Original Article

Edema and elasticity of a fronto-temporal decompressive craniectomy

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Abstract

Background: Decompressive craniectomy is undertaken for relief of brain herniation caused by acute brain swelling. Brain stiffness can be estimated by palpating the decompressive cranial defect and can provide some relatively subjective information to the neurosurgeon to help guide care. The goal of the present study was to objectively evaluate transcutaneous stiffness of the cranial defect using a tactile resonance sensor and to describe the values in patients with a decompressive window in order to characterize the clinical association between brain edema and stiffness.

Methods: Data were prospectively collected from 13 of 37 patients who underwent a decompressive craniectomy in our hospital during a 5-year period. Transcutaneous stiffness was measured as change in frequency and as elastic modulus.

Results: Stiffness variables of the decompressive site were measured without any adverse effect and subsequent calculations revealed change in frequency = 101.71 ± 36.42 Hz, and shear elastic modulus = 1.99 ± 1.11 kPa.

Conclusions: The elasticity of stiffness of a decompressive site correlated with brain edema, cisternal cerebrospinal fluid pressure, and brain shift, all of which are related to acute brain edema.

Key Words: Brain edema, decompressive craniectomy, elasticity, palpation, shear elastic modulus, tactile

INTRODUCTION

Decompressive craniectomy (DC) is a neurosurgical procedure used to relieve brain herniation and this procedure is utilized in many patients with herniation. We often palpate the brain during the craniectomy, and we sometimes encounter acute brain swelling that can be detected by transdural and/or transcortical palpation. In other situations, unexpected intracerebral hematoma, hydrocephalus, and edema are incidentally detected while assessing stiffness of decompressive site postoperatively through digital palpation. In fact, brain palpation is one of the simplest examinations that can be used to notice these clinical complications. But brain palpation has not been investigated in clinical research because it is hard to objectively measure the stiffness of living brain tissues.

Palpation can convey information regarding the comprehensive senses composed of temperature, vibration, pressure, and touch sense. The digital palpation of the brain can detect tumor, swelling, or tension,
Assessment of stiffness was conducted through vibrography, and indentation methods. A tactile resonance sensor developed by Lindahl and Omata has yielded results similar to those achieved by palpation and has already been used in studies assessing the stiffness of soft tissues. The stiffness of living tissue can be quantitatively derived from elasticity and viscosity in mechanical analysis, and hence measurement of elasticity with a tactile resonance sensor placed on an external decompression may be an objective measure of brain stiffness. Overall brain stiffness is derived from the stiffness of the pia-arachnoid, gray matter, white matter, cerebrospinal fluid (CSF), and cerebral blood vessels. In the absence of intervening cranium (e.g., when a postoperative decompressive site is present), overall brain stiffness can be assessed through manual means or using a tactile resonance sensor.

Thus, the purpose of this study was to objectively measure the transcutaneous elasticity of a decompressive site in a cranial defect using a tactile resonance sensor and to evaluate the relationship between brain edema and that elasticity. We would like to discuss the stiffness of a DC site in quantitative terms. Finally, we aimed to find the clinical application of brain stiffness to facilitate the non-invasive detection of postoperative edema. A tense decompressive site may be indicative of various postoperative complications, including hematoma, hydrocephalus, brain edema, and so on. This clinical research was aimed at a possible mechanism to facilitate the non-invasive assessment of brain edema which was one of the postoperative complications. Thus, in addition to screening for potential brain edema, daily assessment of brain stiffness may also help determine if therapy instituted to address such edema is successful.

