Interhemispheric supratentorial intracranial pressure gradients in head-injured patients: are they clinically important?

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Object. It is generally accepted that the intracranial compartment behaves as a unicameral space in which intracranial pressure (ICP) is uniformly distributed. However, this concept has been challenged many times. Although there is general agreement on the existence of craniospinal and suprainfratentorial gradients, the existence of interhemispheric gradients is still a matter of debate. The object of this study was to reexamine the issue of interhemispheric supratentorial ICP gradients in patients with head injuries and the clinical significance of these gradients in their management.

Methods. The authors present the results of a prospective study conducted in 50 head-injured patients to determine the clinical significance of supratentorial ICP gradients. In each case a concurrent bilateral frontal intraparenchymatosus device was implanted within the 6-hour window after computerized tomography (CT) scanning. According to CT criteria, each patient was categorized into one of three different groups: 1) diffuse lesions, in which no unilaterally measured volumes greater than 25 ml were present and the midline shift was 3 mm or less; 2) Focal A, in which added hemispheric volumes were greater than 25 ml and midline shift was 3 mm or less; and 3) Focal B, in which all patients with a midline shift greater than 3 mm were included. From the results of the entire group the authors were able to distinguish four different patterns of supratentorial ICP. In Pattern I, the intracranial compartment behaved as a true unicameral space with similar mean ICPs and pulse amplitudes in both hemispheres; in Pattern II, different mean ICPs and amplitudes were observed although ICP increases or decreases were congruent; and in Pattern III, patients with different mean ICPs, different ICP amplitudes, and no congruent increases or decreases of ICP were included. All (15 cases) but one patient with a diffuse lesion presented with ICP Pattern I. Fifteen patients with focal lesions showed a Type II pattern, whereas only one patient presented with a Type III pattern. In 10 patients, of whom all but one presented with a focal lesion, transient gradients that disappeared in less than 4 hours were also observed.

Conclusions. In many patients with focal lesions, clinically important interhemispheric ICP gradients exist. In this subset, transient gradients that disappear with time are frequently observed and may indicate an increase in the size of the lesion. The clinical relevance of such gradients is discussed and guidelines for adequately monitoring ICP are suggested to optimize head injury management and to avoid suboptimal or even harmful care in patients with mass lesions.

Key Words • head injury • intracranial pressure gradient • focal lesion • diffuse lesion • intracranial pressure monitoring

Despite wide variations in methodology, intracranial pressure (ICP) monitoring is almost routinely used in the management of severely head injured patients. The rationale for its use has been supported by the report from the Traumatic Coma Data Bank (TCDB) and the recently published Guidelines for the Management of Severe Head Injury. In the TCDB report, elevated ICP (> 20 mm Hg) was observed in 72% of 654 severely head injured patients. Furthermore, Marmarou, et al., discovered that mortality and morbidity rates resulting from severe head injury are strongly related to raised ICP and hypotension. Maintaining an adequate cerebral perfusion pressure (CPP) and avoiding ischemic insults are the accepted main goals in the standard management of head-injured patients. Although some authors propose a CPP threshold of greater than 85 mm Hg as an end point in head injury management, most agree that a CPP of at least 60 to 70 mm Hg is a key goal in these patients. As a result, accurate estimates of CPP and therefore, reliable monitoring of both ICP and mean arterial blood pressure are essential to guide patient care in the acute phase of head injury.

The ventricular catheterization method, still considered the gold standard for ICP monitoring, has been replaced in many medical centers by extradural or brain tissue pressure monitoring. The use of these compartmental measurements of ICP has reopened the controversy of the equality of pressures in the entire intracranial space. According to the traditional concept of ICP monitoring, the intracranial space behaves as a unicameral compartment with pressure equally distributed in each chamber. However, this idea has been challenged many times on the
basis of clinical and experimental observations. In studies in which monkeys were used, Langfitt, et al., documented marked supratentorial ICP gradients in the presence of mass lesions. Nevertheless, clinical studies in which different methods of measurement were used have reached contradictory conclusions. By using subarachnoid catheters, Weaver, et al., observed unilateral ICP gradients in four of 20 patients with mass lesions, whereas Yano, et al., concluded that in patients with head injuries and mass lesions, ICP is identical throughout the supratentorial space.

Discrepancies between studies may be the result of the use of different types of methodologies or of unreliable fluid-coupled transducers. Over the last few years, high-fidelity solid-state fiberoptic devices have been used increasingly in monitoring brain tissue pressure in head injury and also in patients with a wide variety of intracranial lesions. By monitoring brain tissue pressure, Gambardella and colleagues have observed transient ICP gradients in patients with unilateral mass lesions and midline shift. The purpose of our study was to reexamine the issue of interhemispheric supratentorial ICP gradients in head-injured patients and to clarify its clinical relevance in their management.

