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AUDITORY BRAIN-STEM RESPONSES IN HYDROCEPHALIC PATIENTS

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The multiple problems associated with hydrocephalus put patients with this disorder at risk for hearing loss and brain-stem damage. As a measure of both hearing and brain-stem dysfunction (Starr and Achor 1975; Davis 1976; Galambos and Hecox 1977), auditory brain-stem response (ABR) is a valuable diagnostic tool for use in these patients, especially infants and neonates.

We became interested in studying the ABRs of hydrocephalic patients when it became apparent from our clinical experience that the incidence of ABR abnormalities suggesting clinically unsuspected brain-stem dysfunction was unusually high in this group. The intent of this investigation was to delineate the incidence and nature of ABR abnormalities in hydrocephalic patients.

Methods

ABR and clinical findings were examined in 40 patients (80 ears) with confirmed hydrocephalus. Twenty-nine patients were less than 3 years old; 9 patients were between 3 and 11 years old; 2 patients were adults. Follow-up testing was conducted in 9 patients several months after the initial test date.

Auditory brain-stem responses were obtained by averaging a differentially recorded EEG signal (G1: vertex; G2: ipsilateral mastoid; ground: forehead). The averaging computer recorded 20 msec of poststimulus time using 20 μsec sampling bins. The EEG signal was recorded using gold cup electrodes and was differentially amplified (amplification 20,000) with bandpass filters at 100 and 2000 Hz (6 dB/octave). Acoustic rarefaction clicks produced by rectangular wave pulses (0.1 msec duration) were presented monaurally at a rate of 20/sec to TDH-39 earphones mounted in MX-41 cushions. Click hearing level (HL) was referred to average thresholds from a group of normal hearing subjects and power spectrum characteristics of the click stimuli were the same as published previously (Özdamar and Stein 1981). Stimuli were presented in 10 dB increments ranging from threshold to 90 dB HL. Threshold was defined as the lowest intensity stimulus yielding a measurable response.

ABR abnormalities were of several types and were characterized in the following manner. ABRs were considered neurologically abnormal, that is, reflecting dysfunction of the auditory brain-stem pathways, if there were abnormalities in I–V interwave latency, V/I amplitude ratio, or abnormalities in wave shape, latency, or amplitude of the major ABR components, I, III and V. Any V/I ratio less than 1 was considered abnormal (Stockard and Rossiter 1977). Amplitude ratio criteria were used only for patients older than 16 months so that any abnormality detected could not be attributed to developmental causes (Picton et al., 1981). ABR threshold values were characterized as normal ($\leqslant$ 20 dB HL), elevated (> 20 dB HL), and no response.

The diagnosis of hydrocephalus was based on the presence of macrocephaly (HC > 97th percentile) plus ventriculomegaly, progressive enlarge-

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ment of the ventricles, even if the head was not macrocephalic, or signs of increased intracranial pressure in the presence of ventriculomegaly. All of the patients studied were treated with ventriculo-peritoneal shunting prior to ABR testing. Several of the patients with severe brain damage and a functioning ventriculo-peritoneal shunt were microcephalic at the time of testing. Most of the patients had mental impairment of mild to marked degree.

Etiology of hydrocephalus was noted, and particular attention was paid to the 3 most common etiologies: congenital anomaly, meningitis, and intracranial hemorrhage. Patients were classified according to Nellhaus categories: normocephalic, microcephalic (HC < 3rd percentile), and macrocephalic (HC > 97th percentile), based on measurements of head circumference obtained at or close to the ABR test date (Nellhaus 1968). Hydrocephalic symptoms associated with brain-stem dysfunction, such as nystagmus, other eye movement abnormalities and ataxia were noted. CT scans were reviewed, and the type of hydrocephalus, communicating or obstructive, was determined. Each of these clinical parameters was then analyzed with chi-square tests to determine possible relationships to specific ABR abnormalities.

Results

Classification of ABR abnormalities

A normal response (trace A) is compared with different types of ABR abnormalities observed with hydrocephalus in Fig. 1. The most common abnormal response was distortion of wave V, while waves I and III were normally shaped and were obtained at normal latencies. As shown in the second tracing (B), wave V tended to be broad and of low amplitude, lacking the characteristic sharp negative slope. As a result of the reduction in wave V, abnormal amplitude ratios were obtained (tracing C). It was not uncommon for wave V to be absent, as shown in tracing F. Tracings D and E illustrate instances in which all of the ABR wave forms were affected. The bottom tracing shows the case in which no sound-evoked bioelectric activity was obtained.

