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Ambulatory intracranial pressure in humans: ICP increases during movement between body positions

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ABSTRACT

Introduction: Positional changes in intracranial pressure (ICP) have been described in humans when measured over minutes or hours in a static posture, with ICP higher when lying supine than when sitting or standing upright. However, humans are often ambulant with frequent changes in position self-generated by active movement.

Research question: We explored how ICP changes during movement between body positions.

Material and methods: Sixty-two patients undergoing clinical ICP monitoring were recruited. Patients were relatively well, ambulatory and of mixed age, body habitus and pathology. We instructed patients to move back and forth between sitting and standing or lying and sitting positions at 20 s intervals after an initial 60s at rest. We simultaneously measured body position kinematics from inertial measurement units and ICP from an intraparenchymal probe at 100 Hz.

Results: ICP increased transiently during movements beyond the level expected by body position alone. The amplitude of the increase varied between participants but was on average ~5 mmHg during sit-to-stand, stand-to-sit and sit-to-lie movements and 10.8 mmHg [95%CI: 9.3,12.4] during lie-to-sit movements. The amplitude increased slightly with age, was greater in males, and increased with median 24-h ICP. For lie-to-sit and sit-to-lie movements, higher BMI was associated with greater mid-movement increase ($\beta = 0.99$ [0.78,1.20]; $\beta = 0.49$ [0.34,0.64], respectively).

Discussion and conclusion: ICP increases during movement between body positions. The amplitude of the increase in ICP varies with type of movement, age, sex, and BMI. This could be a marker of disturbed ICP dynamics and may be particularly relevant for patients with CSF-diverting shunts in situ.

1. Introduction

Positional changes in intracranial pressure (ICP) have been described in humans, with ICP higher when lying supine than when sitting or standing upright (DAntona et al., 2021; Andresen and Juhler, 2014; Andresen et al., 2015; Norager et al., 2021; Loman et al., 1935; Poca et al., 2006; Chapman et al., 1990; Farahmand et al., 2015; Qvarlander et al., 2013; Petersen et al., 2016). These studies described ICP averaged over minutes or hours whilst patients were stationary and often positioned the patient passively using a tilt table. Humans are often ambulant with frequent changes in position self-generated by active movement. How ICP changes during movement between positions has not been described.

Study of ICP during movement is clinically significant given patients with various neurological conditions and disorders of cerebrospinal fluid (CSF) dynamics often report exacerbation of their symptoms either during movement or whilst in particular postures. Whilst the influence of movement on ICP is unknown, variation in ICP from other causes is well established. One of the largest causes of variation in ICP is due to pulsatile fluctuation in cerebral arterial blood pressure over the cardiac cycle (Wilson, 2016; Miller and Pickard, 1974; Sullivan et al., 1978; Wagshul et al., 2011). Analysis of ICP pulse amplitude (PA) over the

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cardiac cycle has proven useful for understanding pathophysiological intracranial dynamics in Chiari malformation and high-pressure states with larger PA indicative of less compensatory reserve (or 'compliance') of the cranial compartment (Wagshul et al., 2011; Chari et al., 2017; Czosnyka and Pickard, 2004).

Continuous ICP monitoring is commonly used in assessing ambulatory adult patients with CSF-dynamics disorders (Andresen et al., 2015; Chari et al., 2017; Eide and Kerty, 2011; Eide and Sorteberg, 2010; Evensen and Eide, 2020a). New wearable technologies like inertial measurement units (IMUs) now allow continuous sensing of body position at high sampling frequencies. In this exploratory study, we measure continuous ICP and body position simultaneously in a large, mixed pathology, ambulatory cohort. Participants moved back and forth between sitting and standing or lying and sitting positions at 20 s intervals.

2. Methods

Single-centre, prospective, exploratory observational study. Ethical approval was gained from the relevant Research Ethics Committee (UCLH project ID 15/0769). All included participants provided written informed consent to clinical ICP monitoring and involvement in the study separately. The study conformed to the Declaration of Helsinki.

2.1. Patients

Sixty-two patients with suspected ICP dynamics disturbances admitted for elective 24-h intraparenchymal ICP monitoring were recruited. There were a wide variety of ages, pre-existing pathologies, body habitus and prior interventions (Table 1). Body mass index (BMI) was defined as per the updated guidance from the World Health Organisation in May 2023 (healthy 18.5–24.9; overweight 25–29.9; obese class I 30–34.9; obese class II 35–39.9; obese class III >40). Sixteen patients had pre-existing CSF diversion in situ at the time of ICP monitoring, of which thirteen had anti-siphon valves in situ. Indications for clinical ICP monitoring were predominantly suspected high pressure (n = 23 (37%)), suspected shunt malfunction (n = 16 (26%)) and presence of known Chiari malformation for whom intervention was being considered (n = 12 (19%)).

