Overnight Recordings of Intracranial Pressure and Electroencephalography in Neurosurgical Patients

Part I : Intracranial Pressure Waves and Their Clinical Correlations

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Abstract : Simultaneous overnight recordings of intracranial pressure (ICP) and electroencephalography (EEG) were conducted on 85 neurosurgical patients with intracranial hypertension and/or ventriculomegaly. Intracranial pressure waves were classified into five types according to the pattern of appearance, and their correlation with sleep cycles and clinical conditions of patients were investigated. A-waves appeared exclusively in patients with long-standing intracranial hypertension, and episodic B-waves appeared in patients with chronic hydrocephalus or a postoperative tumor-free condition. When these episodic pressure waves appeared, the patients were conscious and sleep cycles including REM stage were observed. Persistent, high pressure B-waves were seen mostly in patients with an acute phase of intracranial hemorrhages. The consciousness of these patients ranged from drowsy to stupor. EEG showed alternate appearances of light sleep and waking rhythms in accordance with cyclic oscillations of B-waves which coincided with periodic, apneic respiratory rhythms. When markedly regular B-waves of moderately high pressure appeared continuously, the patients were severely impaired in consciousness and were mainly in a subacute phase of intracranial hemorrhages. EEG showed continuous slow activities and sleep stages were not scored in these patients. No characteristic clinical features were found in patients whose ICP remained within normal range without pressure waves throughout the recording.

Key words : ICP, EEG, overnight recording, pressure wave, periodic respiration.

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Introduction

The measurement of intracranial pressure (ICP) is essential in determining the therapeutic modality for patients with intracranial hypertension. The clinical significance of ICP is expressed not only by the pressure elevation, but also by wave forms, called “pressure waves”, obtained by continuous recording. Since Lundberg (1960) described three types of intracranial pressure waves, A-, B- and C-waves, his classification has been widely accepted. Among these pressure waves, C-waves are defined as rhythmic oscillations of

small amplitude occurring at a rate of about 6 per minute and are considered to be of little clinical significance (Lundberg, 1960; Langfitt, 1982). A-waves, subsequently termed "plateau waves", are characterized by an acute elevation of ICP from a lower resting pressure and a rapid fall in pressure at the termination of the plateau, which lasts from 5 to 20 minutes (Lundberg, 1960). A-waves are known to appear in chronic intracranial hypertension, but their pathogenesis is currently much debated (Hayashi *et al.*, 1984; Katayama *et al.*, 1984). B-waves, which appear most frequently in ICP recordings, are defined as rhythmic oscillations at a frequency of 1/2 to 2 per minute (Lundberg, 1960), but because B-waves are observed in patients either with markedly elevated ICP (Lundberg, 1960) or with normal ICP (Martin, 1978), or either with acute intracranial hypertension (Popo *et al.*, 1979; Voldby & Enevoldsen, 1982) or with a chronic hydrocephalic condition (Symon & Dorsch, 1975; Tamaki *et al.*, 1983), their clinical correlations are not well defined. This ill-defined clinical significance of B-waves seems to result from ignorance of their pattern of appearance and is considered to reflect disputes regarding their pathogenesis. We introduce a new classification of B-waves besides Lundberg's definition and investigate their clinical correlation. This study of continuous ICP recordings were conducted overnight together with recordings of electroencephalography (EEG), since pressure waves have been reported to appear more frequently during sleep than waking (Cooper & Hulme, 1966; Di Rocco *et al.*, 1975).

Clinical Materials and Methods

Overnight recordings of both ICP and EEG were conducted on 85 neurosurgical patients with intracranial hypertension and/or ventriculomegaly. The patients consisted of 16 children aged 3 months to 15 years and 69 adults up to the age of 75. Twenty-five patients suffered from brain tumors, 31 had subarachnoid hemorrhage (SAH), 11 had intracerebral hemorrhage (ICH), 3 had progressive hydrocephalus in infancy and childhood, 14 had chronic ventricular dilatation of diverse etiologies in adulthood and one suffered from benign intracranial hypertension.

General procedure. ICP was measured by ventricular or lumbar cerebrospinal fluid (CSF) pressure in all but 3 cases, with the patient in the supine position using calibrated strain-gauge transducers referenced to the external auditory meatus. The indwelling external ventricular drainage catheter was used for therapeutic purposes either before or at the time of major surgery in 70 patients, and a lumbar spinal drainage catheter was placed percutaneously for ICP measurement in 12 patients with chronic ventriculomegaly of adult and benign intracranial hypertension. In 3 adult patients with supratentorial brain tumors, ICP was measured by a Geltec model ICT/6 transducer placed extradurally. ICP was recorded polygraphically with impedance pneumography and heart rate in all patients and with systemic arterial pressure and end-tidal CO₂ in some. ICP recording was done by two strip chart recorders, one at a paper speed of 10 mm/min and the other at 1 mm/min.