MATERIALS AND METHODS

Patient population
Between April 2006 and March 2011, 37 patients underwent DC at our university hospital for relief of increased intracranial pressure (ICP) resulting from traumatic brain injury (TBI), subarachnoid hemorrhage (SAH), massive intracerebral hematoma (ICH), hemispheric infarction of middle cerebral artery (MCA), brain tumor, and other conditions. Eight of the 37 patients died within 30 days after the operation, and the 1-month mortality rate was 21.6%. Twenty-nine patients were selected on the basis of inclusion criteria (unilateral fronto-temporal DC) and exclusion criteria (brain tumor, intracranial infection, n = 3; posterior fossa decompression, n = 2; bilateral DC, n = 1). Given the nature of the patient population, these patients were unresponsive prior to surgery, and therefore had no opportunity to give informed consent preoperatively. Thus, written informed consent was instead obtained from the patients’ guardians preoperatively and from the patients themselves, if possible, upon improvement in the level of consciousness. Data were prospectively collected from 13 subjects [male/female = 5/8, mean age ± standard deviation (SD) = 65.15 ± 9.41 years, median age = 62 years, 95% confidence interval (95% CI) = 51–80] who had undergone DC. All DC procedures were undertaken through fronto-temporal (and/or -parietal) craniectomy with dural plasty. The dural plasty was made with either muscle fascia (n = 8) or artificial substitute dura (n = 5). Disease conditions included SAH (nine cases), massive ICH (three cases), and hemispheric MCA infarction (one case). The mortality rate of the participants was 23.1% (3 of 13). The cause of death was brain herniation resulting from brain edema (two cases) and re-rupture of aneurysm (one case). All protocols were performed in accordance with the ethical standards of the committee on human experimentation. This study was approved as an observational study without any interventions for patients by our Institutional Review Board (study number 475).

Tactile resonance sensor
A tactile resonance sensor (Venustron II®, ver. 2.5, Axiom Co. Ltd, Fukushima, Japan) was utilized to measure brain stiffness. The principle of the sensor is based on the fact that each material has its own stiffness-specific resonance frequency. The device’s control system ensures that the sensor probe reciprocates automatically. The system was designed with a feedback circuit, which consisted of a piezoelectric sensor and a phase shift circuit. The feedback circuit system of this device was very similar to that operating during palpation. Measurements were expressed in terms of three variables: depth (Dp; in mm), pressure (Pr; in gf), and change in frequency (dF; in Hz). The term dF represents the change in frequency of the probe itself, which was proportional to the stiffness of soft material in uniformity. The term Pr was the force applied by the indenting probe, and the term Dp was the indenting depth of the probe. The Pr and the dF values were measured simultaneously at the same indentation depth using the counter-weight and depression method. Assessment of stiffness was conducted through measurement of the change in frequency (dF) and shear elastic modulus (G) calculated from the Pr-value, which reflects the elasticity of the brain.

Movement of the probe was set within a safe range, with a depth of 3.0 mm (except for the first case in which a depth of 4.0 mm was used), a speed of 1.5 mm/s, a contact pressure of 1.0 g/mm², and a frequency of 57
kHz. The other settings of the device were controlled by a computer [Figure 1].

Tactile resonance sensor protocol
Stiffness measurement was performed after removal of the subcutaneous drain. Data were collected once a day at the time of dressing change and on the day of follow-up computed tomography (CT) scan, the timing of which was determined by the attending physician. For measurement of stiffness, the patient was kept supine in a relaxed condition and the measurement site was selected as the most elevated central portion of the skin overlying the skull defect. The tip position of the handheld probe was adjusted while in contact with the skin surface using a guide attachment set on the scalp by three-point footplates. One investigator evaluated the condition of external decompression by digital palpation and then held the probe in a manner equivalent to that used in routine manual brain palpation, while the other investigator operated the computer. Measurement time of load-unload cycle was undertaken by 4.0 s. The interval of each cycle was 1 minute, and the number of cycles was more than three. The Pr and dF values obtained at each depth were averaged individually.

Stiffness variables and time course of brain edema
The dF was the frequency change detected by the tactile resonance of the phase shift, which was based on the imaginary part of acoustic impedance. It was independent of the maximum depth. The Pr was defined as the loading force at a depth and was dependent on the maximum depth.[12] In order to generalize the pressure for a depth, the shear elastic modulus (G) was calculated according to the shear elastic modulus (G) was the elastic modulus in shearing force, expressed as kilopascals (1 kPa = 10.1972 gf/cm² = 101.972 mmH₂O). Stiffness variables (dF_maxDp and G_maxDp) were determined at the maximum depth.

For evaluation of the stiffness, the normal distribution was confirmed by constructing a histogram of stiffness variables dF_maxDp and G_maxDp and by calculating the mean ± SD, median, and 95% CI of these values. Brain edema typically progresses to a peak at 3 or 4 days and can persist for 2–3 weeks. Thus, the chronological sequence of stiffness variables was analyzed in 13 participants with brain edema. The measurement day from onset was plotted as the time axis, and the stiffness variables were plotted as the Y-axis.