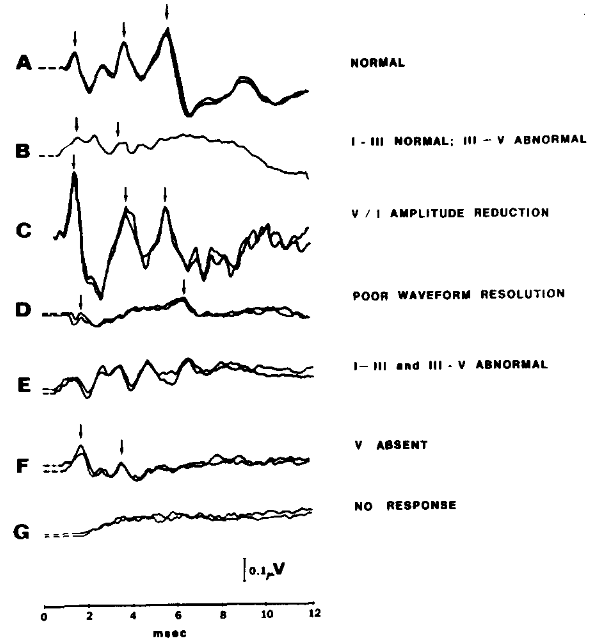

Fig. 1. Types of ABR abnormalities associated with hydrocephalus. Arrows designate components I, III and V.

Table I illustrates the incidence of these abnormalities in our patient population. Since ABR findings were bilaterally symmetric in nearly all (88%) of the patients tested, percentages refer to patients and not to individual ears. Approxi-

TABLE I

Incidence of ABR abnormalities in hydrocephalic patients (N = 40).

	Percent abnormal
Neurologic	
I–V latency	38
V/I amplitude ratio	33
Wave I	0
Wave III	27
Wave V	53
Threshold	
Elevated > 20 dB HL (including no response)	70
No response	25
ABR abnormality (total) (including neurologic and threshold)	88

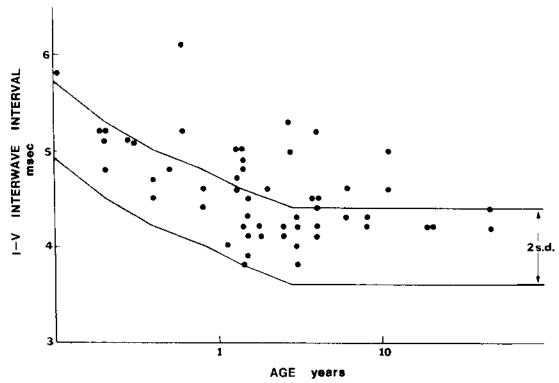

Fig. 2. I–V interwave latency. Values of hydrocephalic patients plotted as a function of age (logarithmic scale). The solid lines enclose 2 S.D. of the mean I–V conduction times obtained from normal subjects.

mately one-third of the patients showed abnormalities in I–V latency (Fig. 2), and V/I amplitude ratio. Wave V abnormalities were observed in half of the patients studied, while one-third of the patients showed abnormalities in wave III. Since waves III and V are believed to reflect pontine and midbrain activity respectively, the observed ABR abnormalities appear to indicate more frequent dysfunction of the rostral than the caudal brainstem.

ABR click thresholds were elevated ($>$ 20 dB HL) in 45% of the patients tested. No ABR activity was obtained in another 25% of cases. Therefore, 70% showed some form of threshold abnormality. The extent to which these threshold abnormalities may reflect brain-stem dysfunction vs. peripheral hearing loss is addressed in the Discussion. In all, 88% of the hydrocephalic patients exhibited some form of ABR abnormality (neurologic or threshold).

Clinical correlations

As a majority of the patients (88%) had hydrocephalus due to congenital abnormalities, meningitis, or intracranial hemorrhage, we examined the possible correlation of these etiologies with specific ABR abnormalities. Chi-square analyses suggested that no one etiology was associated with particular wave form abnormalities. Presence of hydrocephalus, regardless of etiology, seemed to be the major factor in producing abnormal wave forms.

