine, University of Glasgow, G12. 8QQ, United Kingdom.
E-mail addresses: amarahsaeed838@gmail.com (A. Saeed), Richard.Boulton@ggc.scot.nhs.uk (R. Boulton), roddy.o'kane@ggc.scot.nhs.uk (R. O'Kane), Martin.Shaw@ggc.scot.nhs.uk (M. Shaw), Laura.Moss@glasgow.ac.uk (L. Moss).

https://doi.org/10.1016/j.bas.2024.102859
Received 14 June 2023; Received in revised form 16 May 2024; Accepted 3 July 2024
Available online 4 July 2024

1.2. Current study and aims

A series of high amplitude, low frequency ICP spikes, forming a 'comb-like' pattern have been observed in some overnight paediatric ICP recordings at the study site, including many children with hydrocephalus or craniosynostosis. There is currently no clear interpretation of this pattern and its clinical significance.

Previous examples of this pattern identified in the literature are scarce: a 1976 case series where regular, steep-rising waves of raised ICP related to REM sleep were reported in some children with arrested/slowly progressive hydrocephalus (Pierre-Kahn et al., 1976); a 1982 case series of children with craniosynostosis where waves of increased ICP were recorded during REM sleep (and reduced postoperatively) (Renier et al., 1982); and a 2017 case report of a girl with syndromic craniosynostosis whose ICP spiked during REM sleep in association with oxygen desaturations, which improved postoperatively (Reddy and Amos, 2017).

This clinical evaluation was conducted in two parts. Part one aims were: 1) to define the spike pattern observed in ICP traces from a cohort of paediatric patients, and 2) to describe the group of patients where this pattern is more likely to occur. Part two expanded on the initial study through comprehensive high-resolution waveform analysis. Aims were: 1) to organise and automate import classification of peaks and troughs of high frequency waveform data; and 2) to summarise (per spike and per spike train) key characteristics of the waveforms, including timepoints, averages and frequency.

2. Materials and methods

2.1. Ethics

Local Caldicott Guardian (data protection) approval was obtained.

2.2. Study design and participants

A retrospective dataset of 40 ICP recordings from 40 patients aged between 0 and 5 years (inclusive) at the Royal Hospital for Children Glasgow, recorded between April 2017 and May 2021, was used. These patients were ambulatory and had been admitted overnight for ICP monitoring due to clinical indication. Recordings were made using single-use Raumedic probes (Measurement of ICP) and either of the two Spiegelberg monitors available at the study site (ICP Monitors Hamburg), with an appropriate adapter used. No interventions were carried out during monitoring. ICP is measured solely in millimetres of mercury (mmHg) at the study site – note the conversion to centimetres of water (cmH_2O) is 1 mmHg = 1.36 cmH_2O if required (Heiferman et al., 2019).

Data collection was conducted in two stages: clinical data and waveform data. Firstly, electronic patient records were reviewed alongside an expert paediatric neurosurgeon (ROK) to extract relevant demographic information and categorise patients according to their clinical history. Data collection was extensive with regards to presenting complaint; details of investigations and procedures prior to ICP monitoring (however pre- and post-operative recording is not routinely undertaken at the study site); as well as diagnostic classifications (including sutural involvement and presence/type of genetic syndrome in craniosynostosis; cause of hydrocephalus; or alternative diagnosis). Due to heterogeneity and power concerns, it was decided that present analysis would focus on initial broad categories: whether craniosynostosis was present or absent, and the number of procedures rather than the type.

Secondly, waveform data was analysed alongside an expert clinical physicist (RB). Elements of the spike pattern that were considered important to quantify a priori were the amplitude and time between spikes, to distinguish the pattern from minor baseline changes and improve certainty that this was not artefact. A small number of traces were initially inspected to quantify variation in ICP amplitude. Minimums were set to capture this variation whilst establishing a baseline difference from normal ICP fluctuations. Once parameters were agreed upon, regions of interest were visually identified and patients were stratified according to whether the spikes were present, as agreed by two reviewers (AS & RB). Duration of the 'spike train', number of spikes, and average spike amplitude were recorded (Clifford, 2002).

