

The correlation between pulsatile intracranial pressure and indices of intracranial pressure-volume reserve capacity: results from ventricular infusion testing

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OBJECTIVE The objective of this study was to examine how pulsatile and static intracranial pressure (ICP) scores correlate with indices of intracranial pressure-volume reserve capacity, i.e., intracranial elastance (ICE) and intracranial compliance (ICC), as determined during ventricular infusion testing.

METHODS All patients undergoing ventricular infusion testing and overnight ICP monitoring during the 6-year period from 2007 to 2012 were included in the study. Clinical data were retrieved from a quality registry, and the ventricular infusion pressure data and ICP scores were retrieved from a pressure database. The ICE and ICC ($= 1/ICE$) were computed during the infusion phase of the infusion test.

RESULTS During the period from 2007 to 2012, 82 patients with possible treatment-dependent hydrocephalus underwent ventricular infusion testing within the department of neurosurgery. The infusion tests revealed a highly significant positive correlation between ICE and the pulsatile ICP scores mean wave amplitude (MWA) and rise-time coefficient (RTC), and the static ICP score mean ICP. The ICE was negatively associated with linear measures of ventricular size. The overnight ICP recordings revealed significantly increased MWA (> 4 mm Hg) and RTC (> 20 mm Hg/sec) values in patients with impaired ICC (< 0.5 ml/mm Hg).

CONCLUSIONS In this study cohort, there was a significant positive correlation between pulsatile ICP and ICE measured during ventricular infusion testing. In patients with impaired ICC during infusion testing (ICC < 0.5 ml/mm Hg), overnight ICP recordings showed increased pulsatile ICP (MWA > 4 mm Hg, RTC > 20 mm Hg/sec), but not increased mean ICP (< 10 – 15 mm Hg). The present data support the assumption that pulsatile ICP (MWA and RTC) may serve as substitute markers of pressure-volume reserve capacity, i.e., ICE and ICC.

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KEY WORDS intracranial pressure; single pressure wave; intracranial elastance; intracranial compliance; hydrocephalus; mean wave amplitude

CONTINUOUS monitoring of intracranial pressure (ICP) has an important role in the treatment of neurosurgical patients.^{8,9} The ICP is characterized by the static ICP, which is the pressure difference between the intracranial compartment and atmospheric reference pressure, and the pulsatile ICP, which are pressure waves created by cardiac contractions.² Part of the reason for ICP monitoring is the desire to obtain information about the intracranial pressure-volume reserve capacity, which is defined by the intracranial elastance (ICE; change in pressure [dP]/change in volume [dV]). As expressed in the

pressure-volume curve (Fig. 1), when ICE is increased, a minor intracranial dV causes a major dP.^{25,28,29} While monitoring of ICE or intracranial compliance (ICC; the inverse of elastance, or $ICC = 1/ICE$) gained much attention in the neurosurgical literature decades ago, it has been used clinically only to a very limited extent, related to the risk of adding/subtracting volume to the intracranial compartment.²⁹ To overcome the risk aspect, minor repetitive dV was developed,³¹ while several other researchers examined how the pulsatile ICP could be used as an indicator of ICE and ICC.^{6,35,41} Raised ICP amplitudes could be in-

ABBREVIATIONS CI = confidence interval; dP = change in pressure; dV = change in volume; EVD = external ventricular drain; ICC = intracranial compliance; ICE = intracranial elastance; ICP = intracranial pressure; MWA = mean wave amplitude; P_o = opening pressure; P_p = plateau pressure; R_{out} = resistance to CSF outflow; RT = rise time; RTC = RT coefficient.

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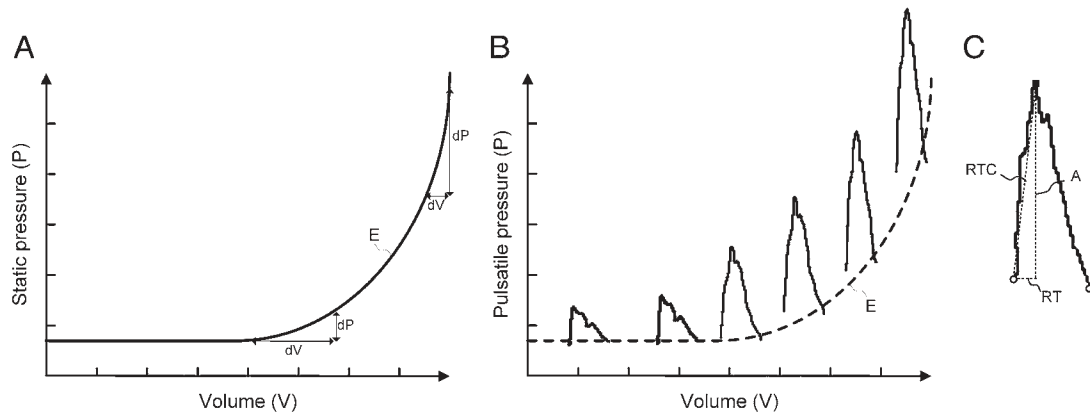


FIG. 1. A: The intracranial pressure-volume curve (elastance curve) describes the change in static pressure (dP) in response to a given intracranial volume change (dV), which depends on the intracranial volume load. The ICE (dP/dV) is increased when intracranial pressure-volume reserve capacity is reduced. The pressure-volume curve refers to the static pressure, i.e., mean ICP. Ventricular infusion increases the intracranial volume load and causes movement to the right on the pressure-volume curve. **B:** The present study examined the association between the ICE and the cardiac-induced pulsatile ICP, based on an assumption that pulsatile ICP changes with ICE. **C:** The hypothesis was that with increased ICE the single-wave amplitudes (A) and RTCs ($= A/RT$) increased, while the RT shortened. $E = ICE$.

dicative of impaired intracranial pressure-volume reserve capacity,^{2,3,6,20} but could also be affected by several other mechanisms such as altered vascular compliance and cerebral blood volume variability.^{5,39}

In recent years, measurement of the pulsatile ICP, in particular the ICP pulse wave amplitude, has received renewed attention.^{13,17,21,33,40} This is related to the fact that computerized analysis of the ICP waveform allows for improved information about the pulsatile ICP.^{11,37} It remains a topic of debate as to how the various indices of pulsatile ICP analyzed with modern computerized methods are associated with the intracranial pressure-volume reserve capacity.^{5,7,21,24} Hence, further studies are needed to determine the association between pulsatile ICP and ICE.