EEG of all patients was recorded together with electro-oculogram (EOG) and electromyogram (EMG) on a strip chart recorder at 15 mm/sec. All the data obtained simultaneously from ICP and EEG recording systems were stored on a magnetic tape for further analysis.

These recordings were made overnight for 10 to 12 hours at an interval of 1 to 2 days from the day of CSF drainage or 3 to 7 days after major intracranial surgery to avoid the effects of anesthetics on sleep. In some patients the recordings were repeated 2 to 3 times at an interval of 1 to 2 weeks.

Data analysis. ICP recordings on strip charts recorded at the paper speed of 10 mm/min were analyzed to determine the pressure waves. Overnight ICP profiles obtained from the recordings made at the paper speed of 1 mm/min were compared with diagrams of sleep stages analyzed from overnight EEG recordings. Sleep stages were scored visually using the criteria of Rechtschaffen & Kales (1968). The relationship between the overnight ICP profiles and the patient's clinical condition, including the level of consciousness, and stage and nature of illness, was investigated.

Results

Pressure waves were classified into 5 types according to the level of resting pressure and pattern of appearance (Fig. 1), and their clinical correlations are summarized in Table 1.

Type I: A-waves of 40 to 100 mmHg appeared at least once with a resting pressure of 10 to 40 mmHg in 15 patients who showed sleep cycles including REM's (Fig. 2). The patients included 10 with brain tumors (7 children and 3 adults), 3 with infant and child non-tumorous hydrocephalus, one with adult hydrocephalus developed in the subacute phase of SAH, and one with benign intracranial hypertension. The recordings in this group were conducted prior to major surgery on all patients but one with SAH, and the consciousness of the patients ranged from alert to slightly drowsy at the time of the recordings.

Type II: Clustered B-waves of 25 to 75 mmHg appeared episodically from the resting pressure of 5 to 25 mmHg in 22 patients (4 children and 18 adults). The patients consisted of 9 postoperative patients who had undergone surgery for brain tumors, 12 with chronic communicating hydrocephalus after SAH or of idiopathic origin and one with Chiari type I malformation. They were all conscious, and sleep cycles that included REM were observed in all of them (Fig. 3).

Type III: B-waves of 40 to 100 mmHg persisted throughout the overnight recording. B-waves of this type appeared continuously at the rate of one per 1 to 2 minutes and formed saw-tooth waveform variations in 3 patients. They were invariably accompanied by apneic respiratory rhythm (Fig. 1). These high pressure B-waves were seen in 15 adult patients (8 underwent recording 4 to 8 days after SAH, 4 underwent recording 10 to 21 days after SAH or ICH, and 3 had supratentorial brain tumors with acute progressive

Fig. 1. Classification of intracranial pressure waves. Note that B-waves are almost always associated with periodic, apneic respiratory rhythm.

Fig. 2. Overnight ICP profile of Type I (lower column) and sleep stage diagram (upper column) in a 7-year-old boy with pineal tumor. A-waves appear 7 times episodically from the relatively low resting pressure and the last 4 times coincide with REM sleep stages. (REM I, II, III, IV indicate sleep stage REM, Stage I, Stage II, Stage III, Stage IV, respectively)

Fig. 3. Overnight ICP profile of Type II (lower column) and sleep stage diagram (upper column) in a 61-year-old man with normal pressure hydrocephalus. Clustered, episodic B-waves appear 3 times in normal pressure conditions and coincide with the REM sleep stage.

symptoms). EEG in this group showed alternating light sleep and waking rhythms in all patients but one comatose individual who showed continuous diffuse slow activity. Most of the patients were drowsy to stuporous, but two were alert and one was comatose. ICP recordings in this group were temporarily interrupted to drain off the ventricular fluid when ICP remained above 60 mmHg or the patient complained of severe headaches (Fig. 4).

Type IV: B-waves of 10 to 30 mmHg appeared with marked regularity at a rate of 1 to 2 per minute for more than 60 minutes. This was observed in 12 adult patients suffering

Fig. 4. Overnight ICP profile of Type III (lower column) and sleep stage diagram (upper column) in a 62-year-old man who suffered from SAH 5 days before. High pressure B-waves persist throughout the recording. Because of risk of herniation, increased ICP is mediated by administration of Glycerol (broken line) and by draining off the ventricular fluid (arrow). In the sleep stage diagram only the light sleep phase (Stage I) is distinguished from the arousal pattern on EEG, and alternating sleep and waking cycles are fairly well observed after the ventricular fluid is drained off.