2.3. Statistical analysis

Statistical analysis and feature engineering were conducted using R software (version 4.1.3) (The R Project).

Unadjusted logistic and Poisson regressions were conducted to examine the relationship between variables and the incidence and number of spikes respectively. An initial significance threshold of 0.1 was used. Significant parameters were considered for collinearity, then carried forward to an adjusted Poisson regression, with a significance threshold of 0.05.

Regions of interest (spike trains) were visually identified on waveform files. Start and end timepoints, start and end ICP values and the number of spikes in each train were extracted. A set of automated scripts were created to process the high-frequency raw ICP data (40 Hz data recorded over approximately 2 days, averaging 8 million data points), into higher resolution plots that could be analysed and summarised. Plots were generated for the entire spike train, then 5-s segments from the start and peak of the trains were extracted. Summary characteristics were generated for each spike in a train (mean/maximum/increase in ICP and spike duration) and filtered to remove outliers. Properties of these filtered spikes were then summarised for each spike train (global mean/maximum/increase in ICP, number of spikes, spike frequency and global spike duration).

3. Results

The spike pattern was defined as the presence of 2 consecutive spikes of at least 8 mmHg, with a gap of at least 30 min between spikes.

Presenting complaints were categorised as: Headache, Visual Difficulties, Respiratory Compromise, Cosmetic, Developmental Delay, Macrocephaly, Vomiting, or Other (e.g. lethargy, irritability). Patients could be labelled with more than one presenting complaint – Headache, Cosmetic and Other were most common.

Patient characteristics are shown in Table 1. The median age was 2.33 years, and the sample was predominantly female (70%). Overall,

Table 1
Patient characteristics.

Characteristic	Overall, N = 40[a]	No Spikes, N = 14[a]	Spikes Present, N = 26[a]	p-value[b]
Age (Years)	2.33 (1.50, 3.67)	2.62 (2.23, 4.73)	1.92 (1.50, 3.27)	0.14
Sex (Male)	12 (30%)	6 (43%)	6 (23%)	0.3
Number of Procedures Before ICP				0.8
0	22 (55%)	8 (57%)	14 (54%)	
1	9 (22%)	2 (14%)	7 (27%)	
2	7 (18%)	3 (21%)	4 (15%)	
3	2 (5.0%)	1 (7.1%)	1 (3.8%)	
Diagnosis				0.2
Craniosynostosis	16 (40%)	4 (29%)	12 (46%)	
Hydrocephalus	18 (45%)	9 (64%)	9 (35%)	
Alternative Diagnosis	6 (15%)	1 (7%)	5 (19%)	
Median ICP (mmHg)[c]	12 (8, 15)	9 (7, 12)	13 (10, 16)	0.026
Maximum ICP (mmHg)[c]	37 (30, 51)	30 (26, 32)	40 (34, 53)	0.006

[a] Median (IQR); n (%).
[b] Wilcoxon rank sum test; Fisher's exact test; Pearson's Chi-squared test.
[c] 38 patients were included in this analysis instead of 40, due to perceived inadequacy of recording duration.

16 patients had craniosynostosis, 18 had hydrocephalus and 6 had an alternative diagnosis. Spikes were present in 26 patients. Baseline characteristics were relatively similar between the spikes and no spikes cohort, although the spikes cohort had a significantly higher median and maximum ICP (calculated from the mean ICP values from each patient) than the no spikes cohort. These median and maximum values were calculated from 38 patients instead of all 40, as two patients (both of whom did not have the spikes present) were deemed to have an inadequate duration of recording (less than 12 h). The pattern was observed on both monitoring systems.