Head size was also examined with respect to ABR. Again, there was no significant correlation between the type of ABR abnormality and head circumference. Normal, abnormal and no response cases were evenly distributed among normocephalic, macrocephalic and microcephalic patients. Presence of clinical signs of brain-stem dysfunction (nystagmus, other eye movement abnormalities, or ataxia) also did not significantly correlate with the patients' ABR.

There was a significant correlation between the type of hydrocephalus (communicating vs. obstructive) ($P < 0.01$) and ABR abnormality. Specifically, absence of ABR activity and prolonged I–V latencies were highly associated with communicating hydrocephalus.

Transient ABR abnormalities

An interesting characteristic of ABR abnormalities associated with hydrocephalus is that they may be transient. Four of the 9 patients retested showed ABR improvement on retest, and one showed response deterioration over time. Response improvements consisted of reduction in ABR threshold ($\geqslant$ 30 dB HL), improved wave form resolution and shortened latencies.

Findings from a retested patient are shown in Fig. 3. Initial test findings are shown at the left side of the figure, with follow-up results on the right. The first time this patient was tested, auditory brain-stem responses were obtained at suprathreshold values only ($>$ 70 dB HL). Wave form morphology and latencies were grossly abnormal. On retest, the major ABR components were present at appropriate latencies, and responses were obtained at normal and near-normal threshold levels. Clinically, the patient was markedly macrocephalic and showed signs of increased intracranial pressure on the initial test date. Clinical signs of increased intracranial pressure had subsided by the second test date following placement of a ventriculo-peritoneal shunt, although the patient was still macrocephalic.

In another patient, no ABR activity was obtained on the two initial test dates. Subsequently, responses of normal morphology were obtained at 55 dB HL bilaterally. These findings were con-