Table 1
Demographics.

Variable	Overall (n = 62)
Demographic	
Age (mean years ± SD)	43 ± 13
Gender (female/male)	46 (74%)/16
Weight (mean kg ± SD)	87.4 ± 21.7
BMI (kg/m2)	31.1 ± 7.95
Pre-existing comorbidities	
Hypertension	14 (23%)
Obstructive sleep apnoea[a]	9 (15%)
Pre-existing ICP/CSF-related diagnoses	
Chiari malformation	15 (24%)
Syrinx	8 (13%)
Idiopathic intracranial hypertension (IIH)	11 (18%)
Pre-existing CSF diversion[b]	
VPS	11 (18%)
LPS/VA/VPleural/cystoatrial	5 (8%)
Anti-siphon valve[c]	13 (21%)
Indication for ICP monitoring	
Suspected low pressure	5 (8%)
Suspected high pressure	23 (37%)
Known Chiari malformation considering intervention	12 (19%)
Suspected shunt malfunction	16 (26%)
Known IIH considering intervention	4 (6%)
Investigation of confirmed CSF leak	2 (3%)

[a] Known pre-existing diagnosis of obstructive sleep apnoea (OSA), OR, based on our findings, we asked participant's GP to refer for formal sleep studies as OSA may be contributing factor to symptoms.

[b] Pre existing CSF diversion in situ at the time of this episode of ICP monitoring.

[c] Anti-siphon valve of any brand/type present at the time of this episode of ICP monitoring.

2.2. Protocol

Participants performed repeated movements between body positions at 20 s intervals. Two recordings were performed: in the first, participants moved between sitting and standing positions; in the second, participants moved between sitting and lying supine positions. Sit-to-stand and stand-to-sit movements were performed in a chair with back support. Lie-to-sit and sit-to-lie movements were performed in a hospital bed with a single pillow underneath the head for comfort. Unlike sitting in the chair, the legs remained horizontal whilst sitting in the bed. Each recording started with the participant standing upright. In the lie-sit recording, participants then moved to lie supine on the bed for at least 60 s before the first movement. In the sit-stand recording, participants then either remained standing (n = 19) or sat in the chair (n = 43) for 60 s before the first movement. The starting position prior to the first movement did not affect the results. Fig. 1A and B shows typical recordings for one participant.

Participants repeated each lie-to-sit or sit-to-lie movement up to four times (median n = 3) and each sit-to-stand or stand-to-sit movement up to five times (median n = 4) depending on volition. One participant performed two stand-to-sit movements and one separate participant performed two lie-to-sit and sit-to-lie movements; otherwise, a minimum of three repeats were performed. One participant did only sit-stand movements owing to volition.

All movements between body positions were self-generated by the participant. An experimenter kept time and instructed the participant to move between positions at 20 s intervals. Participants were permitted to use their arms for support whilst in a given body position and/or to aid movement between positions. We reminded participants: (1) to remain still when not instructed to move between positions; (2) to position their torso vertically when in sitting or standing positions; (3) to avoid moving the head away from the anatomical position; and (4) to breathe normally.

2.3. ICP monitoring

Surgical procedures were performed in an operating theatre under local anaesthetic, with or without conscious sedation. The right frontal area was scrubbed and prepared then a small skin incision was made posterior to the hairline. A hand twist drill was used to make a small hole through the skull. The dura was opened with a sharp probe and the bolt was fixed to the skull. The ICP wire probe (Neurovent-P intraparenchymal ICP bolt, Raumedic) was introduced into the parenchyma and then connected to a recording device (MPR1, Raumedic) which stored the raw data. The raw data was downloaded via Datalog software (Raumedic/Delta Surgical) and exported for processing.