In our department, ventricular infusion testing has been used in patients with questionable shunt-dependent hydrocephalus.^{26,27} During steady-state ventricular infusion testing, the intracranial volume load is artificially increased, and the static ICP determined. In 2007, we introduced a computerized ventricular infusion test, including determination of the pulsatile ICP (Fig. 2). In the present study, information about ICE was retrieved from ventricular infusion tests to further examine the association between pulsatile ICP and ICE. The hypothesis was that the pulsatile ICP correlates positively with ICE. The study also addressed the association between ICE and ventricular size measures.

Methods

Patient Population and Study Design

The study included all patients who underwent ventricular infusion testing during the period from 2007 to 2012 within the Department of Neurosurgery, Oslo University Hospital–Rikshospitalet, Oslo. Oslo University Hospital–Rikshospitalet approved the study, and the Regional Committee for Medical and Health Research Ethics of Health Region South-East, Norway, was informed in writing, and had no objections to the study.

The aim of the present work was to examine the association between pulsatile ICP scores and indices of intracranial pressure-volume reserve capacity, i.e., ICE and ICC. The hypothesis was that pulsatile ICP correlates positively with ICE.

This study also addressed the association between ICE and indices of ventricular size. The rationale for ventricular infusion testing in patients with possible treatment-dependent hydrocephalus is that increased ventricular size may be compensatory to reduced pressure-volume compensatory reserve capacity, which would be reflected in a negative correlation between ICE and ventricular size. The aim was not to examine the diagnostic value of ventricular infusion testing in hydrocephalus, nor the utility of the test in different types of hydrocephalus.

Pressure Monitoring and Ventricular Infusion Testing

Under local anesthesia, a small straight incision was made frontally on the right side. A bur hole approximately 1–1.5 cm was made, and underneath, a small incision in the dura. An external ventricular drain (EVD) with a built-in Codman ICP MicroSensor (Codman external drainage with ICP sensor, Codman/Johanson & Johnson) was introduced into the frontal horn of the cerebral ventricles. The distal end of the EVD was at the level of the foramen of Monroe/third ventricle. The bur hole opening was closed with bone wax to avoid CSF leakage.

The patient was transferred to the neurosurgical intermediate ward. The Codman ICP microsensor was connected to the Codman ICP Express monitor (Codman/Johanson & Johnson), and then connected to an analog-digital converter (Sensometrics Pressure Logger, dPCom), which was connected to a computer with the Sensometrics Software (dPCom) used for online recording of ICP signals (sampling rate 200 Hz). The monitoring was continued overnight until the next morning, when the ventricular infusion test was performed.