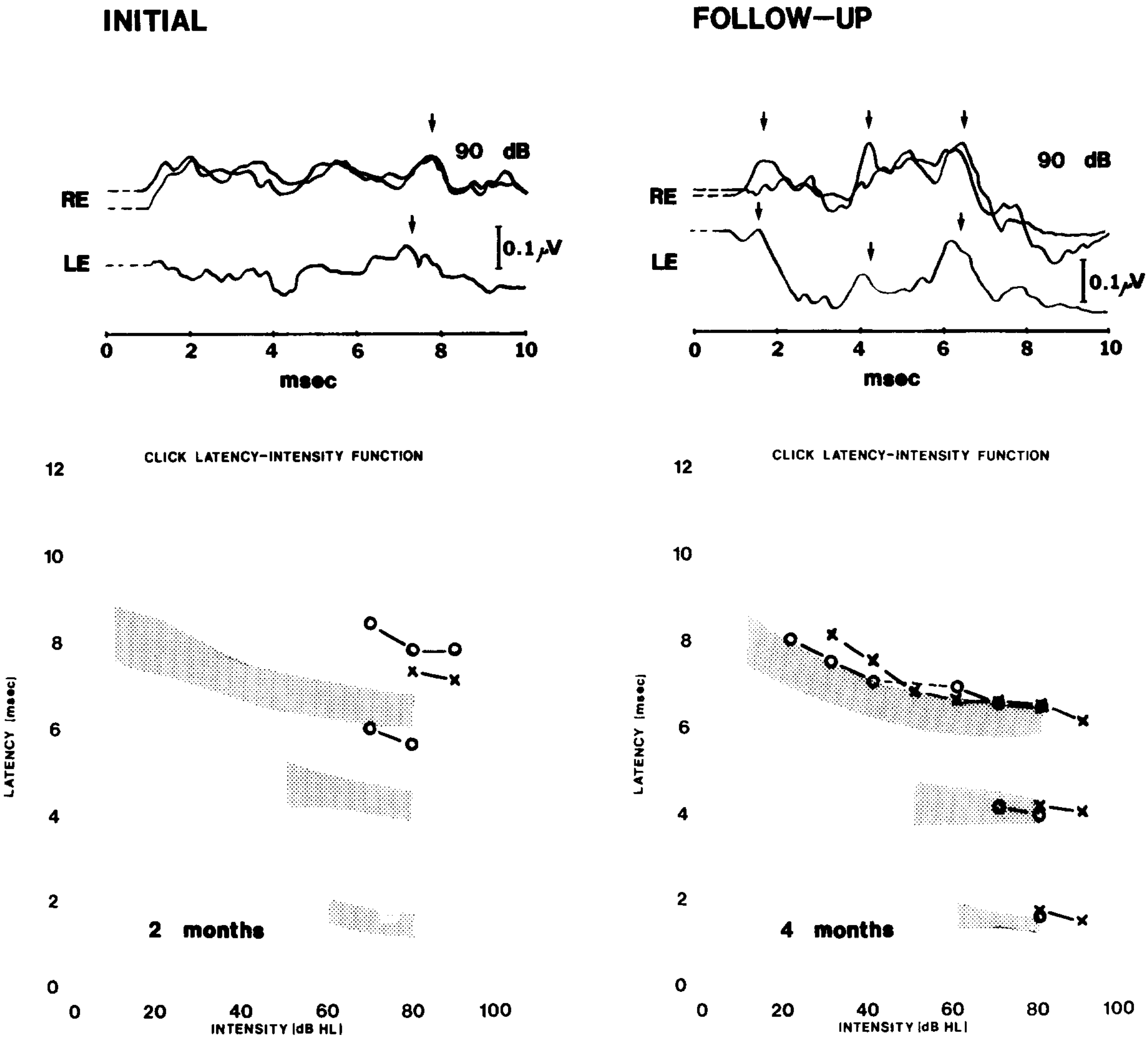

Fig. 3. Comparison of initial and follow-up test results obtained from a hydrocephalic patient. Top of figure shows actual wave forms obtained. Arrows designate wave V on initial test data and waves I, III and V on follow-up. Stippled areas at bottom of figure represent normal latency values (2 S.D.) of waves I, III and V plotted as a function of stimulus intensity. The patient's latency values are shown with circles representing the right ear and X's for the left.

sistent with a flat, moderate sensorineural hearing loss confirmed by behavioral audiometry.

Discussion

Comparison with other patient groups

The ABR test results in hydrocephalic patients reported here can be compared with results from two other groups of patients that frequently show ABR abnormalities. Using comparable test paradigms, we have examined a group of 60 patients with postbacterial meningitis and a group of 100 institutionalized, profoundly retarded children with multiple handicaps (including the absence of speech or ambulatory ability) (Özdamar and Kraus 1983; Özdamar et al. 1983a). As indicated in Table II, frequency of prolonged I–V latency and

TABLE II

Incidence of ABR abnormalities in 3 patient populations tested under similar conditions.

I – V latency abnormality		
Hydrocephalus (N = 40)	33%	
Multiply handicapped (N = 100)	23%	
Meningitis (N = 60)	10%	
Threshold abnormality	> 20 dB HL	> 20 dB HL including no response
Hydrocephalus	45%	70%
Multiply handicapped	42%	47%
Meningitis	35%	42%
No ABR response		
Hydrocephalus	25%	
Multiply handicapped	5%	
Meningitis	7%	

elevated ABR thresholds was higher among hydrocephalic patients than in either meningitic or multihandicapped patients. Incidence of absent ABRs in the hydrocephalic group was more than 3 times higher than in the other groups. These findings suggest that there is something specific to the hydrocephalic process that produces ABR abnormalities. For example, postmeningitic patients with hydrocephalus are more likely to have an abnormal ABR than are those without hydrocephalus. Thus, the pathophysiology of hydrocephalus appears more likely to produce abnormal wave forms than are certain other CNS disorders without hydrocephalus, such as those occurring in meningitic or in profoundly retarded, multiply handicapped patients.

Pathophysiology

The auditory brain-stem pathways appear to be affected in the majority of patients with hydrocephalus. The mechanisms by which brain-stem involvement occur are open to speculation. One possibility is that disruption of brain-stem function may be directly tied to increased intracranial pressure. Nagao et al. (1979a, b) have demonstrated disruption of neural activity in the rostral auditory brain-stem following experimentally induced increased intracranial pressure in cats. Intracranial pressure was raised by expansion of a supratentorial balloon. They report associated reduction in amplitude of waves IV and V as well as prolonged latencies of waves III, IV and V.