Clinical Material and Methods

Patient Selection and Monitoring

Fifty patients with a moderate or severe head injury (postresuscitation Glasgow Coma Scale [GCS] score ≤12) who were admitted to our hospital between April 1992 and November 1994 were included in the study protocol. Patients were included in the protocol after the admission or postoperative computerized tomography (CT) scan was performed. Each patient underwent implantation of a concurrent bilateral frontal intraparenchymatous ICP measuring device (model 110-4B; Camino Laboratories, San Diego, CA) within 6 hours of the CT scan. The study protocol was approved by the Institutional Ethical Committee on Human Research of Vall d’Hebron University Hospitals. Informed consent was obtained from the patients’ next of kin.

Patients in whom a dural or bone defect was present were excluded from the study. Both sensors were inserted at the same time, 10 to 12 cm from the nasion and 3 cm from the midline, at an insertion depth of 2 cm. Each sensor was connected to an independent V-420 monitor (Camino Laboratories). The analog output of both monitors was connected to a strip chart recorder (Konik 2010; Ladd Research Industries, Inc., Burlington, VT), with two analog input channels and a recording speed of 20 cm/hour. Simultaneously, the standard recorder (model 427; Camino Laboratoris) was also used at a recording speed of 5 cm/hour. Additionally, hourly concurrent ICP values were recorded by the nurse in charge.

Bilateral ICP readings were recorded for a maximum of 24 hours after the CT scan was obtained to avoid contamination of the results by both the appearance of new lesions and/or methodological problems with the zero drift. After this period of time a new CT scan was obtained in all but five cases. Although dual monitoring was continued in many cases for longer periods of time, only the first 24 hours were included in the analysis. Because only one intraparenchymatous device was removed at the end of the study, the mean ICP was not corrected for the zero drift detected in the removed catheter. Nevertheless, the estimated zero drift for this catheter type has been reported to be approximately 0.6 to 2 mm Hg/day and was found to be 0.3 mm Hg/day in a series of 108 severely head-injured patients studied in our institution (unpublished results).

Classification of CT Scan

Every focal lesion was measured on the CT scan using a planimetric method and the results were added in each hemisphere. The midline shift was also measured and recorded in both initial and control CT scans. In patients in whom a repeated study was obtained, the “worst” CT scan (the one with the highest midline shift and/or the highest measured volume of focal lesions) was used to classify the patient. Patients were categorized into three groups according to the CT criteria: 1) diffuse lesion, in which hemispheric mass lesion volumes greater than 25 ml were not present and the midline shift was 3 mm or less; 2) Focal A, in which the summed volumes of at least one hemisphere were greater than 25 ml and midline shift was 3 mm or less; and 3) Focal B, in which patients had a midline shift greater than 3 mm independently of the total measured volume of each hemisphere. This classification was used in preference to the widely used TCDB classification because in a preliminary statistical analysis we found that the cutoff point to detect ICP gradients was a midline shift of 3 mm, whereas the TCDB classification uses 5 mm of midline shift to categorize some lesions. Furthermore, the high number of categories included in the TCDB classification make statistical analysis difficult with only 50 patients. With the simple diffuse compared with focal classification, we have tried to define very broad categories of patients that can be easily used in the clinical setting. However, the critical volume used to differentiate Focal A and B groups was based on that proposed in the TCDB classification (25 ml).

Analysis of ICP

In each case, the results of dual ICP monitoring were analyzed by one of the authors. The mean ICP was calculated manually at 15-minute intervals with the aid of a precision ruler according to the method suggested by Price and Driscoll. When this method was compared with the nurses’ “end hour” mean, excellent agreement was found between the two methods. The global amplitude of the ICP (cardiac and respiratory component) was also evaluated and measured bilaterally on the chart recording. In addition, each patient’s bilateral ICP recording obtained during the total monitoring time was visually examined to discern transient ICP gradients between both hemispheres that could have been overlooked by comparing only hourly means or amplitudes. In cases in which short-lived gradients were detected, the duration of each episode was measured and the total time was added and rounded off to the nearest minute. The total duration of transient gradients was expressed as a percentage of the total recording time.
Patterns of ICP

In a preliminary analysis of our results, we found that despite the repeated and consistent ICP patterns that were detected, the statistical analysis of the different cases did not give a clear idea of the obvious differences observed. Therefore, we decided to classify ICP findings into four different patterns.