Table 2 displays further details of the diagnoses. Of the 16 craniosynostosis patients, 8 of these had multisuture craniosynostosis, including 5 with syndromic craniosynostosis (not all patients with craniosynostosis involving multiple sutures had been diagnosed with a genetic syndrome). 12 of the 18 hydrocephalus patients had a malformation-related aetiology, with 5 acquired and 1 other.

As shown in Table 3 (based on the median of the mean ICP values), ICP recording lengths were variable, but all recordings were at least 12 h long, with most recordings over 24 h long. When spikes were present, the median duration of the pattern was 7 h with 7 spikes present, and the average amplitude of a spike was 19 mmHg.

Variables included in regression analysis were age; sex; presence and number of procedures before ICP monitoring; presence of craniosynostosis, including multisuture/single-suture involvement and syndromic/non-syndromic. In the logistic regressions (Table 4), no parameters were significantly associated with presence of spikes. In the unadjusted Poisson regressions (Table 5), age, craniosynostosis, multisuture craniosynostosis (compared to no craniosynostosis) and syndromic craniosynostosis (compared to no craniosynostosis) were significantly associated with the number of spikes. When considering significant unadjusted parameters for collinearity, it was decided that age would be included in the adjusted model; as well as multisuture craniosynostosis, because all patients with multisuture craniosynostosis were included in both the 'craniosynostosis' and 'syndromic craniosynostosis' categories for this cohort. In the adjusted Poisson regression containing age and multisuture craniosynostosis (Table 5, Fig. 1), only age was significantly associated with the number of spikes (IRR 0.80, 95% CI 0.70 to 0.92, p-value 0.001).

As this spike train could be present more than once in a night, or because more than one night's worth of recordings was available for some patients, there was a total of 38 spike trains available for analysis. This further analysis utilised the high-frequency raw ICP data, as opposed to mean ICP. Values below −10 mmHg and above 100 mmHg were filtered out to remove artefact. Outputs for one patient ('Patient A'), representative of the spike pattern identified and plots generated for the cohort, are shown in Fig. 2. A 'per spike' summary table for this spike train is available in Supplement 1. Analysis showed that Patient A's spike train lasted 7.8 h during which there were 9 spikes, with one spike lasting 52 min on average. The spike frequency was 0.00032 Hz. The mean ICP was 27.98 mmHg, the maximum ICP was 77.80 mmHg, and the mean ICP rise (increase in amplitude from average) for a spike was 56.44 mmHg.

Table 2
Diagnostic information.

Characteristic	Overall, N = 40[a]	No Spikes, N = 14[a]	Spikes Present, N = 26[a]	p-value[b]
Craniosynostosis	16 (40%)	4 (29%)	12 (46%)	0.3
Multisuture Craniosynostosis (vs Single Suture Craniosynostosis)[c]	8/16 (50%)	1 (25%)	7 (58%)	0.6
Syndromic Craniosynostosis (vs Non-Syndromic Craniosynostosis)[c]	5/16 (31%)	0 (0%)	5 (42%)	0.2
Hydrocephalus	18 (45%)	9 (64%)	9 (35%)	>0.9
Acquired	5/18 (28%)	3 (33%)	2 (22%)	
Malformation	12/18 (67%)	6 (67%)	6 (67%)	
Other	1/18 (6%)	0 (0%)	1 (11%)	
Alternative Diagnosis	6 (25%)	1 (10%)	5 (36%)	0.3

[a] Median (IQR); n (%).
[b] Wilcoxon rank sum test; Fisher's exact test; Pearson's Chi-squared test.
[c] 8 of the 16 patients with craniosynostosis had multiple suture involvement (multisuture craniosynostosis); 5 of these patients had been diagnosed with an associated genetic syndrome (syndromic craniosynostosis).

Table 3
Outcomes (spikes).