2.4. Body position monitoring

Whilst ICP monitoring was ongoing, participants wore small, lightweight wireless IMUs (MTw Awinda, Xsens Technologies B.V., Netherlands) that recorded 3-dimensional body position data. All participants wore IMUs attached at the level of the sternum and left lateral thigh during the sit-stand recording and sternum and forehead during the lie-sit recording. Thirty-nine participants also wore IMUs at the level of the pelvis (posterior – over lumbo-sacral junction), bilateral lateral thigh, bilateral medial lower leg, feet, and forehead during both recordings owing to a protocol update after further equipment purchase. IMUs were attached to the participant with adjustable Velcro bands in line with manufacturer recommendations. IMU data was collected and exported in MT Manager v4.6 (Xsens Technologies B.V., Netherlands). IMU orientation was estimated using Xsens' proprietary strap-down

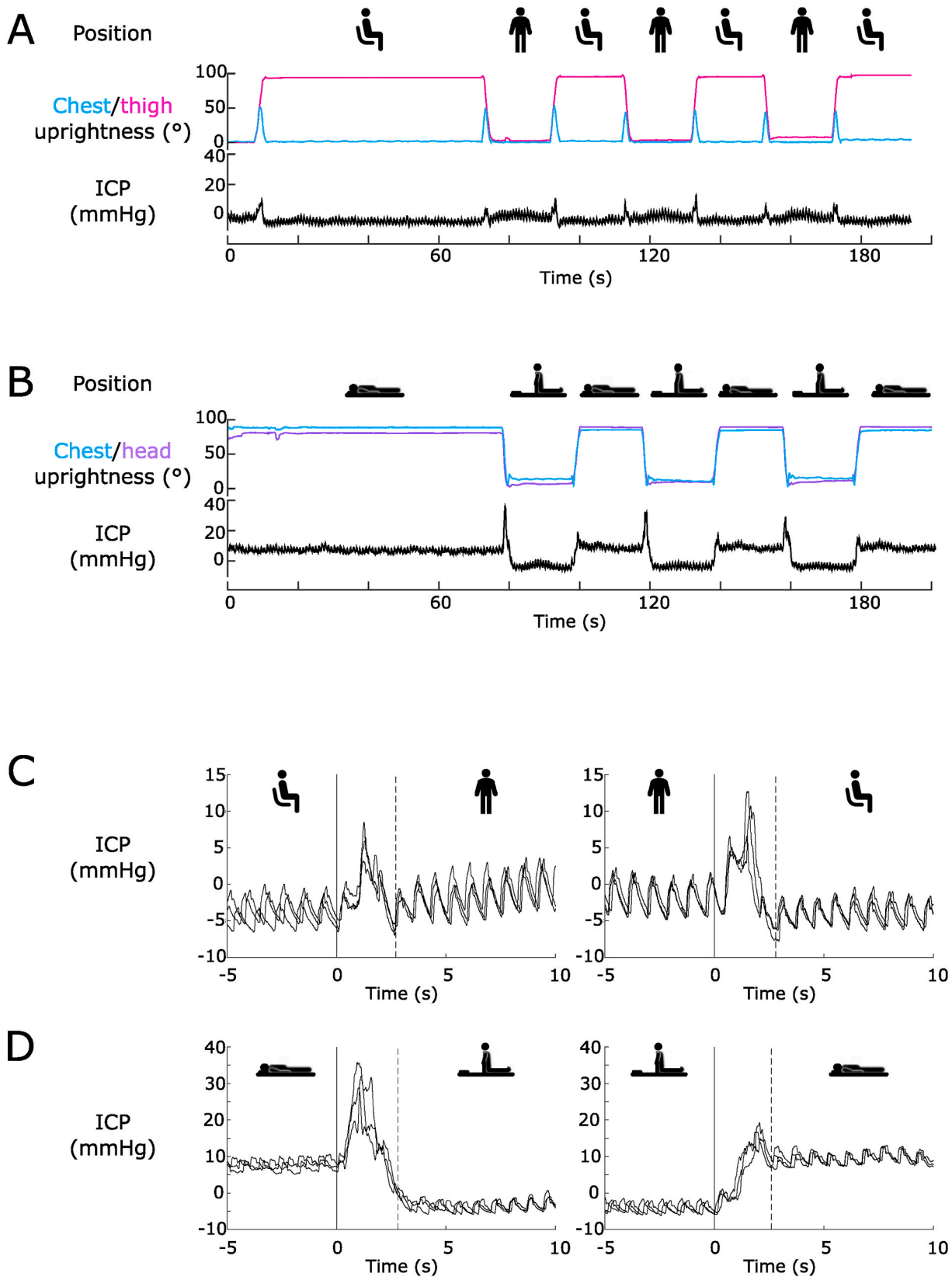

Fig. 1. Single patient example. A: Chest (blue) and thigh (pink) position (as recorded by the chest and thigh IMUs) and ICP (black) over time during one sit-stand recording. B: Chest (blue) and head (purple) position and ICP (black) over time during one lie-sit recording. Movements between body positions were made at 20s intervals. Body position is recorded by the IMUs and expressed as the degree of uprightness, where 0° is upright and 90° is horizontal. Graphics above A and B aid interpretation of uprightness and position. C: ICP pre-, during and post-sit-to-stand (left) and stand-to-sit movements (right). D: ICP pre-, during and post-lie-to-sit (left) and sit-to-lie movements (right). Each trace in C and D is a repetition of the movement. Continuous and dashed vertical lines depict the start (time = 0) and end of movement, respectively, calculated based on IMU data. All data are from the same patient (55 year-old male, BMI 33.8, with no shunt in-situ, without IIH and without Chiari malformation).

integration and Kalman filter algorithms.