Type I Pattern: Unicameral Space. In this pattern, the intracranial compartment behaves as a true unicameral space with similar mean ICP in both hemispheres. Patients included in this group should have a mean ICP difference between hemispheres of 3 mm Hg or less and differences in global ICP amplitude of 2 mm Hg or less. Spontaneous or therapeutically induced ICP increases and decreases in both hemispheres were always synchronous and perfectly congruent in this group (Fig. 1).

Type II Pattern: Different Compliance. A different mean ICP (> 3 mm Hg) and/or global amplitude (> 2 mm Hg) was observed, although in each case ICP increases and spontaneously or therapeutically induced decreases were always synchronous and highly congruent in both hemispheres (Fig. 2). In this pattern, the ICP profile of the intracranial compartment looked as though both hemispheres had a different compliance.

Type III Pattern: True Bicameral Pattern. In this group we included patients with a completely different ICP profile (mean ICP and/or amplitude) and no congruent ICP increases or decreases in both sides. Those patients who had transient gradients in more than 25% of the total recording time were also included in this group (Fig. 3).

Transient Gradients. The ICP chart recording was carefully examined to detect transient differences in mean ICP, amplitude, or ICP profile. In each case, the duration of the transitory differences in ICP was recorded and the number was totaled and expressed as a percentage of the total recording time (Fig. 4). Therefore, a patient included in one of the previously defined patterns (Type I, II, or III) might also have transitory gradients. Patients with gradients that spanned more than 25% of the total recording time were included in the Type III pattern.
Interhemispheric supratentorial ICP gradients in head-injured patients

![Graph showing Type III ICP pattern](image)

**Fig. 3.** Charts showing Type III ICP pattern. The bilateral ICP recording was made with a strip chart recorder in a 16-year-old boy with a GCS score of 4 as evaluated at the referring hospital. The first CT, which was obtained on admission to our center, showed multiple bilateral intracerebral hematomas with an estimated volume of 40 ml and 10 ml in the right and left hemispheres, respectively. The midline shift was 13 mm. The hematoma in the left hemisphere was not evacuated because of its location in the basal ganglia. Incongruency can be seen between the ICP recordings in both hemispheres. The mean ICP during the 24-hour recording was 71 mm Hg in the right hemisphere, whereas in the left it was 54 mm Hg. The bilateral recording showed a different ICP profile in each hemisphere for more than 75% of the total recording time. There was a difference in amplitude of ICP in both hemispheres and an increase in ICP in the left hemisphere that was not reflected in the right side. This patient was the only one in whom the hemispheres behaved as completely different compartments.

**Statistical Analysis**

The mean ICP in each hemisphere was summarized as the mean ± standard deviation. Differences between means in both hemispheres were statistically analyzed using the paired t-test. Differences were considered statistically significant when the probability value was less than 0.05. All pairs of measurements in each patient were also evaluated using a simple linear regression model. The slope and intercept were calculated using the least squares method. The goodness of fit of the linear relationship was measured using Pearson’s coefficient of linear correlation. For regression analysis, and in patients in whom a diffuse lesion was present, the left hemisphere was arbitrarily chosen as the independent variable. In patients who had focal lesions, the hemisphere with the highest estimated volume was taken as the independent variable.

The mean ICP gradient between both hemispheres in each case was plotted against the mean ICP according to the method suggested by Bland and Altmann4 to assess agreement between quantitative measured variables. According to this method the mean ICP was calculated by adding together the mean for each hemisphere and dividing the result by 2.

As an additional analysis and to determine the clinical relevance of the observed gradients and their repercussion in CPP management, the number of CPP readings of 60 mm Hg or lower was calculated for each hemisphere and for each group of patients (diffuse, Focal A, and Focal B). The mean CPP was calculated from the difference between the mean ICP and the mean blood pressure. The percentage of CPP readings of less than 60 mm Hg in the hemisphere with the greatest mass volume was compared with that calculated from the “no-mass” side by using the chi-square method. As an additional way to determine the clinical relevance of ICP gradients, we calculated the differential CPP for every dual reading. The absolute value of the difference was then taken and the results grouped by 5-mm Hg differences.

**Results**

**Age, Sex, and Type of Lesion**

The mean age of patients in our series was 34 ± 14.4 years (mean ± standard deviation) with ages ranging from 16 to 65 years. Forty-seven patients were male (94%) and three were female (6%). Of the 50 patients, 43 (86%) had been injured in motor vehicle accidents. Analysis of the best postresuscitation GCS score showed that 25 patients (50%) had scores of 5 or lower, 16 patients (32%) had scores of between 6 and 8, and nine (18%) had a GCS score between 9 and 12. All patients in the severely injured group (GCS score ≤ 8) lost consciousness immediately on impact.