Characteristic	Overall, N = 26[a]	No Craniosynostosis, N = 14[a]	Craniosynostosis, N = 12[a]
Recording Length (Hours)			
12-24	3 (12%)	0 (0%)	3 (25%)
≥24	23 (88%)	14 (100%)	9 (75%)
Duration of Spikes (Hours)	7.0 (5.3, 8.0)	7.0 (6.0, 7.8)	6.5 (4.8, 9.0)
Number Of Spikes	6.5 (5.0, 8.0)	6.0 (5.0, 7.8)	7.5 (5.0, 8.0)
Average Amplitude (mmHg)	19.0 (13.2, 20.0)	19.0 (18.0, 20.0)	17.5 (13.0, 21.2)

[a] n (%); Median (IQR).

Table 4
Unadjusted logistic regression models (incidence of spikes).

Characteristic	OR[a]	95% CI[a]	p-value
Age (Years)	0.67	0.40, 1.06	0.10
Sex	0.40	0.10, 1.62	0.2
Zero Procedures Before ICP	0.88	0.23, 3.24	0.8
Number of Procedures Before ICP	0.90	0.44, 1.85	0.8
Craniosynostosis	2.14	0.56, 9.47	0.3
Multisuture Craniosynostosis			
Single Suture	1.19	0.23, 6.91	0.8
Multisuture	5.00	0.72, 101	0.2

[a] OR = Odds Ratio, CI = Confidence Interval.

Table 5
Poisson regression models (number of spikes).

Characteristic	Unadjusted IRR[a] (95% CI[a])	*p-value*	Adjusted IRR[1] (95% CI[a])	*p-value*
Age (Years)	0.79 (0.70, 0.89)	<0.001	0.80 (0.70, 0.92)	0.001
Sex	0.75 (0.52, 1.06)	0.11	–	-
Zero Procedures Before ICP	0.94 (0.70, 1.28)	0.70	–	-
Number of Procedures Before ICP	0.94 (0.79, 1.11)	0.50	–	-
Craniosynostosis	1.43 (1.06, 1.94)	0.02	–	-
Multisuture Craniosynostosis				
Single Suture	0.98 (0.63, 1.48)	>0.90	0.75 (0.47, 1.16)	0.20
Multisuture	1.88 (1.33, 2.64)	<0.001	1.42 (0.98, 2.07)	0.06
Syndromic Craniosynostosis				
Non-Syndromic	1.14 (0.79, 1.63)	0.50	–	-
Syndromic	2.07 (1.39, 3.01)	<0.001	–	-

[a] IRR = Incidence Rate Ratio, CI = Confidence Interval.

4. Discussion

As mentioned, average ICP is not representative of the data. Whilst median and maximum ICP are significantly raised in the spikes cohort as shown in Table 1, these values are based on the mean ICP of each patient therefore this difference is likely due to the cumulative increased

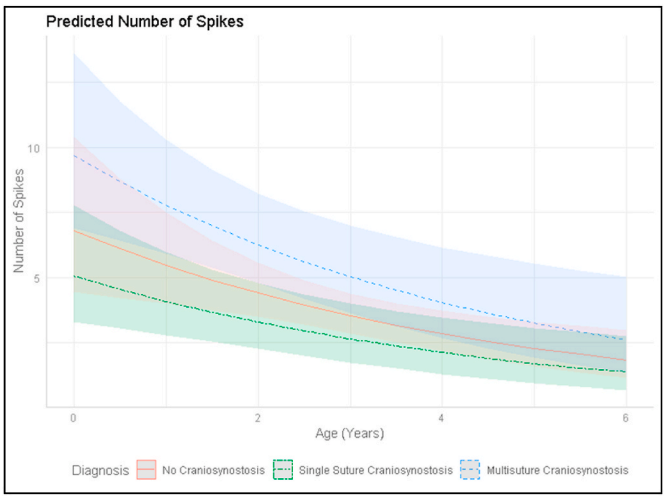

Fig. 1. Effect of Age and Multisuture Craniosynostosis on Number of Spikes (Adjusted Poisson Regression) [Generated using R software]
Plot illustrating the adjusted Poisson regression model for the predicted number of spikes in children aged 0–6 years with no craniosynostosis, single suture craniosynostosis and multisuture craniosynostosis.

amplitude of the spikes themselves. That the ICP reached these increased values in children then resolved without intervention, with no apparent initial harm, is interesting.