In addition to this, demographic data was collected from patients' notes, including age, sex, BMI, median 24-h ICP, pre-existing diagnoses and comorbidities, existing presence of CSF diversion, indication for undertaking this episode of ICP monitoring, and final outcome/consensus after post-monitoring multidisciplinary team meeting (Table 1). BMI was measured at the time of ICP monitoring.

2.5. Data processing

ICP and body position were both recorded at 100 Hz. ICP and body position data were synchronised by sending a voltage from the body position data storage device to the ICP data storage device at the start and end of each position recording. The voltage acted as a timestamp with which to synchronise the two data streams offline. Once synchronised, the time of movement between body positions (sit-to-stand, stand-to-sit, lie-to-sit, sit-to-lie) was detected in each recording using a custom-written interactive Matlab program. Sit-to-stand and stand-to-sit movements were detected by the change in angle between the sternum and thigh. Lie-to-sit and sit-to-lie movements were detected by the change in angle between the sternum and vertical (degree of uprightness). Onset and offset of movements were defined by threshold crosses of angular speed (5 deg/s) and acceleration (50 deg/s^2) for at least 50 consecutive samples (500 ms). Data was segmented into static and movement periods.

Visual inspection suggested ICP increased during movement (Fig. 1). The amplitude of this increase was formally quantified as the difference in peak ICP during movement minus peak ICP during the period either immediately pre- or post-movement. The period pre-movement was used for sit-to-stand, stand-to-sit and lie-to-sit movements; the period post-movement was used for sit-to-lie movements to ensure the amplitude value returned did not include the expected increase in ICP between sitting and lying positions (Table 2). ICP was increased in standing relative to sitting positions (Table 2) so, like sit-to-lie movements the period post-movement could have been used for sit-to-stand movements. However, ICP tended to be less stable in the post-movement than pre-movement period, and the degree of stability could vary between patients, potentially due to blood pressure fluctuations (Borst et al., 1984). We therefore used the period pre-sit-to-stand movement. The periods immediately pre- and post-movement were of equal duration to the movement so can be assumed matched for number of cardiac cycles; the amplitude can therefore be considered somewhat independent of cardiac cycle-driven PA. The amplitude value was unbounded and could be positive or negative.

Data processing was performed in Matlab (version 2021a; MathWorks, Natick, MA).

2.6. Statistical analysis

We ran a multi-level mixed-effects linear regression model to examine the amplitude of the increase in ICP during movement. The model included a nested random effect of repetition number within participant to account for any clustering effect within each participant and between repeats within each participant. The increase in ICP during movement was generally more variable in lie-to-sit, and to a lesser extent sit-to-lie, movements compared to sit-to-stand or stand-to-sit movements. Consequently, instead of fitting a standard mixed model that assumed a homogeneous variance structure, we allowed the random-effects and within-person residuals to differ between movements with an independent residual structure. In this paper we aimed to assess the influence of within-participant factors such as type of movement (sit-to-stand, stand-to-sit, lie-to-sit, sit-to-lie) and basic demographic factors (age, sex, BMI, median 24-h ICP), which were all included as fixed effects. We also adjusted for idiopathic intracranial hypertension (IIH; present, absent), Chiari malformation (present, absent) and shunt status (present-functioning, present-malfunctioning, absent) owing to clinical reasoning. For brevity and clarity, we do not explore the influence of IIH, Chiari malformation or shunt status here. Interactions between type of movement, age, sex and BMI were added to the model iteratively and log-likelihood ratio tests were performed to assess improved model fit, with $p < 0.05$ considered a better fit. The final model with the best fit adjusts for type of movement, Chiari malformation, sex, age, shunt status, IIH, median 24-h ICP and an interaction between type of movement and BMI as fixed effects and a nested random effect of repetition number within participant.