Classified according to their CT scans and the aforementioned criteria, 15 patients (30%) were included in the diffuse group and 35 (70%) in the focal lesion categories. Of the 35 patients with a focal lesion, nine (26%) had a focal lesion without midline shift (Focal A group) and 26 (74%) had a mass lesion with midline shift greater than 3 mm (Focal B group). Of the 15 patients in the diffuse lesion group, three had a bilateral swelling with compressed (two cases) or absent (one case) basal cisterns.
Lesion Type and ICP Pattern

The type of lesion according to the aforementioned criteria and the type of ICP pattern are summarized in Table 1. Thirty-three patients (66%) of the entire group presented with a Type I ICP pattern. Fourteen (42%) of these 33 patients had a diffuse lesion and 19 (57.6%) had a focal lesion. A midline shift greater than 3 mm was found in 15 of these 33 cases (Table 1). The correlation coefficient for ICP readings between both hemispheres was 0.95 ± 0.04 in this group (range 0.82–0.99, Fig. 5). The difference between the mean ICP in both hemispheres was 1.8 ± 1.1 mm Hg.

Sixteen patients (32%) demonstrated a Type II ICP pattern (Fig. 2). In all these cases, the higher ICP was observed in the side with the highest measured volume. All but one patient had a focal lesion and in 10 a midline shift greater than 3 mm was found. The correlation coefficient in this group ranged from 0.49 to 0.99, with a mean of 0.85 ± 0.15. The mean ICP gradient between hemispheres was 7.5 ± 6.4. In three of these cases, the mean ICP gradient was higher than 5 mm Hg and in three it was higher than 10 mm Hg.

Only one patient in the entire group presented with a Type III ICP pattern. This patient had a midline shift of 13 mm and an unevacuated 40-ml right basal ganglia hematoma. The ICP profile was completely different in each hemisphere, with no congruent ICP increases or decreases in response to therapeutic maneuvers (Fig. 3).

In our series there were only three patients with predominant temporal lobe lesions. The lesions in all these cases were brain contusions of different volumes. In these patients the highest ICP was always detected in the transducer ipsilateral to the mass lesion (Fig. 6).

Transient gradients were observed in 10 cases, and all but one of these patients had a focal lesion and midline shift (Table 1). In these 10 cases, 36 transitory episodes were found and ranged from 15 minutes to 3 hours in duration. A repeated CT scan was obtained in eight of the 10 cases. In six patients the new CT scan revealed a variable increase in the volume of the focal lesion and/or midline shift, whereas in two patients no significant measurable differences were observed. Only one patient with a diffuse lesion presented with transient gradients in the dual ICP recording; this patient did not have a “pure” diffuse lesion but a 16-ml basal ganglia hematoma that had increased to 19 ml on the control CT scan (Fig. 7). Part of this patient’s ICP chart is shown in Fig. 4.

A graphic analysis of the agreement between ICP in both hemispheres in patients in the three different groups is shown in Fig. 8 by using Bland and Altman’s method.

Intracranial Pressure Gradients and CPP

The clinical importance of ICP gradients in managing CPP in these patients was analyzed. To do this, CPP was...
calculated for each hemisphere and the difference in CPP for each pair of ICP readings was calculated according to the following equation:

\[ CPP_d = CPP_{mass} - CPP_{no\ mass} \]

where CPP_{mass} represents the CPP calculated in the hemisphere with the greatest volume. Differences in calculated CPP of greater than 5 mm Hg were considered clinically relevant. The results of this analysis are shown in Fig. 9. Clinically significant differences (≥ 5 mm Hg) in calculated CPP were detected in 24% of the CPP readings in patients in the Focal A category and in 23% of the readings in patients included in the Focal B category. No patient in the diffuse injury group had a calculated CPP difference greater than 5 mm Hg.

**Discussion**

Technological advances in the last decade have led to the development of more accurate and higher quality ICP devices, whereas the use of computers has improved recording methods and permitted sophisticated on-line analysis. Nevertheless, some basic methodological aspects of ICP monitoring are still matters for debate. Among them, the behavior of ICP in the different intracranial compartments is arguably the most important. The recent availability of accurate and reliable solid-state fiberoptic transducers capable of monitoring ICP from every brain compartment has reopened the controversy about the equality of pressures in the entire intracranial space. Furthermore, the importance of obtaining an accurate estimate of CPP for the management of head-injured patients has increased the relevance of this issue.