The patient was awake during infusion testing. Figure 2

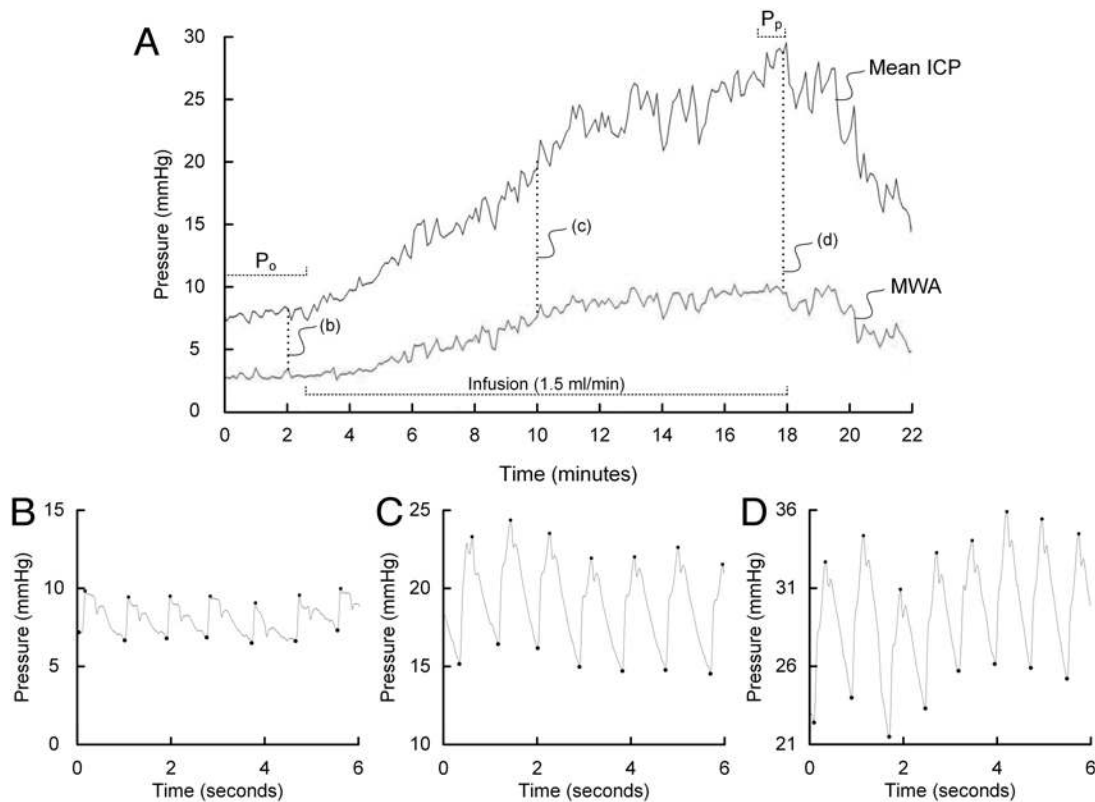


FIG. 2. A: A ventricular infusion test is illustrated by trend plots of mean ICP and MWA, incorporating the period before infusion (P_o) and the period during infusion (infusion rate 1.5 ml/min). The P_p occurs at the end of infusion. Three 6-second time windows of the continuous pressure signal from the period of opening pressure (**B**), infusion period (**C**), and end of plateau pressure (**D**) illustrate the change in ICP wave morphology.

shows one example of a ventricular infusion test. First, ICP was recorded for a few minutes, representing the opening phase (P_o). Via the EVD, Ringer solution was infused at a standard infusion rate of 1.5 ml/min until a plateau pressure (P_p) was reached (Fig. 2). If ICP increased markedly without reaching a plateau, the infusion was ended.

Analysis of Pressure Measurements

The pulsatile ICP scores were computed online, according to a previously published method for automatic identification of cardiac-induced ICP waves.¹¹ Briefly, the cardiac-induced waves were identified by their beginning and ending diastolic minimum pressures and systolic maximum pressures. For each cardiac-beat-induced ICP wave, the amplitude (“pulse amplitude”), the rise time (RT), and rise time coefficient (RTC) were determined (Fig. 1C). The ICP waveform indices mean wave amplitude (MWA), mean wave RT, and mean wave RTC were computed for subsequent 6-second time windows. Only 6-second time windows containing a minimum 4 cardiac-beat-induced waves were considered to be of good quality, and were used for the present analysis. The automatic method also identifies artifact waves due to noise in the pressure signal (e.g., due to patient movement, or sensor movement or dysfunction); artifact waves were thus omitted from the analysis. In addition to the pulsatile ICP, the static ICP (mean ICP) was also computed for each 6-second time window.

The software automatically determines the ICE during infusion. In short, the pressure difference (D) is computed over 15-second time windows as the difference in mean ICP determined over 3-second periods at the end (P_n) and beginning (P_{n-1}) of the 15-second time window ($D = P_n - P_{n-1}$). Hence, while P_{n-1} represents time 0–3 seconds, P_n represents time 12–15 seconds. During this 15-second period, the volume change is 0.375 ml (corresponding to an infusion rate of 1.5 ml/min). Accordingly, $ICE = (P_n - P_{n-1})/0.375$ ml. The software applies a moving time window, allowing an updated value every subsequent 3-second period. For each infusion test, the ICE and ICC represent the average of all named 3-second periods during the infusion period. The ICC is the inverse of ICE ($ICC = 1/ICE$).

During infusion testing, the resistance to CSF outflow (R_{out}) was also calculated as the difference between the P_p and the P_o , divided by infusion rate ($(P_p - P_o)/1.5$ ml/min).¹⁴ With regard to the overnight ICP recordings, a standardized recording time from 11 PM until 7 AM was applied to compare the pressure scores between patients.

Assessment of Ventricular Size

Linear measures of ventricular size were determined based on CT or MRI images obtained at the time of ICP monitoring. As previously described,¹² the linear measures Evan’s index, third ventricle index, cella media index, and the ventricular score were calculated.

Statistical Analysis

The statistical analyses were performed using SPSS software (version 22, IBM Corp.). Associations between observations were determined by the Pearson correlation coefficient. Differences between groups were determined using 1-way ANOVA. Significance was accepted at the 0.05 level.

Results

Patients

During the period from 2007 to 2012, 82 patients underwent ventricular infusion testing in the department. Demographic information about the patient cohort is presented in Table 1. In all patients, the clinical indication was diagnostic assessment of hydrocephalus. None of the patients had shunts.

Ventricular Infusion Testing

No complications in ventricular infusion testing/ICP monitoring were observed. The median volume of infusion was 16 ml (range 5.9–31.8 ml), which corresponds to a median duration of infusion of 10.6 min (range 3.9–21.2 min).

After diagnostic assessment, 72 patients underwent surgery, i.e., shunt surgery in communicating hydrocephalus and endoscopic third ventriculostomy in noncommunicating hydrocephalus (surgery group), while 10 were managed conservatively (conservative treatment group). Among the 72 surgically treated patients, 57 were clinical responders and 15 nonresponders. While 57 patients (97%) were

responders and 7 were nonresponders among 59 patients with a presumptive abnormal infusion test, 5 patients (39%) were responders among 13 patients with a normal infusion test (sensitivity 92%, specificity 53%; positive predictive value 88%, negative predictive value 62%; diagnostic accuracy 83%, diagnostic odds ratio 11.9 [95% confidence interval (CI) 3.0–46.7]).

Table 2 presents the pressures scores for the different management groups during ventricular infusion testing. Significant differences were noted between the groups.

Association Between Pulsatile ICP Scores and ICE

There was a highly significant positive correlation between ICE determined during ventricular infusion and the pulsatile ICP MWA (Fig. 3A) and ICP RTC (Fig. 3B), but not between ICE and RT (Fig. 3C).

With regard to static ICP, the correlation between ICE and mean ICP was not as strong, although significant (Fig. 3D). No significant correlation between ICE and R_{out} was observed (Fig. 4).

In 1 patient, ICE was measured simultaneously within the ventricular CSF and the brain parenchyma, with close to identical ICE (2.85 mm Hg/ml in parenchyma vs 2.92 mm Hg/ml in ventricular CSF). In another patient ICE was determined simultaneously from the epidural space and the ventricular CSF, showing close to identical values (4.06 mm Hg/ml vs 4.14 mm Hg/ml).