Statistical analyses were performed in Stata (version 18.0; StataCorp LLC, College Station, TX) and GraphPad Prism (version 9.5, San Diego, California). We report two-sided P-values (alpha level: $P < 0.05$). Multilevel model outputs are reported as estimated coefficients or estimated marginal means with 95% CIs.

3. Results

3.1. ICP during movement between body positions

A total of 915 individual movements (multiple observations of each movement from each participant) were observed and inputted to the multilevel model (see Statistical Analysis). ICP increased during movement in the vast majority of observations (750/915 = 82.0%; i.e. where amplitude was greater than zero). Fig. 1 shows an example from one patient of ICP over time during sit-stand (Fig. 1A and C) and lie-sit movements (Fig. 1B and D). A transient increase in ICP tended to occur during movement. The increase in ICP began shortly after the start of movement and typically finished shortly before the end of movement. Movement lasted 3.40 s (95% CI: 3.21, 3.60) on average meaning the period of increased ICP was relatively brief. The increase in ICP was apparent across movement types and represented an 'overshoot' of ICP above the level expected in the body position either before or after movement. The amplitude of the increase varied between participants and could vary, to a lesser extent, between repetitions of the same movement within a participant.

After controlling for disease state (IIH, Chiari malformation) and shunt status (shunt functioning, shunt malfunctioning, no shunt), there was a modest but significant effect of age on the amplitude of the increase in ICP during movement (Table 3; $p < 0.001$). Each one-year increase in age was associated with a 0.11 mmHg on average (95% CI: 0.05, 0.16) increase in amplitude. The amplitude of the increase in ICP during movement was significantly greater in males than females (Table 3; $p = 0.043$; male = 7.67 mmHg [95% CI: 6.19, 9.14]; female = 5.90 mmHg [95% CI: 5.05, 6.74]) and increased by 0.23 mmHg per unit

Table 2
ICP in static positions and the increase during movement.

	Static position (estimated marginal mean + 95% CIs)				Movement (estimated marginal mean + 95% CIs)			
	Lying	Sitting in bed	Sitting in chair	Standing	Sit to stand	Stand to sit	Lie to sit	Sit to lie
ICP (mmHg)	12.32 (12.30, 13.35)	3.03 (1.91, 4.15)	3.21 (0.90, 5.51)	5.49 (3.19, 7.78)	5.27 (4.50, 6.04)	4.19 (3.40, 4.98)	10.84 (9.29, 12.40)	5.82 (4.74, 6.90)

Footnotes: Left section displays ICP for the whole cohort for each body position during the static portions of each recording. Right section shows the amplitude of increase in ICP during each movement shown, after applying the reported mixed effects model. Values are adjusted for age, sex, BMI, median 24-h ICP, Chiari malformation, IIH and shunt status.

Table 3
Multilevel model regression results.

		Coefficient	95% CI	P value
Movement	Stand to sit	1.91	−0.96, 4.77	0.193
	Lie to sit	−28.79	−35.15, −22.42	<0.001
	Sit to lie	−18.26	−22.57, −13.96	<0.001
Chiari		−0.63	−2.48, 1.23	0.502
Sex	Male	1.78	−0.55, 3.49	0.043
Age	Per one-year increase	0.11	0.05, 0.16	<0.001
Shunt status	Malfunctioning shunt	1.40	−1.50, 4.29	0.344
	No shunt	2.25	−0.07, 4.57	0.057
IIH		2.51	0.42, 4.60	0.019
Median 24 h ICP	Per unit increase	0.23	0.08, 0.39	0.003
Movement x BMI	Sit to stand	−0.12	−0.23, −0.01	0.042
	Stand to sit	−0.21	−0.32, −0.10	<0.001
	Lie to sit	0.99	0.78, 1.20	<0.001
	Sit to lie	0.49	0.34, 0.64	<0.001
Constant		−0.27	−5.19, 4.66	0.92

Footnotes: residual level 2 variance: between participants = 4.49 (95% CI: 2.39, 8.44); between repetitions = 0.24 (0.07, 0.80). Residual level 1 variance (within-participants): sit-to-stand = 14.95 (12.16, 18.39); stand-to-sit = 16.60 (13.20, 20.29); lie-to-sit = 110.44 (90.19, 135.24); sit-to-lie = 43.97 (35.53, 54.41). Values are multilevel model regression estimates and 95% CIs.

increase in median 24-h ICP (95% CI: 0.08, 0.39; p = 0.003).