Presence of craniosynostosis was not significantly associated with the incidence or number of spikes. Whilst age was not significantly associated with the incidence of the spike pattern, the adjusted Poisson model showed that a one-year increase in age was associated with a 20% (95% CI 8–30%) decrease in the number of spikes when present.

The spikes all occurred overnight, presumed to be during sleep based on nursing notes, ICP changes by posture and the reduced variability in ICP, however ideally polysomnography would have aided confirmation of this. The elevated baseline ICP demonstrated throughout Patient A's trace (Fig. 2a) is likely partially explained by them lying flat/sleeping. The underlying cause of the spikes (Fig. 2b) remains unknown. Fig. 2c and Fig. 2d demonstrate reduction in intracranial compliance from the start to peak of the spike train. All aforementioned case reports hypothesised that the spikes were related to "increased vasogenic dynamics" during REM sleep (Pierre-Kahn et al., 1976), with suggested contributing factors including increased blood flow/volume, related to hypercapnia. Altered cranial structure and pressure dynamics in craniosynostosis were posited to increase susceptibility to the spikes, for example because the venous system is maximally compressed thus unable to offset an increase in the other intracranial compartments (Renier et al., 1982). It was suggested that as hydrocephalus and craniosynostosis involve reduced space for the cerebral parenchyma, the spikes may indicate a 'diminution' of intracranial compliance (Reddy and Amos, 2017). Given the importance of REM sleep in these hypotheses, and the relationship of age with REM sleep, future ICP monitoring at the study site could involve simultaneous polysomnography where possible.

The spikes identified are comparable in some respects to Lundberg A (plateau) waves, however there are differences to be noted. The spike pattern morphology is 'comb-like' where the amplitude fluctuates sharply, and has only been observed overnight, with no immediate sequelae or associated symptoms identified. In comparison, A waves are noted to have a 'plateau' shape where ICP remains elevated, are often symptomatic, indicate poor prognosis, and not exclusively linked to occurring overnight (Lundberg, 1960). The presence of these spikes in children is notable compared to A waves which have scarcely been documented in paediatric cohorts.

The study has notable strengths. Firstly, the dataset was comprehensive, minimising the risk of selection bias. All recordings took place at the same site with the same devices. Waveform analysis was detailed and objective.

This was a simple pilot study. The population of interest is rare and heterogeneous, with no available reference cohort. All clinical data and waveform data was reviewed in the same manner by the same contributors respectively, including relevant experts. Three patients with the spikes had ICP recording for over 12 but less than 24 h. Ideally all patients would have recording for at least 24 h, however this reflects the practicalities of performing invasive monitoring in a paediatric cohort and it was felt that inclusion of the data was warranted. The process of defining the pattern was a pragmatic decision based on clinical data, but given the role of clinical subjectivity there is potential for observer bias. An alternative method for consensus of baseline characteristics may have provided a more objective definition. Data collection was extensive, but analysis ultimately limited due to power concerns. This early-phase work cannot yet directly inform patient management.

There is scope for expanding on this preliminary work - namely comparing the high-resolution waveform summaries in conjunction with clinical data; and inclusion of a larger dataset, such as older children and multicentre involvement, to boost power and analysis opportunities and discern the upper age range in which the spikes occur. This work does not definitively demonstrate whether this pattern could be categorised as Lundberg A (plateau) waves, therefore further investigation would be required to delineate this. Analysis of repeat measures data where available could provide insight into how intervention may affect the ICP waveform. Hypothesis-generating research as to the causation and clinical consequences of these spikes is warranted, including whether intervention is necessary in their presence, to ultimately guide patient care.

