Intracranial Pressure—
Theory of the Driving Pressure
and a New Pressure Index

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Summary

In order to understand the pathogenesis of increased intracranial pressure, the concept of the driving pressure (DP) from the intracranial vascular system was proposed. The DP consists of combined pressure continuously transmitted from the arterial pressure (ADP) and venous pressure (VP) systems. The theoretical equation of the intracranial pressure (ICP) is expressed as follows:

\[ ICP = ADP + VP \]  

\[ ADP = \eta (BP - VP) \]

\( \eta \) is defined as \( \Delta ICP/\Delta BP \). The authors chose the term driving pressure rate to designate this ratio. Thus, \( \eta \) may be taken for a kind of transfer function which can be expressed as the pressure transmission rate from the arterial system to the cerebrospinal fluid system. Measurement of the \( \eta \) index is simple and allows frequent checks of the often momentary changes in a patient’s condition, thus providing an important index of intracranial pressure environment. Analysis of intracranial pressure by means of the driving pressure concept facilitates understanding of both mean pressure and pulse pressure. The validity of analysis of intracranial pressure in terms of the driving pressure was shown from clinical data and animal experiments.

Introduction

The increase in intracranial pressure has thus far been considered within the context of a kind of closed-type, elastic cranial cavity. Following the Monro-Kellie doctrine, this has been attributed to an increase in the overall volume of elements of which it is composed (brain, blood, and cerebrospinal fluid). Thus, there is a functional relationship between the increase in the intracranial volume and that in the intracranial pressure. This functional relationship between the intracranial pressure and the volume has been the subject of many studies, and considerable discussion has also been devoted to the significance of the dp/dv (or dv/dp) elasticity index of the cranial cavity. However, when one considers blood flow into and out of the cranial cavity (i.e., approximately 1000 ml/min), the question is raised as to whether or not, in fact, this is solely a matter of a relationship between the intracranial pressure and the volume.

The authors have conducted a series of clinical tests and experiments involving animals \(^1\) in which the intracranial pressure was continuously recorded. Extreme intracranial hypertension was found to follow exactly the same pattern as the arterial pressure, and these very high pressures were also found to fall almost to the atmospheric pressure with cardiac arrest. These facts were taken as possible evidence that the intracranial pressure was derived to some extent from the so-
called driving pressure generated from the arterial and venous pressures. Hence, the authors attempted to apply this concept of driving pressure to the study of intracranial pressure.

1) Pressure Driving Rate (η) and Driving Pressure (DP)

In light of the continuous pressure on the intracranial pressure from the arteries and veins, the authors chose the term “driving pressure” (DP) to designate this particular kind of pressure. Thus, the driving pressure of the arterial pressure on the intracranial pressure is expressed as the arterial driving pressure (ADP), and the driving pressure rate may be stated:

\[ \eta = \frac{\Delta ICP}{\Delta BP} \]  

Because \( \eta \) in this equation varies with the level of intracranial pressure, it must be computed in terms of organic conditions. When the blood pressure varies from 100 to 120 mmHg, the cerebrospinal fluid pressure changes from 50 to 55 mmAq. Thus, theoretically, by calculating \( (55-50)/(120-100) \times 13.56 \), we obtain \( \eta = 1.82 \times 10^{-2} \). In this way, \( \eta \) serves as a key index of intracranial pressure conditions corresponding to dp/dv for the volumetric pressure. Cross sections of open (A) and closed (B) cavity systems and of an actual elastic-type cranial cavity (C) system are shown in Fig. 1. The driving pressure and the pressure-volume relationship in each cavity system are shown in Fig. 2. In an open type cavity, this \( \eta \) is put at 0; in a closed cavity system, it is arbitrarily assumed to be 1.0. The actual cranial cavity is considered to be a semi-closed system like an elastic-type cavity, and \( \eta \) is positioned somewhere between 0 and 1.0, the driving pressure level being indicated by the arterial pressure as intracranial pressure.