There was a significant effect of type of movement on the amplitude of the increase in ICP during movement (p < 0.001). Generally, the increase tended to be greater in lie-to-sit (10.84 mmHg [9.29, 12.40]) than sit-to-stand (5.27 mmHg [4.50, 6.04]), stand-to-sit (4.19 mmHg [3.40, 4.98]) and sit-to-lie movements (5.82 mmHg [4.74, 6.90]). However, the amplitude of the increase in ICP during movement also depended on a combination of the type of movement and BMI (Fig. 2; p < 0.001). There was a modest but significant negative correlation between BMI and amplitude during sit-to-stand and stand-to-sit movements (Table 3), where a unit increase in BMI was associated with a smaller increase in ICP by 0.12 mmHg during sit-to-stand (95% CI: −0.23, −0.01; p = 0.042) and by 0.21 mmHg during stand-to-sit movements (95% CI: −0.32, −0.10; p < 0.001). However, for both lie-to-sit and sit-to-lie movements there was a significant positive correlation between BMI and amplitude (Table 3). For lie-to-sit movements, each unit increase in BMI was associated with an increase in amplitude by 0.99 mmHg (95% CI: 0.78, 1.2; z = 9.22; p < 0.001). For sit-to-lie movements, each unit increase in BMI was associated with an increase in amplitude by 0.49 mmHg (95% CI: 0.34, 0.64; p < 0.001). Fig. 2 shows the predicted amplitude of the increase in ICP during each movement as a function of BMI. To aid interpretability, Fig. 2 also depicts the predicted increase in ICP at the centre value of each BMI category (healthy, overweight, obese class I, obese class II, obese class III). Note, no participant was underweight (BMI<18.5) so no estimate was calculated.

3.2. Increased ICP during movement between sitting and standing positions is unlikely to be due to deviation of the chest from vertical

ICP is known to increase as the head and chest are tilted further from upright [9]. During lie-to-sit and sit-to-lie movements, the orientation of the chest and head changes from horizontal to vertical or vice versa. Given ICP is higher when horizontal than vertical, it is difficult to explain the increase in ICP during movement beyond that when horizontal based on body position mid-movement (i.e. ICP 'overshoots' the level expected based on body position). However, when moving between sitting and standing positions, the chest and head start and end the movement vertical but may deviate from vertical during movement

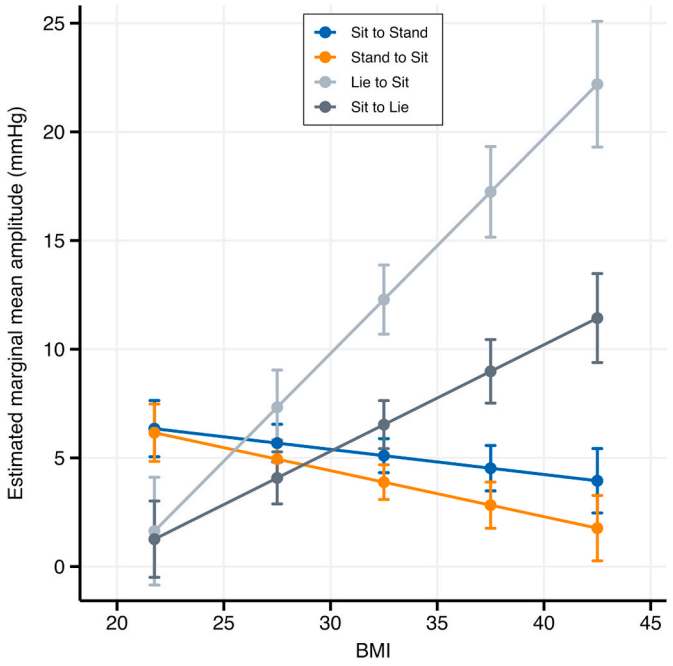

Fig. 2. Amplitude of increase in ICP during movement as a function of BMI and type of movement. Lines are estimated linear regression coefficients from multilevel models after adjusting for age, sex, median 24-h ICP, pathology (IIH, Chiari malformation) and shunt status (functioning, malfunctioning, no shunt). Estimated marginal mean amplitudes (circles) and 95% CIs (error bars) are overlaid for each movement at the centre of each BMI category (healthy weight range [18.5 < BMI<25] = 21.75; overweight [25 < BMI<30] = 27.5; obese class I [30 < BMI<35] = 32.5; obese class II [35 < BMI<40] = 37.5; obese class III [BMI>40] = 42.5). Sit-to-stand = blue; stand-to-sit = orange; lie-to-sit = light gray; sit-to-lie = dark gray.