Association Between ICE and Ventricular Size

ICE determined during ventricular infusion correlated negatively with the linear measures of ventricular size, i.e.,

TABLE 1. Demographic and clinical data of the patient cohort*

Variable	Total Cohort	Surgery Group	Conservative Treatment Group
No. of patients	82	72	10
Median age in yrs (range)	53 (19–78)	53 (19–78)	47 (29–66)
Sex (F/M)	40/42	36/36	4/6
Type of hydrocephalus (%)			
Communicating	35 (43)	30 (42)	5 (50)
Noncommunicating	47 (57)	42 (58)	5 (50)
Gait disturbance	53 (65)	48 (67)	5 (50)
Incontinence	28 (34)	26 (36)	2 (20)
Cognitive impairment	56 (68)	51 (71)	5 (50)
Headache	42 (51)	35 (49)	7 (70)
Nausea	12 (15)	10 (14)	2 (20)
Lethargy	20 (24)	18 (25)	2 (20)
Visual disturbances	13 (16)	11 (15)	2 (20)
Median duration of symptoms in yrs (range)	2 (0.3–20)	2 (0–10)	1 (0.3–20)
Ventricular size (range)			
Median Evan's index	0.4 (0.2–0.7)	0.4 (0.2–0.7)	0.4 (0.3–0.7)
Median ventricular score	108 (52–194)	108 (52–194)	99 (73–178)
Outcome after surgery (%)			
Responders	—	57 (79)	—
Nonresponders	—	15 (21)	—

* None of the differences between surgery and conservative groups were significant as determined by 1-way ANOVA for continuous data and by the Pearson chi-square test for categorical data.

TABLE 2. Comparison of pressure scores during ventricular infusion testing for the different management groups

Ventricular Infusion Testing	Surgery Group				Conservative Treatment Group (n = 10)		p Value*
	Responders (n = 57)		Nonresponders (n = 15)		Mean	95% CI	
	Mean	95% CI	Mean	95% CI			
Opening phase							
MWA (mm Hg)	3.6	3.3–4.0†	2.1	1.7–2.5	2.7	2.3–3.1	<0.001
RT (sec)	0.21	0.19–0.23	0.24	0.20–0.27	0.19	0.14–0.25	NS
RTC (mm Hg/sec)	20.8	17.9–23.6‡	11.1	7.3–14.8	18.9	11.6–26.2	<0.001
Mean ICP (mm Hg)	8.1	7.0–9.2	7.4	4.0–10.8	5.3	2.8–7.9	NS
Plateau phase							
MWA (mm Hg)	9.6	8.7–10.6†	4.6	3.4–5.8	5.6	4.5–6.7	<0.001
RT (sec)	0.26	0.25–0.27	0.29	0.25–0.32	0.24	0.21–0.27	0.04
RTC (mm Hg/sec)	37.2	34.2–40.2†	17.1	11.9–22.2	26.0	20.8–31.3	<0.001
Mean ICP (mm Hg)	24.2	22.1–26.3	19.0	15.1–22.9	16.8	13.3–20.4	0.005
Infusion phase							
MWA (mm Hg)	6.3	5.8–6.8†	3.5	2.7–4.3	4.4	3.7–5.2	<0.001
% MWA >5 mm Hg	60.5	52.5–68.4†	21.4	5.3–37.4	25.5	8.3–42.7	<0.001
RT (sec)	0.24	0.23–0.25	0.27	0.24–0.30	0.22	0.18–0.26	0.03
RTC (mm Hg/sec)	28.1	25.6–30.7†	13.7	9.9–17.6	24.4	17.7–31.1	<0.001
Mean ICP (mm Hg)	16.3	15.1–17.5	14.1	10.4–17.8	12.6	9.5–15.7	0.05
ICE (mm Hg/ml)	6.1	5.4–6.8‡	3.4	3.0–3.9	4.3	3.2–5.3	0.001
ICC (ml/mm Hg)	0.47	0.43–0.50†	0.66	0.59–0.74	0.60	0.50–0.70	<0.001

NS = nonsignificant.

* Significant differences between all the 3 groups were determined by 1-way ANOVA. Significant differences between responders and nonresponders were determined by 1-way ANOVA with a Bonferroni-corrected post hoc test (†p < 0.001, ‡p < 0.01).

Evan's index (Fig. 5A), cella media index (Fig. 5B), third ventricle index (Fig. 5C), and ventricular score (Fig. 5D). Thus, increasing ventricular size was accompanied by reduced ICE.

Pulsatile and Static ICP Scores for Different Levels of ICC

Given the literature referring to an upper threshold of ICC of 0.5 ml/mm Hg as indicative of impaired compliance, the ventricular infusion tests with ICC < 0.5 ml/mm Hg (n = 36) and ICC ≥ 0.5 ml/mm Hg (n = 46) were compared. In the group with ICC < 0.5 ml/mm Hg, both the MWA (Fig. 6A–C) and RTC (Fig. 6D–F) values were significantly increased during the opening, plateau, and infusion phases. Mean ICP was not as strongly increased, although it was significantly different during the infusion phase (Fig. 6G–I).

The overnight pulsatile ICP scores of MWA and RTC were increased in the group with ICC < 0.5 ml/mm Hg during infusion testing, as compared with the group with ICC ≥ 0.5 ml/mm Hg (Table 3). Hence, in the group with ICC < 0.5 ml/mm Hg, the MWA values were > 4.0 mm Hg and RTC > 20 mm Hg/sec, which we tentatively consider as abnormal. On the other hand, the mean ICP was normal (< 10–15 mm Hg) in the groups with either ICC ≥ 0.5 ml/mm Hg or ICC < 0.5 ml/mm Hg, even though mean ICP was significantly higher in the latter group (Table 3).