The most relevant studies in the literature concerning ICP gradients in the supratentorial space have been conducted using fluid-filled catheters and the ICP has been monitored from the subarachnoid or subdural compartments. With this type of transducer, differences between the levels of the catheter tips in both hemispheres can cause significant discrepancies in the measured ICPs. Furthermore, the different measuring methods used have made it difficult to compare results. The main advantage of transducer-tipped pressure monitoring devices is that there is no need to determine a reference point because the resulting pressure is unaffected by hydrostatic force. Therefore, these catheters are free of the possible artifacts generated by the differences in the leveling of the external transducers, a problem commonly encountered when using fluid-filled catheters.

**Gradients of ICP Between the Supra- and Infratentorial Compartments**

The existence of gradients between the supratentorial compartments or between the posterior fossa and the spinal subarachnoid space has been observed and confirmed both in experimental models in different animal species and in clinical studies. Using an extradural balloon as a model of mass lesion in monkeys, Langfitt, et al., demonstrated the existence of gradients and their dependency on the patency of the basal cisterns surrounding the brainstem at the level of the tentorial incisura. In a model of epidural bleeding in swine, Ganz, et al., also demonstrated ICP gradients between the pressures measured in the lateral ventricles and in the cisterna magna. In this model, supratentorial was higher than infratentorial ICP, with a pressure gradient ranging from 15 to 33 mm Hg.
depending on the final mass volume. Supra/infratentorial ICP gradients were also observed in experimental animal models that simulated subdural bleeding.

In the clinical arena, Smyth and Henderson showed pressure gradients between the ventricular fluid and the lumbar subarachnoid pressures in the presence of supratentorial tumors. A block at the tentorial incisura was suggested as the mechanism for these differences. An additional study was performed by Rosenwasser, et al., in 20 patients who had mass lesions in the posterior fossa and in whom simultaneous measurements of ICP were recorded in the posterior fossa and supratentorial compartment. These authors found a 50% difference in mean ICP between both compartments during the first 12 hours of monitoring. However, these differences disappeared after 48 hours.

**Differences in ICP Within the Supratentorial Compartment**

**Experimental Models.** It would appear that under normal circumstances there is little intercompartmental difference in pressures between the cerebral hemispheres. Nevertheless, the existence of brain shifts or blocks in the subarachnoid spaces may break the equilibrium that usually exists between these well-communicating compartments. In an early, outstanding paper on this subject, Cushing already distinguished between “local” and “general” compression. Local compression was experimentally produced by inflating a subdural rubber bag with mercury, which resulted in an “unequal distribution of intracranial tension.” Later, in a theoretical study of the mechanisms of herniation of the brain tissue, Holbourn put forward the theory that ICP is an inadequate description of the true conditions in which expanding masses exist within the intracranial compartment. According to this author, “…the hydrostatic pressure was higher near the tumor than elsewhere.”

Although in some experimental animal models brain tissue pressure has been measured and it has been demonstrated that ICP gradients can exist between both hemispheres, some authors have stated that the cause of these gradients in some cases may be attributed to methodological problems and artifacts. This is a point to consider given that most of the studies in animal models that have demonstrated these gradients have used the inaccurate so-called “wick” or “floppy cuff” catheters as measuring devices. By using floppy-cuff intracerebral catheters both in cats and monkeys, Miller, et al., showed evidence of temporary ICP gradients between both hemispheres in animal models of mass lesion. They observed interhemispheric differential pressures ranging from 5 to 14 mm Hg. In another study, Tulleken, et al., showed gradients across the supratentorial space in cats and baboons in which cerebral infarcts were induced by middle cerebral artery occlusion. In the same study these authors reported no evidence of interhemispheric gradients when blood was injected into the subdural space or the occipital lobe. However, the size of the mass and the induced midline shift were not mentioned in the report on this model. The main conclusion of the study was that the speed of growth of the intracranial space-occupying lesion is very critical in the development of supratentorial gradients and that transient gradients are the most common ICP pattern found between both hemispheres in the presence of mass lesions. In another animal model, in which mass lesions were induced by a posterior parietooccipital extradural balloon in baboons, Symon, et al., also demonstrated the existence of significant interhemispheric ICP gradients. In their elegant paper, interhemispheric differences in calculated CPP were also observed. When the ICP was lower than 10 mm Hg, the pressures measured in the four selected extradural points (frontal and parietal bilaterally) were almost identical. However, when the pressure was higher than 30 mm Hg, the ICP was greater in the hemisphere in which the mass lesion was located. In contradiction, Crutchfield, et al., who used the same type of intraparenchymatous fiberoptic transducer that we used in our study, did not find differences between compartments in one mongrel dog in which an epidural balloon was inflated intracranially. However, the absence of essential data regarding the volume of the balloon and the midline shift induced makes the analysis of their results difficult.