(for example blue traces in Fig. 1A). Such a deviation from upright is typical when tilting forward to generate the necessary momentum to stand or counter-balance oneself when sitting. This raises the question as to whether the increase in ICP during sit-to-stand and stand-to-sit movements can be explained by deviation of the head and/or chest from vertical towards horizontal, which could increase ICP. To answer this, we further analysed the sit-to-stand and stand-to-sit data using the same multilevel model as described in Statistical Analysis but with an added fixed effect of the maximal chest deviation from vertical during movement. Likelihood ratio testing informed the best model fit with an interactive effect between type of movement and chest deviation from vertical. We hypothesised that the maximal chest deviation from vertical would correlate with the increase in ICP if it could explain the effect. However, we found no significant correlation between chest deviation from vertical and the increase in ICP for either sit-to-stand (slope = −0.03 [−0.11, 0.04], p = 0.383) or stand-to-sit movements (slope = 0.06 [−0.01, 0.12], p = 0.052).

4. Discussion

We asked a large, ambulatory, relatively well, mixed pathology cohort of patients to move between sitting and standing or sitting and lying supine body positions repetitively. We show that ICP increases during movement between body positions. The increase in ICP during movement was generally greatest during lie-to-sit movements but depended on a combination of BMI and the type of movement. The increase in ICP was positively associated with BMI for lie-to-sit and sit-to-lie movements but relatively constant with BMI for sit-to-stand and stand-to-sit movements. The increase in ICP during sit-to-stand and stand-to-sit movements could not be explained by a transient positional effect whereby the chest deviated from vertical during movement. We

discuss other potential explanations and the potential clinical relevance of our findings.

4.1. ICP increases during movement between body positions

We describe that ICP increases during movement between body positions. To our knowledge this is the first description of this phenomenon. This finding was enabled through simultaneous measurement of continuous body position and ICP at high sampling frequency (100 Hz) in a relatively well (non-trauma), ambulatory, mixed pathology cohort. We were therefore able to precisely determine the onset and offset of movement between body positions and isolate the change in ICP during movement. Whilst patients were relatively well, they cannot be considered clinically normal as they were symptomatic enough to be considered for ICP monitoring. Whether ICP increases during movement in normal human physiology is yet to be revealed.

ICP was found to increase during movement between body positions beyond the level expected by body position alone. This was evident both in lie-sit movements where ICP 'overshot' the expected value when lying supine and in sit-stand movements where the increase in ICP was not correlated with the degree of chest deviation from upright. Together, this suggests that the increase in ICP during movement between body positions cannot be explained by current knowledge of the effect of body position on ICP.

After controlling for pre-existing disease states (IIH, Chiari malformation), shunt statuses (functioning shunt, malfunctioning shunt or no shunt) median 24-h ICP, we found that age, sex and an interaction of BMI and type of movement influenced the amplitude of the increase in ICP during movement. The increase in amplitude with age was small but potentially reflects an age-related degradation of ICP control mechanisms that has not been reported previously. Chari et al. found that ICP slowly decreases with age and PA slowly increases with age (Chari et al., 2017). They hypothesised that those findings could be explained by age-associated atrophy. Though their theory is not yet confirmed, their findings do suggest that ICP homeostasis changes with age. That baseline ICP *decreases* with age, but dynamic ICP (mid-movement increase presented here) *increased* with age suggests that ageing influences the control of baseline and dynamic ICP differently.

The effect of BMI depended on transition. In sit-to-stand and stand-to-sit movements with increasing BMI there was a slightly lower amplitude of ICP increase during movement. However, in lie-to-sit and sit-to-lie movements, with increasing BMI there was a higher amplitude of ICP increase. This effect was stronger in lie-to-sit movements than sit-to-lie movements. In both lie-to-sit and sit-to-lie movements, participants in obesity class III (as per May 2023 WHO BMI guidelines) had the largest predicted amplitude increases in ICP during movement (Fig. 2). If the amplitude of the increase in ICP during movement is indicative of abnormal intracranial dynamics, this finding could emphasise the importance of treating high BMI as a step in managing patients with abnormal intracranial dynamics.

4.2. What could explain the increase in ICP during movement between body positions?

Candidate explanations of the increase in ICP during movement between body positions include movement-related increase in arterial blood pressure, and/or the effect of skeletal muscle contraction on intra-abdominal pressure.