Correlation between stiffness and brain edema
Brain edema is associated with an increase in the water content in the brain parenchyma. The end point in this study was brain swelling, including brain edema and vasodilation. However, there are no clinically available instruments for direct assessment of brain water content. Thus, CSF pressure and brain deformity on CT imaging were used as clinical indicators of brain edema. CSF pressure was used to evaluate the relationship between stiffness of the cranial defect and brain edema. In general, the gold standard for assessment of CSF pressure is invasive ICP monitoring to determine parameters such as parenchymal pressure, ventricular pressure, and subdural pressure. However, we did not adopt these invasive monitoring methods, as the goal of this study was to conduct non-invasive measurements. Thus, cisternal pressure (CP) was used as an alternative indicator of CSF pressure and was measured using the cisternal drainage with a 4-Fr-sized tube. The cisternal drainage tube was only inserted at the time of aneurysmal neck clipping with DC, and it was placed in the basal cistern. It was intended to control acute hydrocephalus and to wash out subarachnoid clots from the basal cistern for prevention of vasospasms. After removal of the subcutaneous drain, it was opened to drain xanthochromic fluid with clots. The zero point of CP was set at the opening of external acoustic meatus. The units of CP were cmH₂O. CP was controlled between 5 and 20 cmH₂O as much as possible. Eleven data sets from eight patients were available for correlation analysis between stiffness and CP.

Brain deformation was determined by CT that was conducted within several hours after sensor assessment of brain stiffness. CT parameters employed were brain shift, width of cranial defect, scalp protrusion, dura
protrusion, and swelling distance. Brain shift (CT_shift) was measured on a CT slice through the third ventricle. The width of cranial defect (CT_width) was measured as the maximum width of the cranial defect of DC on a CT slice. Scalp protrusion (CT_scalp) was defined as the vertical maximum distance from the most elevated skin surface of a DC site to the contralateral inner skull bone table [Figure 1].

Confounding factors
Confounding factors for the stiffness variables included body temperature (BT) of the measuring time, mean blood pressure (MBP) of the measuring time, and CT parameters of the measuring day including CT_width and swelling distance (SwD). Correlations between stiffness variables among these confounding factors were assessed.

Phantom study
A phantom study was used to examine the reproducibility of the sensor to account for patient bias and observer bias. A stiffness of agar phantom at concentrations of 5, 10, 15, and 20% was selected because the stiffness of the agar was close to the stiffness of a decompressive cranial defect evaluated by digital palpation. The measurement protocols and the setting parameters of the sensor were the same as those described above. First, an observer measured the stiffness variables of agar five consecutive times, and the statistical values of the dF_maxDp and the G_maxDp were calculated as the patient bias. Two weeks later, these parameters were measured in the same manner and used to calculate observer bias. The intrapatient and intraobserver variability were examined by plotting a scatter graph of test–retest methods.

Statistical analysis
All statistical studies were performed using commercially available statistical software (Dr. SPSS® for Windows version 11.01J, SPSS, Inc., Chicago, IL, USA; and JMP®9, SAS Institute, Inc., Cary, NC, USA). Differences at P < 0.05 were considered to be statistically significant. Statistical power was calculated by Hulley’s textbook. The mean ± SD, median, 95% CI, and coefficient variance (CV) were calculated, and continuous variables, such as stiffness variables, CP, CT parameters, BT, and MBP, were tested by Pearson’s correlation coefficient.

RESULTS

Phantom study
The reproducibility of dF_maxDp and G_maxDp for agar was studied at four concentrations for five consecutive measurements by a single investigator and the process was repeated 2 weeks later [Figure 2]. The mean ± SD of dF_maxDp for agar at concentrations of 5, 10, 15, and 20% was 416.20 ± 14.10, 164.80 ± 39.41, 211.76 ± 32.43, 331.46 ± 34.00 Hz, respectively. Repeating the process 2 weeks later resulted in a mean ± SD of dF_maxDp of 134.60 ± 28.85, 309.74 ± 14.47, 262.80 ± 24.20, and 385.28 ± 14.58 Hz, respectively. Values varied widely with 5 and 10% agar, but the dF value for 15 and 20% agar tended to be consistent over time.