In two separate and recently published studies, Wolfla and colleagues have analyzed this problem in pigs in which frontal and temporal extradural masses were mimicked by inflating a Foley balloon. In both studies the short-term response (< 1 hour) of the pressures at different points in the intracranial space were recorded (both temporal lobes, both frontal lobes, midbrain, and cerebellum). In their first paper, in which they reproduced a frontal extradural lesion, the authors found that consistent ICP gradients appeared after they inflated the balloon and that these gradients could be systematically reproduced in all the animals. In general, frontal transducers measured significantly higher ICPs than the temporal monitors, and the highest pressure was always found in the transducer closest to the mass lesion. The mean maximum differences between regional pressures in both frontal lobes were not significant in most cases. However, despite these observed differences, in all the animals studied, the increasing volume was detected by every device inserted in the intracranial space. In their second study investigat-
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Differences in ICP in the Supratentorial Compartment

Clinical Studies. Few papers have addressed the topic of supratentorial ICP gradients from a clinical point of view and in those that have, conflicting results have been reported. Pressure gradients in the same hemisphere (intrahemispheric gradients) or between the hemispheres (interhemispheric gradients) have been demonstrated.\(^5,8,11,12,24,26,27,40\) Crockard, et al.,\(^8\) observed that in a patient with a thalamic tumor obstructing the ventricular system there were sustained differences between the anterior and posterior part of the same obstructed lateral ventricle. In another study, Broadus, et al.,\(^3\) demonstrated intrahemispheric gradients of more than 10 mm Hg in 47\% of patients with mass lesions by using frontal and parietal subarachnoid bolts placed in the same hemisphere. Differences in brain tissue pressure of up to 28 mm Hg have been reported postoperatively in patients with brain tumors.\(^27\) In the last study, and in most cases, the ICP was higher near the tumor bed. Nevertheless, the contral was also observed in four of the 11 cases.

Interhemispheric gradients were also studied by Weaver, et al.,\(^40\) using Richmond screws. In that report clear-cut differential interhemispheric pressures were found in four of 20 patients with focal lesions. However, according to the authors, “... more than 50\% of the 20 patients evaluated demonstrated significant differential ICPs at some time during their period of continuous monitoring.”\(^40\)

In another study in which bilateral subarachnoid screws were used, Marshall, et al.,\(^22\) found differences in the range of 5 to 10 mm Hg in three of 16 cases studied. The authors suggested that the falx served as a damping point blunting interhemispheric pressure transmission. Using bilateral extradural transducers, Roux, et al.,\(^33\) conducted a study in 13 patients who suffered spontaneous intracerebral hematoma. Although the percentage of patients with significant ICP gradients is not mentioned, the authors presented four in whom such ICP gradients could be observed. The bilateral ICP chart of one patient was shown (Observation 3), which may be classified under what we have called the Type II pattern. In an additional study, Mindermann, et al.,\(^25\) reported on a case of unilateral brain swelling and no midline shift in which an extradurally measured ICP gradient of 30 mm Hg was found.

In contrast to the aforementioned studies, other authors have not found interhemispheric gradients in head-injured patients. Using bilateral subarachnoid transducers in 15 patients with severe head injuries, Yano, et al.,\(^43\) found that the mean ICP was equally distributed throughout the supratentorial space. In their own words, “... the intracranial space, especially the supratentorial space, is one compartment in which pressure distribution is generally uniform.”\(^43\) Yano, et al., found similar ICPs in both hemispheres in spite of patients presenting with focal lesions and midline shift. Nevertheless, in this study no measurements of midline shift or volume of the mass lesions were reported, making it difficult to compare their findings with our results. However, when analyzing the data presented by Yano et al.,\(^43\) differences in ICP amplitude are observed in some of the cases studied. These cases would probably correspond to our described Type II ICP pattern. Furthermore, in this paper, agreement between measurements in both hemispheres is analyzed using the misleading correlation coefficient. Other studies have shown that significant disagreement can exist between two variables even in the presence of a very high correlation coefficient.\(^1,3,4\)

In another study detailed in separate reports, Gambarrella and colleagues\(^11,12\) demonstrated a good correlation between both hemispheres in six patients in whom simultaneous bilateral brain tissue ICP was recorded. Nevertheless, in four of these patients, transient ICP gradients of 10 to 20 mm Hg that lasted no more than 2 hours were observed. According to these authors, in those cases in which a transitory ICP gradient was detected, an acute increase of the brain volume ipsilateral to the mass was found. In agreement with this study, we found that transient gradients can exist in focal lesions and that these differences in general tend to disappear with time. In these cases, the intracranial space behaves as a bicameral compartment in which the ICP is unequally distributed for a variable period of time. Reduction and complete disappearance of ICP gradients over time may be attributed to the brain’s relaxation and accommodation to the new volume increase.\(^44\)