4.1. Conclusions

In summary, an interesting pattern of high-amplitude, low-frequency, comb-like ICP spikes has been identified in some children aged 0–5 years (inclusive), presumed to occur during sleep. There is an inverse association between age and the number of spikes in this cohort. Waveform morphology differs at the start and peak of this pattern. This pilot study provides novel contribution to a limited knowledge base and a basis for further research, including investigation of clinical outcomes associated with presence of the spikes to aid in establishing their clinical significance. Providing context to the presence of this pattern in some neurological conditions would improve the clinical utility of perioperative ICP monitoring.

Funding

This work was supported by the Neuro Anaesthesia and Critical Care Society via the National Institute of Academic Anaesthesia; and Medical Research Scotland.

Authorship/contributors

Conception and design of study: RB, LM, MS, AS.
Acquisition of data: AS, RB, ROK.
Analysis and interpretation of data: AS, MS, RB, LM, ROK.
Contribution to discussions: IP.
Drafting the article: AS.
Revising the article critically for important intellectual content: LM, MS, RB.
Final approval of the version to be submitted: LM, RB, MS, ROK.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Amarah Saeed reports financial support was provided by Neuro

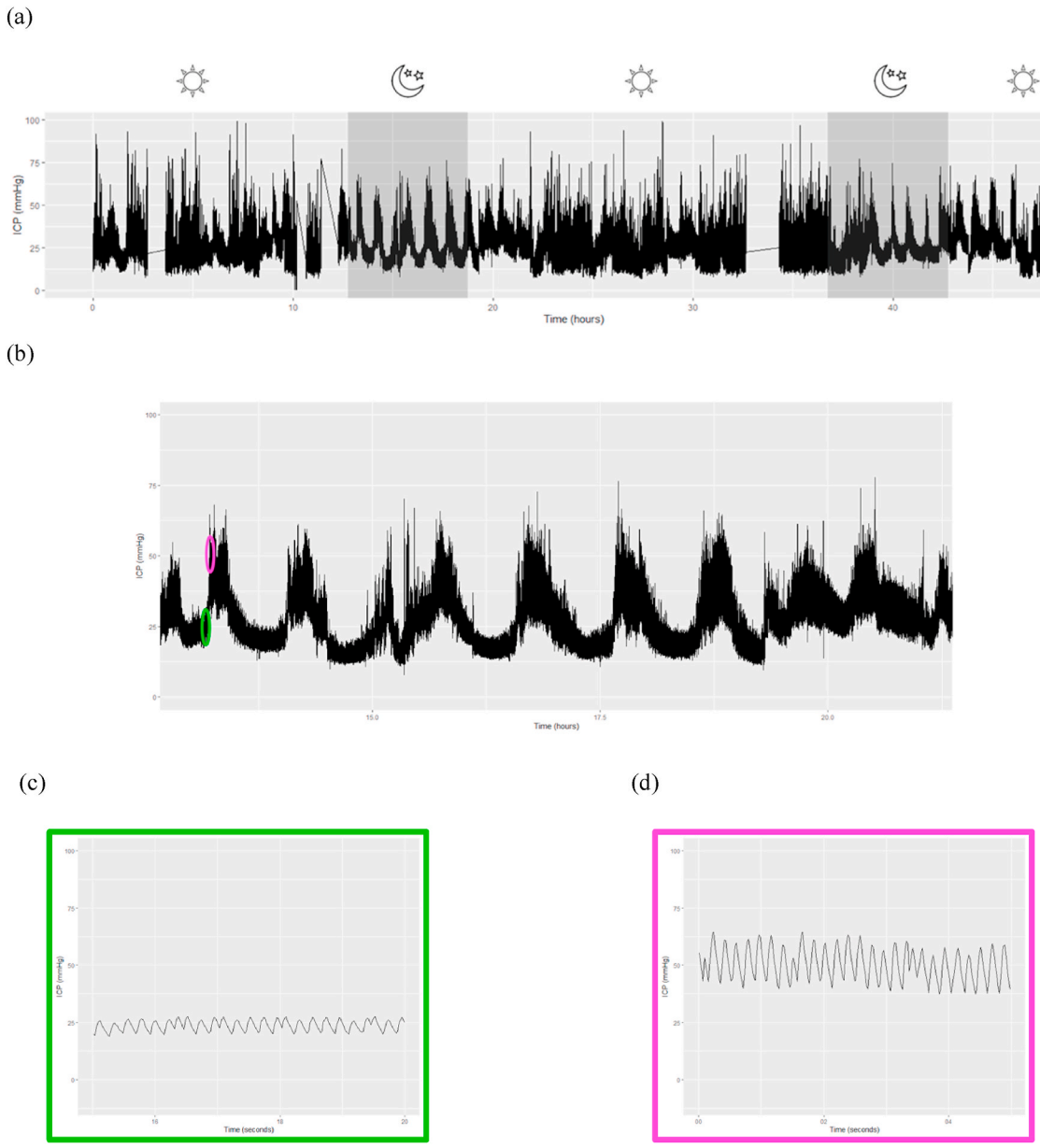

Fig. 2. High-Resolution Waveform Plots for 'Patient A' [Generated using R software]
Patient A was a male with syndromic (Crouzon) craniosynostosis who was 9 months old at the time of recording and had not undergone any prior procedures. (a) Full Trace. Time (hours) is the duration from the start of recording for patient anonymity. Darker areas demonstrate night-time (midnight – 6am, also indicated with moon icon) and lighter