Discussion

The present results from ventricular infusion testing

showed a significant positive correlation between the pulsatile ICP scores and ICE. There was a negative correlation between ICE and linear measures of ventricular size. During overnight monitoring, the pulsatile ICP scores MWA (> 4 mm Hg) and RTC (> 20 mm Hg/sec) were increased in patients with impaired ICC (< 0.5 ml/mm Hg) during infusion testing. Also, mean ICP was increased in this group (ICC < 0.5 ml/mm Hg), although mean ICP was within normal levels (< 10–15 mm Hg).

Ventricular Infusion Testing

The ventricular infusion test has no widespread clinical application. In our department, ventricular infusion testing evolved from the use of lumbar infusion tests. The test primarily assessed shunt dependency in pediatric patients with hydrocephalus.^{26,27} Some other clinical researchers also used the ventricular infusion test to assess shunt dependency in patients with adult hydrocephalus.^{4,22} In patients with noncommunicating hydrocephalus, Tisell et al.³⁸ found that preoperative ICE, determined during ventricular infusion, correlated positively with clinical improvement after third ventriculostomy. Since 2007, we have implemented computation of pulsatile ICP during infusion testing, comparable to the procedure performed during lumbar infusion testing.¹⁴

The current clinical indication for the test is to determine the need for shunt placement in selected patients with hydrocephalus, large ventricles, and questionable shunt dependency. The most common output of infusion testing is the R_{out} ,^{4,14,27,30} which is computed from the static

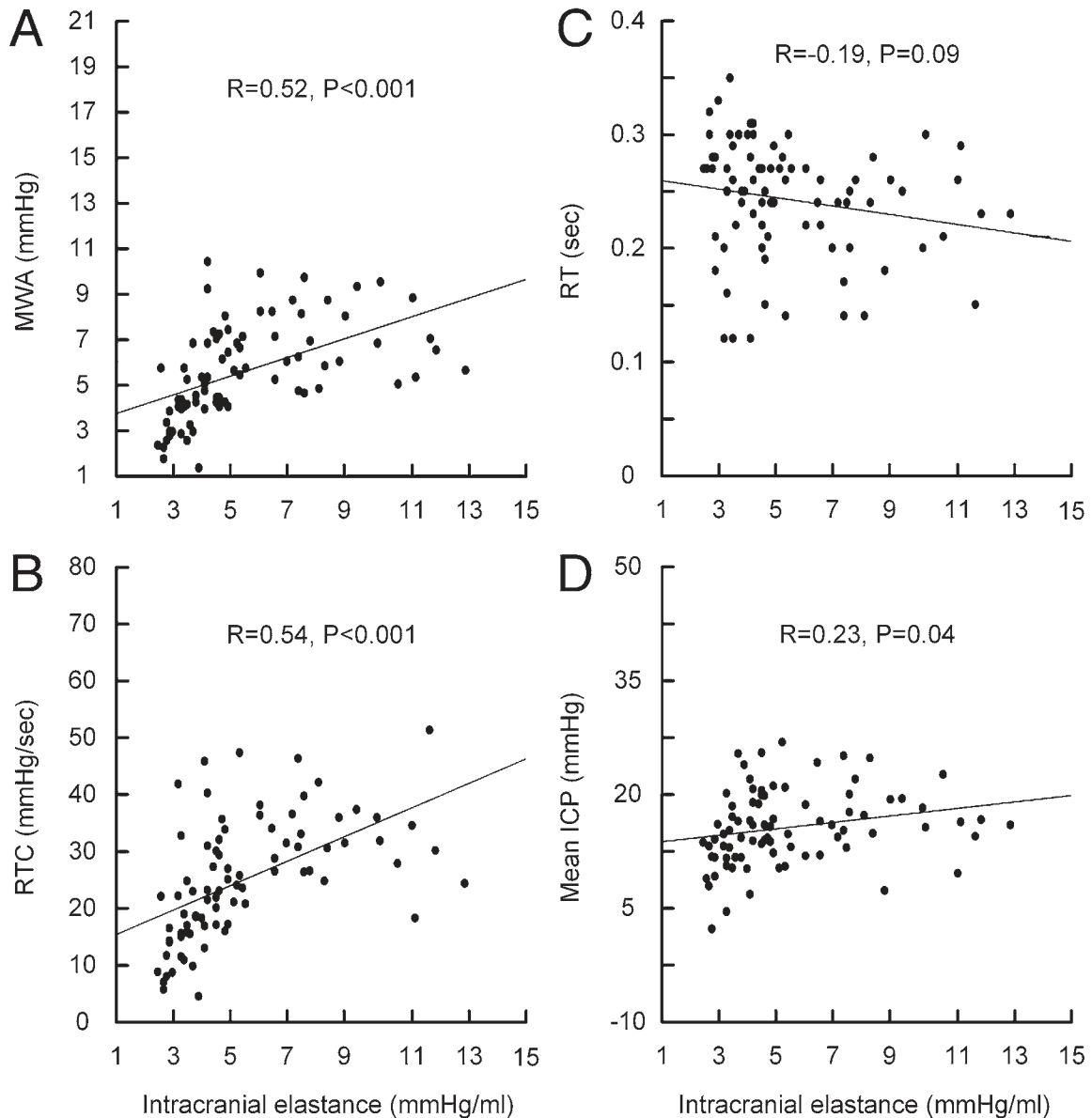


FIG. 3. The association between ICE and MWA (A), RTC (B), RT (C), and mean ICP (D) was determined during the period of ventricular infusion. On each plot the fit line is presented and the Pearson correlation coefficient (R) and significance level (p value) are given.

pressures ($[P_p - P_o]/\text{infusion rate}$). It should be noted that it is presently unknown where the infused fluid is being absorbed. However, independent of the site of CSF absorption, indices of pressure-volume reserve capacity (ICE and ICC) can be determined during infusion testing. It was this latter output that provided the opportunity for determining how pulsatile ICP correlates with ICE in the present study.