In humans, Benna et al. (1982) have documented ABR abnormalities in patients with supratentorial tumors who showed clinical evidence of increased intracranial pressure. ABR abnormalities consisted of latency increases in III–V and I–V conduction times, amplitude reduction of wave V, and disappearance of waves VI and VII. Thus, ABRs characteristic of both humans and cats with increased intracranial pressure are similar to our findings in hydrocephalic patients. It is unlikely, however, that markedly increased intracranial pressure was a factor in our patients, because nearly all were post shunt and showed no obvious signs of increased intracranial pressure, such as stupor or vomiting. Thus, it appears we are demonstrating a high incidence of brain-stem abnormality despite a less severe degree of intracranial pressure than was present in the subjects reported by Nagao et al. (1979a, b) and Benna et al. (1982).

Increased intracranial pressure may cause ischemic damage to the brain-stem from alterations in blood flow in the penetrating vessels of the basilar or posterior cerebral arteries. It has been shown that mechanical compression of the upper brain-stem causes interference with brain-stem circulation (Hassler 1967; Goodman and Becker 1973). Compression ischemia may account for the transient nature of ABR abnormalities witnessed in some of our patients. Reversible changes in ABR have been documented in the cat with manipulation of intracranial pressure (Nagao et al., 1979b). Visual evoked potentials in hydrocephalic humans have also been shown to change following shunt procedures (Ehle and Sklar 1979). In patients without signs of increased intracranial pressure, ABR abnormalities may reflect permanent ischemic damage.

Nagao et al. (1979a, b) have shown that movement of the upper brain-stem is correlated with reduction in wave V amplitude during supratentorial brain compression in cats. They speculate that wave V is affected more than the early ABR waves because the lower brain-stem is anchored by the upper cervical denticulate ligaments, while the upper brain-stem can be directly compressed, laterally or caudally displaced, and rotated (Jennett and Stern 1960; Hassler 1967).

Congenital anomalies affecting the auditory system in the brain-stem may contribute to some of the observed ABR abnormalities. There is good pathologic evidence supporting the existence of brain-stem damage in many of the congenital anomalies leading to hydrocephalus such as aqueductal stenosis, Arnold-Chiari malformation, and Dandy-Walker syndrome (Blackwood et al. 1963). These patients may show fusion of the colliculi into a single mass (Russell 1949; Blackwood et al. 1963) or thinning of the lower pons and upper medulla (Milhorat 1972). Malformation of the midbrain has been associated particularly with the Arnold-Chiari malformation (Feigin 1956).

Another factor that may contribute in part to ABR abnormalities is the alteration of the usual medium through which electrical signals are volume conducted. The fact that recorded neural activity must travel through a greater amount of fluid in hydrocephalic patients may make the responses different from normal values. However, if the change in conductive media alone were sufficient to produce such distortion, one might expect all of the ABR wave forms to be affected, whereas activity from the rostral brain-stem appears to be particularly disrupted.

This study revealed that communicating hydrocephalus was particularly associated with absence of ABR response and prolonged I–V latencies. One might speculate that brain-stem function is more likely to be disrupted because the aqueduct of Sylvius and 4th ventricle may be distended in the communicating and not the obstructive type. Thus, increased pressure or interstitial edema would more directly affect brain-stem structures. Direct damage to the 8th nerve may also be expected in communicating hydrocephalus, because of inflammation and fibrosis of the leptomeninges (Milhorat 1972).

Implications

The high incidence and nature of ABR abnormalities have several implications for the use of ABR in known or unsuspected hydrocephalic patients. First, the diagnosis of brain-stem dysfunction may have some bearing on the clinical management of the patient. The differential diagnosis of the positive ABR findings described here should include hydrocephalus. In addition, ABR may be used to monitor the effectiveness of a ventriculo-peritoneal shunt.