Methodological Issues

In our study the “end-hour” nurse-recorded ICP was used for analysis. One of the advantages of using this variable is that intensive care unit nurses are trained to discard ICP artifacts and consequently spurious or inappropriate readings are detected and rejected before being recorded. The accuracy and reliability of the end hour to estimate ICP has been reported by Turner, et al.,\(^39\) who compared it with a sophisticated computerized system. Based on that pilot study, the TCDB accepted the end-hour recording of bedside ICP as a quantitative descriptor of the ICP course.

A further important methodological issue is the type of analysis used in earlier studies to compare ICPs between both hemispheres. In general, the Pearson correlation coefficient has been widely used to compare agreement between two methods of measurement when observations are made on a continuous scale. Nevertheless, it has been suggested that the correlation coefficient is misleading in identifying agreement because it is blind to systematic differences or bias.\(^1,3,4\) High correlations do not necessarily mean that there is agreement between methods.\(^1\) The cor-
relation coefficient can be high (> 0.9) when, for instance, one monitor systematically gives an ICP two or three times higher than the other. To avoid this problem, Altman and Bland\textsuperscript{41} suggested a new method based on analysis of variance and graphic analysis to compare two variables when both are measured on a continuous scale. We believe that this method is very useful for comparing the ICP in two compartments because it avoids the problems already stated. This method is based on plotting the mean of the two measurements against the difference between both readings. This type of analysis was used in our Fig. 8.

**Interhemispheric Gradients in Diffuse Lesions**

In our study, no patient with a diffuse brain lesion according to the aforementioned criteria (midline shift ≤ 3 mm and hemispheric volume < 25 ml) presented with clinically significant supratentorial ICP gradients. Small, statistically significant interhemispheric gradients were sometimes found, but they probably reflect methodological differences rather than true gradients. In our opinion, these small gradients should be disregarded because they may be caused by technical artifacts such as a more marked zero drift in one of the sensors. Wolfla, et al.,\textsuperscript{42} had already observed small differences (< 2 mm Hg) between monitors in their aforementioned study, in which they used the same fiberoptic transducer as ours. This means that methodological differences are probably unavoidable even in very controlled conditions such as those found in the laboratory. Furthermore, although very small ICP gradients may be important from a theoretical point of view, they are insignificant in the clinical management of severely head injured patients. In patients who have diffuse lesions, we can assume that the intracranial compartment behaves as a unicameral space and therefore ICP is nearly identical in both hemispheres. However, the possibility of an increase in the volume of small focal lesions justifies monitoring the brain tissue pressure on the ipsilateral side.

**Interhemispheric Gradients in Focal Lesions**

Interhemispheric ICP gradients were detected in approximately half of the patients who had a focal lesion. All of these patients presented with the higher pressure in the hemisphere in which the greatest mass lesion volume was present. Our results therefore agree with the majority of findings in experimental animal models of mass lesions, in which the brain tissue pressure was always higher in the hemisphere harboring the mass.\textsuperscript{25} Symon, et al.,\textsuperscript{36} using an extradural balloon and four different extradural transducers, found that the pressures in the supratentorial compartment on the side of the balloon became significantly higher than those in the opposite side of the falx. In our study the highest ICP was never found in the side contralateral to the hemisphere with the higher volume. This was even the case in a few patients who had intradural lesions located in the temporal lobe (Fig. 6). These findings would appear to contradict the observations made by Wolfla and colleagues\textsuperscript{41,42} in the aforementioned swine experimental model of extradural temporal lesions. In their study, the highest ICP was always found in the side contralateral to the mass. These discrepancies may be due to the fact that in those authors’ animal model an extradural mass was reproduced, whereas in our study all of the mass lesions were intradural. A further explanation of these discrepancies may be that in the studies by Wolfla and colleagues\textsuperscript{41,42} only short-term recordings were made. Moreover, anatomical differences between the intracranial compartment of man and swine may also be the basis for these discrepancies, which were only observed in cases of temporal mass lesions and not in frontal masses.