areas demonstrate daytime (6am – midnight, also indicated with sun icon). (b) Spike Pattern Segment From Full Trace - Time (hours) is the duration from the start of recording for patient anonymity. (c) Five Second Segment from Start of Spike Train. (d) Five Second Segment from Peak of Spike Train.

Anaesthesia & Critical Care Society (via National Institute of Academic Anaesthesia). Amarah Saeed reports financial support was provided by Medical Research Scotland.

Acknowledgements

People: Dr Ian Piper, Patients involved in study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bas.2024.102859.

References

Barritault, L., Rimbert, J.N., Hirsch, J.F., et al., 1980. Vasomotor origin of intracranial pressure waves in hydrocephalic infants. Eur. J. Nucl. Med. 5 (6), 511–514. https://doi.org/10.1007/bf00252041.
Christian, E.A., Imahiyerobo, T.A., Nallapa, S., Urata, M., McComb, J.G., Krieger, M.D., 2015. Intracranial hypertension after surgical correction for craniosynostosis: a systematic review. Neurosurg.Focus FOC 38 (5), E6. https://doi.org/10.3171/2015.2.focus14853.
Clifford, G.D., 2002. Signal Processing Methods for Heart Rate Variability Analysis.
Cooper, R., Hulme, A., 1966. Intracranial pressure and related phenomena during sleep. J. Neurol. Neurosurg. Psychiatry 29 (6), 564–570.
Driessen, C., Joosten, K.F., Bannink, N., et al., 2013. How does obstructive sleep apnoea evolve in syndromic craniosynostosis? A prospective cohort study. Arch. Dis. Child. 98 (7), 538–543. https://doi.org/10.1136/archdischild-2012-302745.
Dunn, L.T., 2002. Raised intracranial pressure. J. Neurol. Neurosurg. Psychiatr. 73 (Suppl. 1), i23–i27. https://doi.org/10.1136/jnnp.73.suppl_1.i23.
Eide, P.K., Due-Tønnessen, B., Helseth, E., Lundar, T., 2002. Differences in quantitative characteristics of intracranial pressure in hydrocephalic children treated surgically