A second implication relates to hearing management. Since hydrocephalic patients are frequently too young or too handicapped to comply with conventional audiometric testing, ABR testing is frequently ordered for the purpose of hearing assessment. The high incidence of ABR findings which reflect brain-stem dysfunction must be taken into account in the interpretation of results with regard to hearing. Wave V is usually used as a measure of hearing sensitivity. A common finding in hydrocephalic patients is that wave V is absent, distorted, or of low amplitude. In these cases, one would expect to obtain wave V at suprathreshold levels irrespective of hearing dysfunction. We have found that ABR thresholds are often significantly higher than behavioral thresholds in adult patients with ABRs reflecting brain-stem dysfunction, particularly those reflecting prolonged neural conduction (Özdamar et al. 1983b).

Another common finding in hydrocephalic patients (25% of cases) is the absence of measurable sound-evoked bioelectric activity. In these cases, it is impossible to determine the extent to which findings reflect sensorineural hearing loss, brain-stem neuropathology, or both. It has been our experience that approximately 10% of patients with absent ABR demonstrate no worse than a moderate hearing loss (Kraus et al. 1984). This point is emphasized in the case of the hydrocephalic patient without an ABR response who improved on subsequent testing to have responses at 55 dB HL. Thus, audiologic testing of 'no response' patients is essential to the determination of hearing status. The fact that nearly half of the hydrocephalic patients retested showed improved ABR results on follow-up reinforces the contention that negative inferences regarding hearing sensitivity based on ABR should be made with caution.

Summary

Auditory brain-stem response (ABR) was measured in 40 patients (80 ears) with confirmed hydrocephalus. Eighty-eight percent of these patients showed some form of ABR abnormality. Responses indicative of brain-stem dysfunction consisted of prolonged I–V interwave latency (38%), reduced V/I amplitude ratio (33%), and abnormalities in wave-shape of components III (27%) and V (53%). In addition, 70% of the patients had elevated ABR thresholds; 45% had responses in excess of 20 dB HL and the remaining 25% had no ABR activity. The etiology of the hydrocephalus, head circumference and brain-stem symptoms were not associated with particular ABR abnormalities. Communicating hydrocephalus correlated significantly with both prolonged I–V conduction time and absence of ABR activity, compared with non-communicating hydrocephalus. Four of the 9 patients retested showed ABR improvement on follow-up; one patient showed deterioration.

The results were compared to our prior studies of ABR in 60 post-meningitic patients and in 100 severely neurologically impaired institutionalized children in whom the incidence of intrinsic brain-stem abnormalities was one-third and two-thirds that of the hydrocephalic group, respectively.

The results of this study suggest that ABR can be used to document clinically unsuspected brain-stem pathology that may accompany hydrocephalus. Auditory brain-stem dysfunction is likely to complicate the assessment of hearing sensitivity in hydrocephalic patients.

Résumé

Réponses auditives du tronc cérébral chez des patients hydrocéphales

La réponse auditive du tronc cérébral (RATC) a été enregistrée chez 40 patients (80 oreilles) hydrocéphales confirmés. Quatre-vingt-huit pourcent de ces patients ont présenté des anomalies de ces réponses. Celles-ci, indiquant un dysfonctionnement du tronc cérébral présentaient: une augmentation de la latence interondes I–V (38%), une diminution du rapport des amplitudes V/I (33%), des anomalies de la forme d'onde des composantes III (27%) et V (53%). De plus, 70% des patients ont présenté un seuil élevé pour ces réponses; 45% avaient des réponses à des valeurs supérieures de 20 dB HL et les autres 25% n'avaient pas d'activité RATC. L'étiologie de l'hydrocéphalie, le périmètre crânien, et les symptômes du tronc cérébral n'étaient pas associés à des anomalies particulières de la RATC. L'hydrocéphalie communicante était corrélée de façon significative avec à la fois l'augmentation du temps de conduction I–V et l'absence d'activité RATC, contrairement à l'hydrocéphalie non communicante. Quatre des 9 patients testés à nouveau ont présenté une amélioration subséquente de leur RATC; un patient en revanche a présenté une détérioration.

Les résultats ont été comparés avec nos études précédentes sur la RATC chez 60 patients ayant été atteints d'une méningite et chez 100 enfants sévèrement atteints neurologiquement et hospitalisés, chez lesquels l'incidence des anomalies intrinsèques du tronc cérébral étaient respectivement de 1/3 et 2/3 de celle du groupe des hydrocéphales.