Indices of Intracranial Pressure-Volume Reserve Capacity

The pressure-volume curve was established from studies in animals.^{25,28} The dP in response to dV , either as an addition or subtraction of volume, was expressed as ICE (dP/dV ; Fig. 1). However, monitoring of ICE in the clinical context has not gained widespread application, not least because of the risk associated with artificial alterations of

intracranial volume. To reduce risk, one approach has been rapid repetitive small changes in intracranial volume,³¹ which was implemented in a medical device for computation of ICC based on inflation/deflation of a balloon.³² Other approaches were to retrieve information about ICE/ICC from the ICP waveform (pulsatile ICP).^{6,35} More recently, ICE was derived from phase-contrast MRI.¹

Monitoring of the static ICP (mean ICP) has served as an indicator of the pressure-volume reserve capacity, but may not be useful because mean ICP may be normal despite abnormal ICC.^{16,19}

Association Between Pulsatile ICP and ICE

It is reasonable to further explore how pulsatile ICP associates with ICE. From a theoretical point of view, the

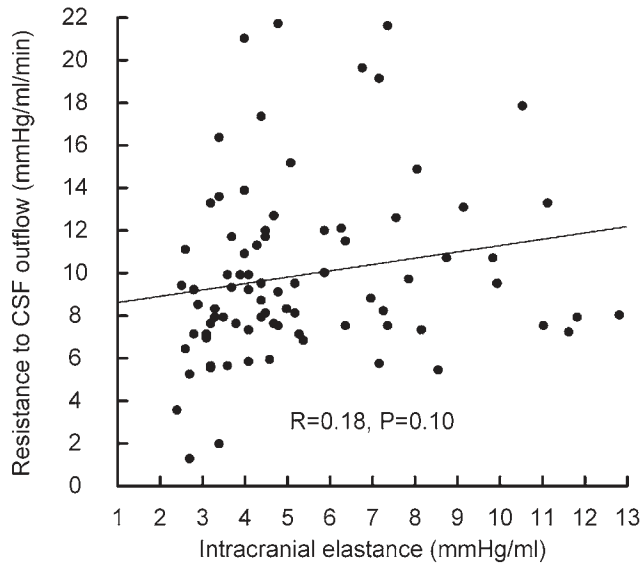


FIG. 4. The association between ICE and R_{out} was determined during the period of ventricular infusion. The fit line is presented as well as the Pearson correlation coefficient (R) with significance level.

pulse pressure is the pressure response to the intracranial volume change during each cardiac contraction. While the intracranial volume change is approximately 1 ml, our results suggest that the upper normal threshold of the pulse pressure amplitude is about 4 mm Hg. Consistent with this assumption, the ICP MWA increased when ICC became reduced. The present data from ventricular infusion testing support the previous results, showing a significant positive correlation between pulsatile ICP and ICE. In addition, the data extend previous observations by examining how the threshold values for pulsatile ICP and ICE/ICC relate.

There was no significant positive correlation between ICE and R_{out} in this study, which suggests no association

between R_{out} and ICE. This observation is consistent with the results of others.³⁰

Even though pulsatile ICP correlates positively with ICE and there is a proportional relationship between levels of pulsatile ICP and ICE, it is important to note that pulsatile ICP is not synonymous with ICE. This is because the pulsatile ICP and ICE are influenced by several factors, such as fluctuations in cerebral blood volume, blood vessel properties (vascular compliance), partial pressure of carbon dioxide levels, and properties of brain parenchyma (water content and cellular changes). However, despite this complex interaction of pathophysiological mechanisms, the present observations of a highly significant positive correlation between pulsatile ICP and ICE is of interest because pulsatile ICP is retrieved directly from the ICP signal used for computation of static ICP. Moreover, the ICP MWA can be measured epidurally with equal confidence as parenchyma measurements.^{10,18} Therefore, minimally invasive monitoring of MWA, indicative of ICE, is feasible.

Ventricular Size and Pressure-Volume Reserve Capacity

The reasoning behind today's ventricular infusion testing is an assumption that increased ventricular size may sometimes be a compensatory mechanism to improve the intracranial pressure-volume reserve capacity. Hence, during ventricular infusion, the intracranial volume load is artificially increased, which causes movement to the right on the pressure-volume curve, thereby increasing ICE and increasing the chance of detecting impaired pressure-volume reserve capacity. This assumption is supported by the present observations of a negative correlation between ICE and ventricular size, i.e., increased ventricular size was associated with reduced ICE. We have previously consistently not found any relationship between ventricular size and static or pulsatile ICP scores.^{12,36}

The association between ventricular size and indices

TABLE 3. The continuous overnight ICP wave/ICP scores categorized according to ICC during the infusion test*

Overnight ICP scores	Ventricular Infusion Tests				p Value
	ICC <0.5 ml/mm Hg (n = 36)		ICC ≥0.5 ml/mm Hg (n = 46)		
	Mean	95% CI	Mean	95% CI	
ICP-wave parameters					
MWA					
Average (mm Hg)	4.5	4.1–4.9	3.9	3.6–4.3	0.04
% ≥5 mm Hg	31.2	20.8–41.5	17.9	10.5–25.3	0.03
Mean wave RT					
Average (sec)	0.20	0.18–0.23	0.22	0.20–0.24	NS
% ≥0.20 sec	55.7	41.9–69.4	66.7	55.0–78.5	NS
Mean wave RTC					
Average (mm Hg/sec)	26.1	22.3–29.8	20.7	18.0–23.4	0.02
% ≥30 mm Hg/sec	28.1	17.4–38.8	16.5	7.5–25.5	NS
Static ICP					
Mean ICP					
Average (mm Hg)	9.4	7.8–10.9	7.0	5.7–8.2	0.02
% ≥15 mm Hg	11.1	4.4–17.8	3.5	1.5–5.5	0.02

* ICP scores recorded from 11 PM to 7 AM. Significant differences between the 2 infusion test groups were determined by 1-way ANOVA.