The mean ± SD of G_maxDp for agar at concentrations of 5, 10, 15, and 20% were 0.217 ± 0.014, 0.084 ± 0.082, 1.963 ± 0.078, and 3.314 ± 0.159 kPa, respectively. Repeating the process 2 weeks later resulted in a mean ± SD of G_maxDp of 0.530 ± 0.050, 1.366 ± 0.041, 2.214 ± 0.108, and 3.255 ± 0.108 kPa, respectively. The difference in these values over time was small and the increment in the SD was proportional to that of the mean. The CV of G_maxDp was 6.2, 9.8, 4.0, and 4.8%, respectively. At the 2-week time point, the CV of G_maxDp was 9.5, 3.0, 4.9, and 3.5%, respectively. The CV was less than 10%, indicating that the precision of a sensor was acceptable. The reliability coefficient for the 2-week interval was 97.8% for G_maxDp and 65.4% for dF_maxDp. The intrasample and intraobserver variations were smaller for G_maxDp than for dF_maxDp.

Descriptive data
Thirty-five sets of data were collected from the 13 subjects. The total number required for a confidence level of 95% was between 31.03 and 31.56, which was less than the sample size (n = 35). Values related to Pr_maxDp were mean ± SD = 96.14 ± 52.41, median = 76.08, and 95% CI = 78.14–114.15. Values related to dF_maxDp were mean ± SD = 101.71 ± 36.42, median = 98.67, and 95% CI = 89.20–114.22. All the data were significant and valid and showed a normal distribution fitting. No complications were observed during stiffness measurement.

Time course of G-value and brain edema
The time course of G_maxDp was determined among 13 participants and revealed two discrete groups: 1) those with G_maxDp consistently <3.0 (9 patients, with one death due to re-rupture of aneurysm) and 2) those with G_maxDp >3.0 on at least one measurement (4 patients, including two deaths due to brain herniation) [Figure 3]. G_maxDp > 3.0 was noted during the acute phase and these patients required intensive medical care for brain edema. By contrast, brain edema associated with G_maxDp < 3.0 was mild. These results suggest that the G-value correlated with the clinical severity of brain swelling.

For comparison, normal stiffness variables were calculated from 13 data sets obtained 10 days later (in the stable
Association among brain edema, variables, and confounding factors

As shown in Figure 4, the correlation coefficient between stiffness variables and CP was $r = -0.30$ ($P = 0.374$) for $dF_{\text{maxDp}}$ and $r = 0.81$ ($P = 0.002$) for $G_{\text{maxDp}}$ ($n = 11$, Pearson’s correlation coefficient). Thus, $G_{\text{maxDp}}$ significantly correlated with CP, and these values were valid because the power exceeded 80%.

Next, the correlation between stiffness variables and CT parameters were analyzed by Pearson’s correlation coefficient testing [Table 1]. The total sample size required for a correlation coefficient of $r = 0.50$ (two-sided alpha error = 0.05 and beta error = 0.20) was $n = 29$.[6] The power of $G_{\text{maxDp}}$ was almost 80% for CT_shift and was more than 80% for CT_dura. Thus, $G_{\text{maxDp}}$ significantly correlated with both CT_shift and CT_dura. The correlation value between SwD and $G_{\text{maxDp}}$ ($n = 31$, Pearson's correlation coefficient) was $r = 0.43$ ($P = 0.015$). The CT_width did not significantly correlate with $G_{\text{maxDp}}$ ($n = 31$, $r = 0.12$, $P = 0.54$).

| Table 1: Pearson’s correlation coefficient for continuous variables such as stiffness, cisternal pressure, CT findings, body temperature, and mean blood pressure |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                | $r$             | $P$ value       | $r$             | $P$ value       | $r$             | $P$ value       | $r$             | $P$ value       |
| CP             | $Pr_{\text{maxDp}}$ | 0.82 | 0.002 | 0.64 | $<0.001$ | 0.36 | 0.050 | 0.72 | $<0.001$ | 0.33 | 0.068 | -0.16 | 0.375 | 0.10 | 0.567 |
|                | $dF_{\text{maxDp}}$ | -0.30 | 0.374 | 0.13 | 0.471 | 0.04 | 0.832 | 0.34 | 0.063 | 0.04 | 0.824 | 0.18 | 0.303 | 0.19 | 0.283 |
|                | $G_{\text{maxDp}}$ | 0.81 | 0.002 | 0.51 | 0.004 | 0.43 | 0.016 | 0.64 | $<0.001$ | 0.43 | 0.015 | -0.06 | 0.715 | 0.02 | 0.923 |

CP: Cisternal pressure, $CT_{\text{shift}}$: Brain shift, $CT_{\text{scalp}}$: Scalp protrusion, $CT_{\text{dura}}$: Dura protrusion, SwD: Swelling distance from the most elevated skin surface of a DC site to the contralateral inner skull bone table, BT: Body temperature, MBP: Mean blood pressure.
Neither BT nor MBP correlated with the stiffness variables [Table 1]. Therefore, it was assumed that no clinical factors affected the transcutaneous stiffness of a cranial defect during DC.