Les résultats de cette étude suggèrent que la RATC peut être utilisée pour déceler cliniquement une pathologie du tronc cérébral non suspectée qui peut accompagner l'hydrocéphalie. Le dysfonctionnement des structures auditives du tronc cérébral pourrait compliquer l'évaluation de la sensibilité auditive chez les patients hydrocéphales.

References

Benna, P., Gilli, M., Ferrero, P. and Bergamasco, B. Brain stem auditory evoked potentials in supratentorial tumours. Electroenceph. clin. Neurophysiol., 1982, 54: 8P–9P.

Blackwood, W., McMenemy, W.H., Meyer, A., Norman, R.M. and Russell, D.S. Greenfield's Neuropathology, 2nd Ed. Edward Arnold, London, 1963.

Davis, H. Principles of electric reponse audiometry. Ann. Otol. (St. Louis), 1976, Suppl. 78: 1–96.

Ehle, A. and Sklar, F. Visual evoked potentials in infants with hydrocephalus. Neurology (Minneap.), 1979, 29: 1541–1544.

Feigin, I. Arnold-Chiari malformation with associated analogous malformation of midbrain. Neurology (Minneap.), 1956, 6: 2.

Galambos, R. and Hecox, K. Clinical applications of the brainstem auditory evoked potentials. In: J.E. Desmedt

(Ed.), Auditory Evoked Potentials in Man. Karger, Basel, 1977: 1–9.

Goodman, S.J. and Becker, D.P. Vascular pathology of the brainstem due to experimentally induced intracranial pressure: changes noted in the micro- and macrocirculation. J. Neurosurg., 1973, 39: 601–609.

Hassler, O. Arterial pattern of human brainstem: normal appearance and deformation in expanding supratentorial conditions. Neurology (Minneap.), 1967, 17: 368–375.

Jennett, W.B. and Stern, W.E. Tentorial herniation, the midbrain and the pupil. Experimental studies in brain compression. J. Neurosurg., 1960, 17: 585–609.

Kraus, N., Özdamar, Ö., Stein, L. and Reed, N. Absent auditory brainstem response: peripheral hearing loss or brainstem dysfunction? Laryngoscope (St. Louis), 1984, 94: 400–406.

Milhorat, T.H. Hydrocephalus and the Cerebrospinal Fluid. Williams and Wilkins, Baltimore, MD, 1972.

Nagao, S., Roccaforte, P. and Moody, R. Acute intracranial hypertension and auditory brainstem responses. Part 1. J. Neurosurg., 1979a, 51: 669–676.

Nagao, S., Roccaforte, P. and Moody, R. Acute intracranial hypertension and auditory brainstem responses. Part 2. J. Neurosurg., 1979b, 51: 846–851.

Nellhaus, G. Head circumference from birth to eighteen years. Pediatrics, 1968, 41: 106–114.

Özdamar, Ö. and Kraus, N. Auditory brainstem responses in infants recovering from bacterial meningitis: neurological evaluation. Arch. Neurol. (Chic.), 1983, 40: 499–502.

Özdamar, Ö. and Stein, L. Auditory brainstem response (ABR) in unilateral hearing loss. Laryngoscope (St. Louis), 1981, 91: 565–574.

Özdamar, Ö., Kraus, N. and Stein, L. Auditory brainstem responses in infants recovering from bacterial meningitis: audiologic evaluation. Arch. Otolaryng., 1983a, 109: 13–18.

Özdamar, Ö., Kraus, N. and Stein, L. Differences between audiometric and auditory brainstem threshold in patients with brainstem neuropathology. Ass. Res. Otolaryngol. Abstr., 1983b: 121.

Picton, T.W., Stapells, D.R. and Campbell, K.B. Auditory evoked potentials from the human cochlea and brainstem. J. Otolaryng., 1981, Suppl 9: 1–41.

Russell, D.S. Observations on the pathology of hydrocephalus. Brit. med. Res. Counc., 1949, 5: 138.

Starr, A. and Achor, J. Auditory brainstem responses in neurological disease. Arch. Otolaryng., 1975, 32: 761–768.

Stockard, J.J. and Rossiter, V.S. Clinical and pathologic correlates of brainstem auditory response abnormalities. Neurology (Minneap.), 1977, 27: 316–325.