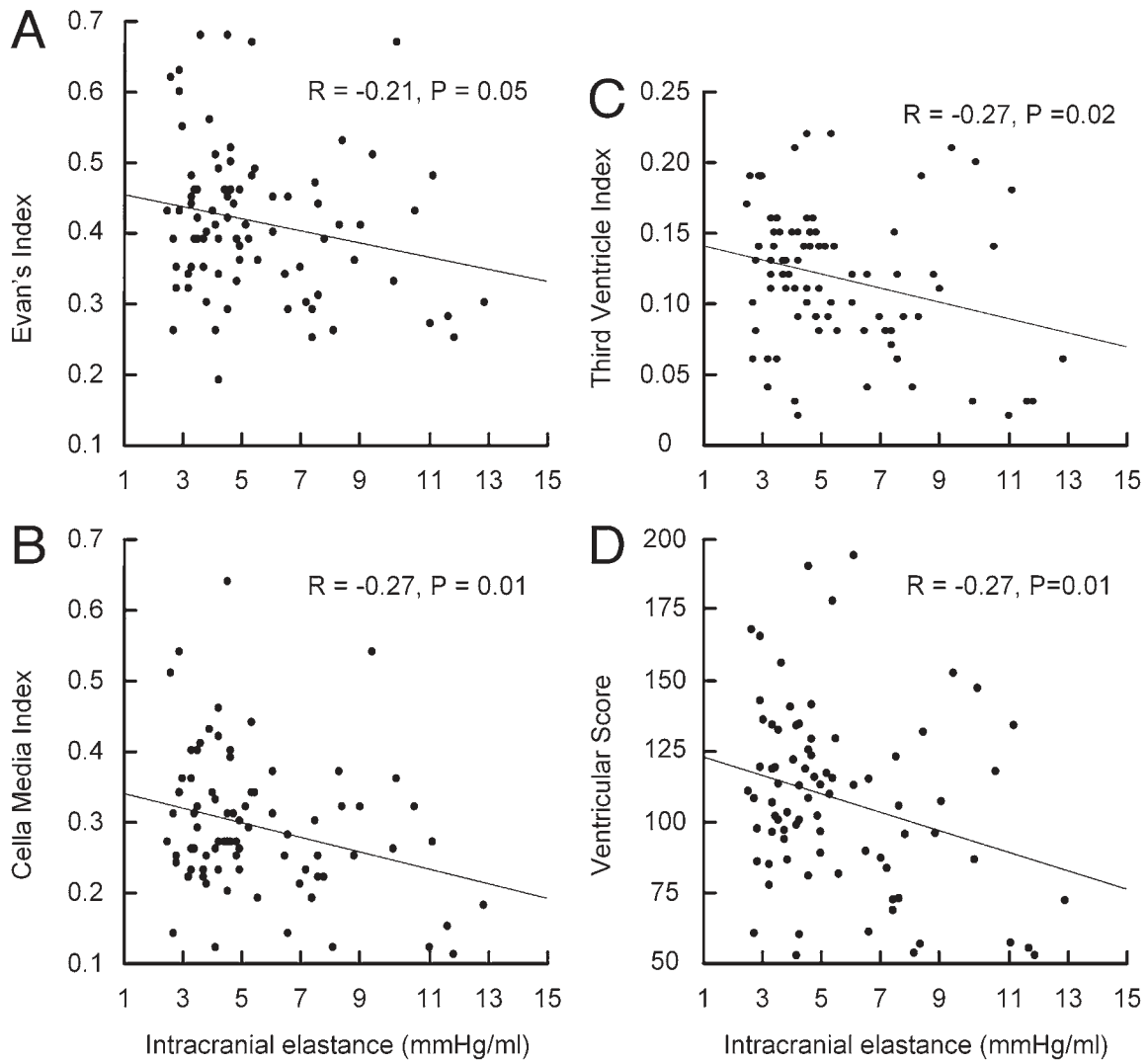


FIG. 5. Graphs showing the association between ICE and Evan's index (A), cella media index (B), third ventricle index (C), and ventricular score (D). For each plot the fit line is presented as well as the Pearson correlation coefficient and significance level.

of pressure-volume reserve capacity most likely depends on the time of measurement during the disease process. While acutely increased ventricular size is probably associated with increased ICE, long-standing ventriculomegaly may be associated with the opposite. In the present cohort, the median duration of symptoms was 2.3 years prior to infusion testing. Further studies are needed to clarify how ventricular size relates to pressure-volume reserve capacity. Recently, we reported retrograde net aqueductal CSF flow (i.e., net direction of CSF flow toward the ventricles) in patients with normal pressure hydrocephalus; following shunting it was changed to antegrade aqueductal CSF flow.³⁴

Clinical Thresholds for Indices of Pressure-Volume Reserve Capacity

While thresholds for ICE remain unclear, several studies have referred to impaired ICC when ICC is < 0.5 ml/mm Hg.^{23,42} In clinical practice, we consider an average MWA of > 4–5 mm Hg as indicative of abnormality. Evi-

dence in favor of this concept was obtained in various groups of patients and clinical settings, including patients with subarachnoid hemorrhage,¹³ normal pressure hydrocephalus,¹⁷ pediatric hydrocephalus, and idiopathic intracranial hypertension.¹⁵ In the present study, the group with ICC < 0.5 ml/mm Hg during infusion testing had significantly higher overnight MWA values (4.5 mm Hg, 95% CI 4.1–4.9 mm Hg), as compared with those with compliance ≥ 0.5 ml/mm Hg. Accordingly, the present observations support our concept of reduced ICC when MWA is > 4 mm Hg.