or conservatively. Pediatr. Neurosurg. 36 (6), 304–313. https://doi.org/10.1159/000063534.
Hanigan, W.C., Zallek, S.N., 2004. Headaches, shunts, and obstructive sleep apnea: report of two cases. Neurosurgery 54 (3), 764–768. https://doi.org/10.1227/01.neu.0000109539.32277.17. ; discussion 8-9.
Heiferman, D.M., Jack, M.M., Johnson, K.D., Katsevman, G.A., Prabhu, V.C., Germanwala, A.V., et al., 2019. Mercury vs. Water: an analysis of multi-institutional survey data assessing intracranial pressure unit of measure awareness. World Neurosurg. 129, e657–e662.
ICP Monitors Hamburg. Spiegelberg GmbH & Co. KG. Available from: https://www.spiegelberg.de/en/products/icp-monitors/. (Accessed 15 April 2022).
Langvatn, E.A., Frič, R., Due-Tønnessen, B.J., Eide, P.K., 2019. Intracranial volume versus static and pulsatile intracranial pressure values in children with craniosynostosis. J. Neurosurg.: Pediatrics PED 24 (1), 66–74. https://doi.org/10.3171/2019.2.peds18767.
Lundberg, N., 1960. Continuous recording and control of ventricular fluid pressure in neurosurgical practice. Acta Psychiatr. Scand. Suppl. 36 (149), 1–193.
Measurement of ICP (intracranial pressure) in the brain: raumedic. Available from: https://www.raumedic.com/neuromonitoring/neuro-icu/icp-measurement. (Accessed 15 April 2022).
Pierre-Kahn, A., Gabersek, V., Hirsch, J.F., 1976. Intracranial pressure and rapid eye movement sleep in hydrocephalus. Pediatr. Neurosurg. 2 (3), 156–166. https://doi.org/10.1159/000119611.
Raboel, P.H., Bartek Jr., J., Andresen, M., Bellander, B.M., Romner, B., 2012. Intracranial pressure monitoring: invasive versus non-invasive methods-A review. Crit. Care Res. Pract. 2012, 950393 https://doi.org/10.1155/2012/950393.
Reddy, H., Amos, L., 2017. 1245 REM associated increase in intracranial pressure in a child with craniosynostosis. Sleep 40, A463–A. https://doi.org/10.1093/sleepj/zsx052.035.
Renier, D., Sainte-Rose, C., Marchac, D., Hirsch, J.F., 1982. Intracranial pressure in craniostenosis. J. Neurosurg. 57 (3), 370–377. https://doi.org/10.3171/jns.1982.57.3.0370.
Sæhle, T., Eide, P.K., 2015. Characteristics of intracranial pressure (ICP) waves and ICP in children with treatment-responsive hydrocephalus. Acta Neurochir. 157 (6), 1003–1014. https://doi.org/10.1007/s00701-015-2410-z.
Tamburrini, G., Caldarelli, M., Massimi, L., Santini, P., Di Rocco, C., 2005. Intracranial pressure monitoring in children with single suture and complex craniosynostosis: a review. Child's Nerv. Syst. 21 (10), 913–921. https://doi.org/10.1007/s00381-004-1117-x.
The R Project for statistical computing: the R foundation. Available from: https://www.r-project.org. (Accessed 15 April 2022).
Thomas, G.P.L., Johnson, D., Byren, J.C., et al., 2015. The incidence of raised intracranial pressure in nonsyndromic sagittal craniosynostosis following primary surgery. J. Neurosurg.: Pediatrics PED 15 (4), 350–360. https://doi.org/10.3171/2014.11.peds1426.
Zipfel, J., Jager, B., Collmann, H., Czosnyka, Z., Schuhmann, M., Schweitzer, T., 2020. The role of ICP overnight monitoring (ONM) in children with suspected craniostenosis. Child's Nerv. Syst. 36 https://doi.org/10.1007/s00381-019-04288-9.