2) Actual Calculation of Driving Pressure Rate (η)

Nevertheless, when actually computing the \( \eta \) index, we must take into account the gradual change in driving pressure rate for mean pressure and pulsations in the CSF. Figure 3 shows a trace of simultaneous measurements of arterial and cisternal pressures in a mongrel dog. The intracranial pressure is accompanied by changes in respiration and heart beat. Therefore, in order to calculate the ratio in terms of gradual wave distortion from the arterial pressure, the driving pressure rate, will assume the following forms.

\[ \eta = \frac{\text{mean ICP} - (VP)}{\text{mean BP} - (VP)} \]  
\[ \eta_{HB} = \frac{\text{amplitude of ICP}}{\text{amplitude of BP}} \]  
\[ \eta_{Resp} = \frac{\text{respiratory variation of ICP}}{\text{respiratory variation of BP}} \]

When these forms are applied to the case of Fig. 3, \( \eta = 1.3 \times 10^{-2} \) and \( \eta_{Resp} = 4.8 \times 10^{-2} \). The difference among these indices makes it clear that the pressure transmission rate from the artery to the CSF varies with the mean pressure and pulsations. The total resistance (Z) in relation to the pressure between arterial blood and CSF contains resistance of a special type (i.e., compliance and internance which work only on pulse waves). Thus, the transmission of mean pressure from the cerebral vascular system to the CSF is not always similar to that of pulse waves. For this reason, if the driving pressure rates of both pulsations and mean pressure are obtained, the characteristics of the resistance (Z) in cerebrovascular walls may be calculated. In this way, measurement of the driving pressure rate was taken to be an important basis for the clarification of both the mean CSF pressure and pulsations.

3) Clinical and Experimental Examples of Intracranial Pressure Analysis

The \( \eta \) indices are easily applied to the pressure study. A recording of ventricular pressure in a case with cerebral aneurysm is shown in Fig. 4. The \( \eta_{Resp} \) is 6.0 \times 10^{-2} or almost double the \( \eta_{HB} \) value of 2.8 \times 10^{-2}. This tendency is similar to that for the adult dog in Fig. 3.

Figure 5 shows simultaneous recordings of the cisternal pressure, the left femoral arterial pressure, the jugular venous pressure and respiration in a dog with stab injury. With an extremely high intracranial pressure, \( \eta \) indices approach 1.0. In this case \( \eta, \eta_{HB}, \) and \( \eta_{Resp} \) are calculated 96.0 \times 10^{-2}, 98.0 \times 10^{-2}, \) and 100 \times 10^{-2} respectively. In general, these \( \eta \) indices do not always show the same value. However, they have the same value under a severe intracranial hypertension.

Measurement of the driving pressure rate was possible through dynamic observation of the systemic blood pressure and CSF pressure.
Figs. 1 and 2 Characteristics of the cavities

A) open system (open cavity); B) closed system (rigid closed cavity); C) semi-closed cavity (elastic). Cross sections for analysis of intracranial pressure by means of volumetric pressure and driving pressure concepts. Pressure-volume relationships within the system are shown in terms of driving pressure. Inside pressure conditions may be determined by investigation of dv/dp using the volumetric pressure concept, and obtaining the η index (CSF/BP) from the driving pressure concept. In this case, Pw indicates intrinsic pressure within the system while Pb stands for the pressure on the system which originates from outside.
Figure 6 shows a course of $\eta$ HB during Valsalva's test in the case of lumbar puncture. This patient displayed a $\eta$ HB change from $2.0 \times 10^{-2}$ to $9.0 \times 10^{-2}$ and demonstrated a close correlation with the pressure level.

4) Theoretical Formulation of Driving Pressure (DP)

Since the intracranial pressure may be taken as the sum of the venous pressure and arterial driving pressure (ADP), as indicated in Fig. 7, we can formulate:

$$ICP = ADP + VP$$  \hspace{1cm} (5)

$VP$ is normally close to the atmospheric pressure ($PO$).

If we posit $VP = PO$, and the $\eta$ concept, the ADP is as in Eq. 6:

$$ADP = \eta (BP - VP)$$  \hspace{1cm} (6)

Equation 6 shows the intracranial effect of arterial pressure for the amount by which the site pressure $VP$ is surpassed, and this driving pressure rate is seen to be $\eta$. Thus, Eq. 5 becomes Eq. 7:

$$ICP = \eta (BP - VP) + VP$$  \hspace{1cm} (7)
Hence, the intracranial pressure as usually measured with a pressure transducer is the pressure determined by Eq. 7, which in turn may be converted to Eq. 8.

\[ ICP = \eta \times BP + (1 - \eta) \times VP \] (8)

Since \( \eta \) is normally close to 0 under low intracranial pressure, from Eq. 8 we find that \((1 - \eta) = 1.0\). In other words, in this case the intracranial pressure in the vicinity of VP reflects only the small increment of driving pressure from the arterial pressure. When the intracranial pressure has increased to an extremely high level, \( \eta \) is almost entirely controlled by systemic blood pressure. Therefore, if we employ the driving pressure concept in measuring intracranial pres-
sure and measure the systemic blood pressure at the same time, the pressure environment in the cranial cavity may be evaluated.