ICP and arterial blood pressure are often closely related (Wilson, 2016; Evensen and Eide, 2020b). For example, ICP pulses with the change in arterial blood pressure driven by the beat of the heart (Wagshul et al., 2011; Avolio et al., 2018; Canac et al., 2020). In a seminal study, Magnaes (1976) reported a transient increase in ICP after movement between body positions which were hypothesised to reflect changes in cerebral blood volume. However, the transition waves in ICP occurred later (~15 s after movement) than could realistically explain the increase in ICP during movement observed here (within ~3 s on average). The timing and nature of the increase in ICP during movement closely resembles the increase in arterial blood pressure measured in healthy individuals during active standing which was hypothesised to result from compression of arteries by postural skeletal muscle during contraction (Borst et al., 1984).

Another possibility is that the increase in ICP is explained by increased intra-abdominal pressure (IAP) induced by muscle contraction during movement. It is possible excess IAP in higher BMI resulted from the need for more forceful muscle contraction to move the body's mass and/or intra-abdominal pressure resulting from more abdominal adiposity (Owens et al., 2012). An additional effect could be that the ICP also affects venous pressure (both centrally and cranially), as an increase in ICP is transferred to the cranial venous pressure, thus possibly increasing ICP in two ways simultaneously. In this case, it would be expected to have less effect in more upright torso postures due to the known collapse of the venous system in the anterior neck in more upright postures (Holmlund et al., 2018).

Alternatively, recent evidence in animals (Young and Cramberg, 2022) suggests that contraction of muscles in the myodural bridge (a connection between cervical skeletal muscles and the dura) can directly influence CSF pressure in alligators that creates waves of ICP (Young et al., 2020; Ma et al., 2021). Whilst animal models are not directly comparable to humans due to anatomical and physiological variations (in particular alligators, unlike humans, are rarely positioned upright), there is evidence that humans also have a myodural bridge (Zheng et al., 2017), which provides a potential mechanistic basis for muscular contraction affecting intracranial dynamics independently or in conjunction with abdominal muscle contraction.

Other possible explanations include a reactionary autonomic mechanism due to rebound in the enclosed cranial vault or due to inertia. The phenomenon of rebound intracranial hypertension has been reported previously in the context of CSF leaks during spinal surgery, often in patients who likely had subclinical raised ICP (Craven et al., 2016). It is not known how rapidly this occurs in these patients however, and may be more insidious than would explain our findings.

4.3. Clinical relevance

Though the mechanism and significance of the increase in ICP during movement are currently unclear, it is possible that it could become a marker of disturbed ICP dynamics or impaired compensatory reserve. Andresen et al. (2015) reported that patients without pathology seemed to be more able to tightly regulate ICP when switching body position than patients with pathology. Similar findings were reported in work by D'Antona (DAntona et al., 2021) who found that patients with normal ICP dynamics had tighter control of their postural ICP changes than the other patients. A larger amplitude increase in ICP during movement could imply dysregulation of ICP.

Our findings on ICP during movement may be particularly relevant for patients with CSF-diverting shunts in situ. Shunts bypass normal physiological adaptations that maintain cerebral homeostasis. It is possible that movement may induce momentary increases in ICP over the shunt valve opening pressure, causing drainage of CSF despite having a pressure at rest that would be below the opening pressure. When movement ceases, the ICP may return to a level much lower than the opening pressure. Such 'micro-overdrainage' events during movement could accumulate and cause symptoms of overdrainage. Future work should investigate this in addition to the effect of pathology, but if this is found to be the case, our findings could inform the design of the long-awaited 'smart shunt' (Lutz et al., 2013).

4.4. Strengths and limitations

Strengths of this work include the large volume of data collected, the simultaneous collection of body position and ICP data, and the high

sampling frequencies of each data stream that enabled mid-movement increases in ICP to be observed. Limitations include a lack of randomisation with regard to which movement sequence was performed first. This is considered unlikely to affect results given that all movement sequences commenced with a period of 1 min in a stationary position in order to achieve a baseline level of stability. Furthermore, though the insertion of the ICP probe was standardised, we did not ascertain that the reference level of the ICP probe was comparable between subjects. This could potentially affect the hydrostatic differences that could affect the baseline ICP, though it is not certain whether this would have a knock-on effect on the amplitude of the increase in ICP during movement.

5. Conclusions

Human ICP and pulse amplitude follow a reproducible pattern of dynamic change during movement. There were significant effects of type of movement on the amplitude of the increase in ICP during movement. However, the amplitude of the increase in ICP during movement also depended on a combination of the type of movement and BMI. The amplitude of the increase is slightly larger with increasing age, and it increases with BMI during lie-to-sit and sit-to-lie movements. Further study is needed aiming to understand the underlying mechanisms and implications of these findings.

Declaration of competing interest

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