Dural plasty was accomplished with either muscle fascia (n = 8) or artificial substitute dura (n = 5). The stiffness variables of the muscle fascia in the stable phase were dF_maxDp = 87.20 ± 34.15 and G_maxDp = 1.81 ± 0.79 (n = 6), and the stiffness variables of the substitute dura in the stable phase were dF_maxDp = 87.00 ± 30.64 and G_maxDp = 1.22 ± 0.53 (n = 2). However, because of the small sample numbers, statistical analysis could not be performed.

**Representative case**
A 58-year-old woman with aneurysmal SAH and ICH underwent clipping and fronto-temporal DC [Figure 5]. Her cisternal drainage was removed on postoperative day 5 due to increasing risk of infection related to drainage dysfunction. She developed acute brain edema on postoperative day 6 and was treated with propofol anesthesia + mild hypothermia under mechanical ventilation. ICP was evaluated empirically by digital palpation of the cranial defect, and the stiffness variables at the site of the skull defect were measured by the sensor, with the probe set at a depth of 4.0 mm. As the brain edema improved, the subjective assessment of stiffness through digital palpation decreased and the stiffness variables declined [Figure 5]. For subsequent patients, the maximum depth of the probe was changed from 4.0 to 3.0 mm to assure the safety of the procedure.

**DISCUSSION**

**Stiffness variables**

Many researchers have investigated the mechanical properties of the brain both in vitro and in vivo.[24,15]

While the stiffness of the living human brain has been not yet characterized by indentation methods, the normal shear stiffness of cerebral gray and white matter measured by MRE has been described to vary between 2.7 and 13.6 kPa.[23] In our present study, the elastic shear modulus at a 3.0-mm probe depth was mean ± SD = 1.99 ± 1.11 kPa. Moreover, the G_maxDp 10 days later (during the stable phase) was ~1.5 kPa, which is consistent with shear elastic modulus determined by MRE, despite the fact that our measurements were conducted transcutaneously through the scalp (i.e., epidermis, dermis, and subcutis).

If the stiffness of brain cortex can be measured directly by a sensor, then the elastic modulus of a decompressive cranial defect might be an objective indicator of brain stiffness in patients after DC. The G_maxDp tended to be associated with CP and CT_shift. The stiffness measured using a tactile resonance sensor may thus provide a quantitative assessment of brain edema. Although larger-scale trials are needed to evaluate the diagnostic accuracy of this sensor, the present data suggest that the stiffness variables measured by a sensor correlated with acute brain edema in patients after DC. Specifically, G_maxDp > 3.0 kPa might indicate an increased risk of mortality [Figure 3b].

**Multiple measurements**

Although the purpose of this study was to characterize the association between the stiffness of a decompressive cranial defect and brain edema, parameters of brain edema change on a daily basis in the acute phase of cranial decompression. A sample data set of stiffness was measured at the time of head CT, whose timing was determined at the discretion of attending physician. Thus, CT data and stiffness data were obtained in a one-to-one fashion. CP, BT, and MBP were also determined at the time of stiffness assessment. Thus, data sets corresponded to the daily conditions of acute brain edema and brain edema related factors rather than to the acute phase of brain edema as a whole. As a result, we collected 35 sample data sets from 13 participants in this observational study.

**Meaning of the G-value**

Shear elastic modulus is defined as the ratio of shear stress to the shear strain. Shear stress is the shear force per unit area, and shear strain is the deformation of a solid due to stress. Thus, these variables are related through units of pressure change per unit of volume change. Since elastance was derived from the ratio of pressure to volume change, we speculated that the G-value was related to elastance and that high elastance could lead to increased ICP.