In our study, the most frequent pattern found in patients with focal lesions and interhemispheric differences was what we have called the Type II pattern. A true bicameral pattern was observed in only one patient who had a severe midline shift. In this patient the ICP recording made on the left side was completely different and incongruent with the recording in the contralateral hemisphere. As a hypothesis, we can suggest that the Type II ICP pattern is probably found when blockage of the cisterns is not complete or in those patients in whom the ICP is still transmitted through the vascular compartment despite complete obstruction. In those cases the compliance of both hemispheres may be different, and therefore the ICP response of the hemispheres to the periodic increases in blood volume induced by each cardiac cycle is reflected differently in each side. Complete obstruction of the subarachnoid spaces probably produces a Type III ICP pattern only when the transmission of ICP through the vascular compartment is also impaired, as when ischemia or infarction is present. In these cases, the ability of the brain to transmit pressure is severely reduced and both hemispheres behave as isolated compartments. In such cases, the incongruent bilateral recording could be generated by the complete blockage of the subarachnoid spaces and/or by important differences in the perfusion pressure of the brain tissue. However, these are only speculations, and to confirm these points the issue should be further studied in animal models.

**Clinical Relevance of Interhemispheric Gradients**

In the management of head injuries, ICP monitoring can be a valuable tool in deciding surgical treatment for patients with an unevacuated mass lesion or those with a high risk of developing new focal lesions. Therefore, reliable and accurate ICP measurement is essential in order to improve patient care, avoid pitfalls, and make everyday clinical decisions simple and straightforward. The most relevant issue regarding the existence of differential pressures in the supratentorial compartment is that inappropriate sensor placement can lead to inadequate management of those patients with predominantly unilateral brain lesions. Concerning these patients we agree with Wolfla, et al.,\textsuperscript{42} when they call into question “the use of ‘global’ ICP management strategies that may not be effective in certain focal brain injuries.”

In 25% of patients who had a focal lesion, the ICP gradients found in our study were considered clinically significant because the therapeutic management based on ICP monitoring, especially the control of CPP, would have to be changed. As previously described by other authors, in some patients who had a focal lesion and midline shift, transient gradients could exist, indicating an increase in

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the mass lesion volume or the development of a new lesion. This situation was found in the majority of our patients in whom the CT scan was repeated after transient ICP gradients had been detected. The existence of these transitory gradients, which usually disappear in a matter of hours, reflects the fact that in some circumstances ICP transmission between hemispheres may be delayed when the volume of mass lesions increases abruptly. It is likely that the increase in pressure brought about by the increase in volume gradually disappears in those patients in whom an incomplete blockage of the subarachnoidal spaces is present.

As a result of our findings, we suggest that to optimize ICP monitoring in patients with a mass lesion larger than 25 ml and/or midline shift, the measuring device should preferably be implanted in both the brain parenchyma and the side of the mass. However, our study has been limited to the monitoring of brain tissue pressure in intradural lesions and it may be that extradural lesions behave somewhat differently. Langfitt, et al. have emphasized that in these cases the dura mater can prevent transmission of pressure from the mass to the underlying brain. Furthermore, because of the design of our study, further studies will be necessary to validate our data when different compartments are monitored, especially when the sensor is implanted in the extradural space or in the intraventricular compartment. We cannot say for sure whether in cases of extradural monitoring the small gradients detected in brain tissue pressure are transmitted equally to the extradural device. In an experimental model in monkeys, in which Langfitt, et al. used bilateral extradural monitoring of the ICP, they observed that the increases provoked by acute injections in the extradural space were not fully transmitted to the contralateral extradural compartment or to the subarachnoid space. On the other hand, when the rise in ICP was induced by subarachnoid fluid injection, this increase was evenly transmitted to the contralateral extradural compartment. In chronic preparations, the ICP gradients also existed but disappeared in the days following injections. Nevertheless, in this chronic experimental model, subarachnoid bolts were used as monitoring devices, and we now know that the reliability of these devices is far from excellent. According to Langfitt, et al., the main limiting factor in the transmission of ICP was the dura mater, which was considered to be nondistendible within the range of pressures observed.

In the unusual case of monitoring extradural temporal lesions, the study of Wolfia, et al. has to be taken into account. However, in our opinion their findings have to be confirmed in humans before changing the practice of implanting the sensing device ipsilateral to the mass. It is also our opinion that bilateral cerebral tissue pressure monitoring could probably be justified in a highly selected group of patients with focal lesions and midline shift. In this particular group, brain tissue monitoring can allow detection of the increase of a mass or the development of a new lesion earlier and therefore, in some cases, help the physician anticipate neurological deterioration. This point is of course debatable, because the risk/benefit ratio for this type of management must be studied and has not yet been reported. Because of this we cannot suggest that this method is appropriate for routine use in the daily clinical care of head-injured patients.

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