The static ICP (mean ICP) was significantly higher in the group with ICC < 0.5 ml/mm Hg during infusion, but it is difficult to use in the individual patient as mean ICP was within normal thresholds (< 10–15 mm Hg) in both ICC groups (ICC < / ≥ 0.5 ml/mm Hg).

Conclusions

In this study cohort, there was a significant positive cor-

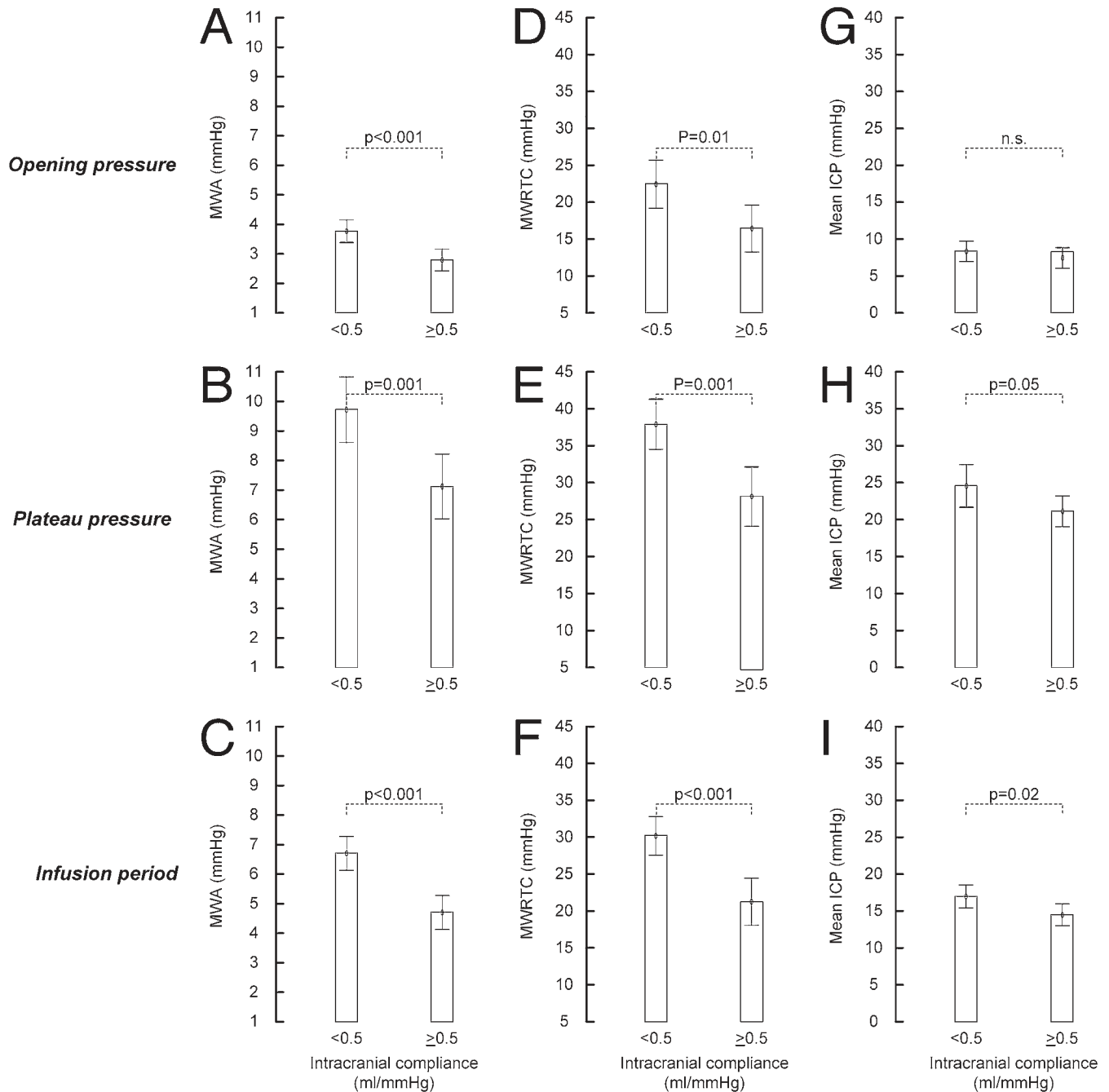


FIG. 6. The ventricular infusion tests ($n = 82$) with ICC either < 0.5 ml/mm Hg ($n = 36$) or ≥ 0.5 ml/mm Hg ($n = 46$) were compared regarding MWA (A–C), RTC (D–F), and mean ICP (G–I) at opening pressure (A, D, and G), plateau pressure (B, E, and H) and infusion period (C, F, and I). Each error bar is presented as mean with 95% CIs. Differences between the 2 infusion test groups were determined by 1-way ANOVA.

relation between pulsatile ICP and ICE measured during ventricular infusion testing. In patients with impaired ICC during infusion testing (ICC < 0.5 ml/mm Hg), overnight ICP recordings showed increased pulsatile ICP (MWA > 4 mm Hg, RTC > 20 mm Hg), but not increased mean ICP (< 10 – 15 mm Hg). The present data support the assumption that pulsatile ICP (MWA and RTC) may serve as substitute markers of pressure-volume reserve capacity, i.e., ICE and ICC.

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Disclosures

Per Kristian Eide has a financial interest in the software company (dPCom AS, Oslo) manufacturing the software (Sensometrics Software) used for analysis of the ICP recordings.

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