**Discussion**

Neurosurgeons have become aware of the importance of systemic blood pressure as a factor affecting ICP. However, little is known as to what degree this affects ICP. Ayer and Davson attempted to clarify the significance of an important effect of arterial and venous pressure, but their considerations were unfortunately insufficient in terms of pressure theory. In 1975, the authors proposed the $\eta$ index and applied it to clinical studies. In these reports, they suggested that ICP was derived to some extent from the systemic blood pressure. Recently, Go et al. calculated "the pressure increase ratio" before and after cold injury as $\Delta VFP/\Delta BP$, which was reduced by hyperventilation. Makatas et al., Symon et al., Nakagawa et al., and de Rougemont et al. calculated the ratio of mean ICP to mean BP and suggested that it was a significant index of cerebral vasomotor tone. These indices represent the pressure transmission rate from the arterial system to the CSF. However, from our theoretical formulation it will be necessary to compensate for venous pressure in order to calculate driving pressure rates accurately.

In a previous report, the pressure transmission rate was examined in the model experiments in which two chambers made of acrylic resin were connected. Various membranes (i.e., rubber, polyester) through which the two acryl chambers were connected side by side were tested, and experimentation was conducted with many kinds of membrane sealing the external surface of the two chambers filled with water. The pressure transmission rate from one chamber to another could be described in terms of the following characteristics: 1) As the compliance of the external membrane becomes larger, the pressure transmission rate was lower; 2) In this condition, not only the external membrane but also the septal membrane specimen affected the pressure transmission rate; 3) The pressure transmission rate of the mean pressure was generally larger than that of the pulsations under this condition; 4) The pressure transmission rate curve of pulsations formed a peak at the point where the mean pressure of the one chamber was equal to that of the other; and 5) As the compliance of both chambers decreased by using solid membranes, the pressure transmission rate through the membrane separation was increased. When the chambers were rigid, the pressure transmission rate of both the mean and pulse pressures showed the same value, that is, 1.0, and this time the membrane specimen did not affect the pressure transmission rate.

From these findings, it is necessary to calculate the $\eta$ indices on both mean and pulse pressures. The different values and the reciprocal relationships among them may enable us to assess the intracranial pressure conditions.

In the human, any disturbance of the CSF circulation and the cerebral blood flow affects the balance of blood flow into and out of the cranial cavity, so it may well have an important role in determining the characteristics of the cranial cavity, namely, the open or closed nature of the cavity. If the cranial cavity is an open system, the arterial blood pressure is not easily transmitted to the CSF system. If, on the other hand, the intracranial cavity becomes on the whole a closed system, the intracranial pressure is easily governed by blood pressure.

Vasomotor tone in the cerebral resistance vessels also plays an important role when the arterial pressure is conveyed to the CSF system. In other words, when the vascular wall is rigid, the arterial pressure is not easily transmitted to the CSF. Conversely, when the vascular wall is less rigid, the pressure is easily transmitted. If the concept of driving pressure is applied, vasodilators could be considered to decrease the elasticity of the vascular walls and thus make it easy to transfer the arterial pressure to the CSF. In this sense our driving pressure concept provides a more advantageous theory with which to explain many phenomena presently dealt with by the concept of volumetric pressure alone.

**Conclusions**

Intracranial pressure can be viewed as a function of pressure in terms of the arterial and venous systems.

Analysis of intracranial pressure by means of the driving pressure concept facilitates under-
standing of both mean pressure and pulse pressure.

Measurement of the driving pressure rate is clinically simple and allows frequent checks of the often momentary changes in patients' condition, thus providing an important index of the intracranial pressure environment.

Acknowledgements

This study was supported (in part) by a Research Grant from the Ministry of Education, Japan.

References