Mathematically, these relationships can be represented as follows:

\[
elastance = \frac{\Delta P}{\Delta V}
\]

\[
\Delta P = \frac{P_t}{S}
\]

\[
\Delta V = \frac{(h \times S)}{3}
\]

elastance = \left(\frac{P_t}{S}\right) \times \left(\frac{hS}{3}\right) = \left(\frac{P_t}{h}\right) \times \left(\frac{3}{S^2}\right)
\]

G = \frac{3P_t}{(16h^2Rh)}

Pr = G \times \frac{1}{13} \times 16hRh

elastance = G \times \frac{1}{13} \times 16hRh \times \left(\frac{3}{S^2}\right)
\]

S = 2\pi Rh

elastance = G \times 16 / (2\pi)^2 \times (Rh)^{-1.5} = 4G / (\pi^2 \times Rh^2h)
\]

where \(P_t\) is loading force of the indenting probe, \(S\) is the contact area of probe, and \(h\) is depth of indentation. If the elastance is evaluated at max depth, \(h = 3.0\ mm\) and \(R = 2.5\ mm\), then,

\[
elastance = 4G / (\pi^2 \times 7.5^2) = 0.02G
\]

This relationship is consistent with the correlation between high G-value and high CP observed in this study and with the relationship between brain edema and elasticity.
Meaning of the Pr-value and dF-value

Our results suggested that the G-value was associated with brain edema. On the other hand, what was the relationship between Pr-value and dF-value? We have created the scattergrams divided into subgroups with $G_{\text{maxDp}} > 3.0$ and those with $G_{\text{maxDp}} < 3.0$ [Figure 6]. There was a linear correlation between Pr and dF values of the individual data sets. It seemed that the borderline between them was Pr-value = 140–160 (gf). In subgroup with $G_{\text{maxDp}} > 3.0$, the correlation between Pr and dF was almost the same. In those with $G_{\text{maxDp}} < 3.0$, the correlation between them was very different in the individual data sets. Lindahl and Omata reported that the change in frequency reflected the superficial portion of the object in contact with the sensor, and they characterized the correlation between tissue fluid translocation during the impression and change in frequency. We previously reported that the dF-value was related to the free water within 2.0 mm from the skin surface. The dF-value might represent the viscosity of the subcutaneous tissue. The problem of dF-value is a challenge for the future.

Study limitations

The limitations of this observational study included the small data sample number and the small patient population. This study had several uncontrolled biases as follows: (1) object bias (age, sex, and underlying disease); (2) measurement timing bias, which was fixed by the CT capturing timing and observer timing; and (3) observer bias for a single investigator, who held the probe manually like a pen to simulate the manner of palpation. Although we continued to keep the perpendicular, non-slipped, and non-pressurized contact on the skin surface as possible for 4 s, the human error derived from the hand-held device was present. However, the statistical power was sufficient to clarify the relationship between stiffness and brain edema in the patients with DC, except for the influence of the substitute dura.

Potential of a tactile resonance sensor

This sensor has the potential to evaluate brain edema by measurements of the stiffness in the area of the DC. Earlier detection of life-threatening brain swelling may help guide prompt treatment and thereby reduce mortality. Establishment of the utility of tactile resonance sensor for clinical screening requires an assessment of its validity, reliability, safety, efficiency, and economic efficacy. With regard to validity, we found that mortality was higher when $G_{\text{maxDp}} > 3.0$ versus $G_{\text{maxDp}} < 3.0$. With regard to reliability, we found that the CV of the sensor in the agar test was almost 10%, although we did not test it in patients after DC. With regard to safety, we did not encounter any adverse effects; the sensor was non-invasive and carried no risk for DC patients. The sensor enabled measurements to be obtained quickly, without any incremental cost for successive measurements. The confounding biases of BT, MBP, and breadth of cranial defect were not significant. Taken together, these findings suggest that the stiffness variables measured by the sensor were of clinical significance. Thus, measurement of stiffness might become a screening test for patients requiring CT imaging, invasive monitoring, hypothermia therapy, and additional craniectomy. The advantage of the sensor is that it is hand-held, works in real time, and provides data quickly, thus being readily applicable for intraoperative assessment of brain stiffness and elastance, if used under sterile conditions.
In conclusion, we determined that the stiffness variables in the area of the cranial defect in patients with DC were $P_r = 96.14 \pm 52.41$ (gf), $dF = 101.71 \pm 36.42$ (Hz), and $G = 1.99 \pm 1.11$ (kPa). The time axis of $G_{\text{maxDp}}$ was associated with the time course of brain edema. A $G$-value $>3.0$ was associated with higher mortality related to acute brain swelling. The $G_{\text{maxDp}}$ was associated with the CP and edema-related brain shift. We believe that this sensor is a simple and useful tool for assessing acute brain swelling in patients with decompressive cranial defects.

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