Fig. 5. Overnight ICP profile of Type IV in a 62-year-old woman who was semicomatose on the 14th day after SAH. Markedly regular B-waves continue throughout the overnight recording at moderately elevated pressure. Background activity shows continuously slow waves, which were impossible to score for each sleep stage on EEG in this patient (upper column).

from intracranial hemorrhages: in eight, 6 to 14 days after SAH and in four, 4 to 25 days after ICH. EEG in this group showed continuous slow activity, intermingled with high or low voltage slow waves in some patients (Fig. 5). The consciousness of these patients ranged from confusion to deep coma, with no well-oriented, alert patients in the group. Marked regularity of B-waves was seen for long periods in 4 comatose or semi-comatose patients, who eventually died or remained in a vegetative state. B-waves were highly corre-

lated with apneic respiratory rhythms (Fig. 1).

Type V: No significant pressure waves were observed in 21 patients in whom ICP remained within 10 mmHg throughout the overnight recording. The recordings were performed in the early postoperative stage of brain tumor or aneurysm on 6 patients who showed normal consciousness and sleep cycles that included REM. In 4 patients with longstanding ventriculomegaly of an idiopathic nature, consciousness was not disturbed and sleep cycles that included REM were observed. In 11 patients with ventriculomegaly of diverse etiologies who showed dementia or were in a vegetative state, sleep stages up to II or III were observed; however, the REM stage was lacking.

Discussion

Intracranial pressure waves classified by Lundberg (1960) are now widely accepted, but clinical correlations of B-waves are not well defined. We have classified the pressure waves in terms of their pattern of appearance rather than by their individual wave forms defined by Lundberg. In this study B-waves were classified into 3 types: those of episodic appearance (Type II), those of continuous appearance with markedly high pressure (Type III), and those of continuous and regular appearance with moderately high pressure (Type IV). Regarding the pattern of appearance of pressure waves, A-waves may be thought of having episodic appearance (Type I).

A-waves are rarely observed in patients with acute intracranial hypertension (Lundberg, 1960; Hayashi *et al.*, 1984) or in comatose patients (Munari & Calbucci, 1981). This study confirmed that A-waves occurred exclusively in patients with long-standing ICP elevation caused by brain tumor, progressive non-tumorous hydrocephalus or benign intracranial hypertension. The consciousness of these patients ranged from mostly normal to drowsy at worst, and sleep cycles that included the REM stage were obtained on EEG in all cases. A-waves are considered to result from a combination of cerebrovascular dilatation and increased cerebral blood volume in a state of reduced compliance of the intracranial compartment (Risberg *et al.*, 1969; Miller, 1987), and their recurrence should be seen in the chronic stage of intracranial hypertension, in which the spatial compensation reserve to accommodate the increased blood volume is assumed to be established relatively well in comparison with the acute intracranial hypertension. However, the neuronal mechanisms that trigger the cerebro-vascular reactions causing plateau waves remain unclear.

Episodic B-waves are designated as a cluster of B-waves which appear sporadically at a relatively low resting pressure and persist for 3 to 10 minutes. They were observed in patients with chronic hydrocephalus and in postoperative, tumor-free patients in this study. These patients were all conscious, and sleep cycles that included the REM stage were observed in all of them. This type of B-wave is known to appear during sleep, particularly in the REM stage, in patients with normal pressure hydrocephalus (Di Rocco *et al.*, 1976; Chawla *et al.*, 1974). In recent years, ICP elevation during REM sleep has been believed

to be a physiological phenomenon, since an episodic rise in ICP is observed in REM sleep in normal persons and experimental animals of normal ICP (Gücer & Viernstein, 1979; Munari & Calbucci, 1981). B-waves appearing episodically in REM sleep have been seen in patients with cerebral atrophy, and their value in predicting the efficacy of the shunting operation for normal pressure hydrocephalus is now considered doubtful (Nornes, *et al.*, 1973; Symon & Dorsch, 1975). In the present study, only 3 of 22 patients with episodic B-waves seen in REM sleep required a shunting operation. We did not examine normal subjects in this study; however, B-waves appearing in REM sleep in persons with normal resting pressure are considered to have no clinical significance.

In contrast to A- and episodic B-waves, which rose steeply or abruptly from a relatively low resting pressure, persistently elevated pressure waves composed of B-waves were observed in the acute or subacute stage of illnesses such as SAH, ICH or brain tumors. These continuous, rhythmic oscillations of B-waves, which had been reported to appear mainly in the acute intracranial hypertension but had not been distinguished from B-waves of episodic appearance (Popo *et al.*, 1979; Voldby & Enevoldsen, 1982), were subclassified in this study into those of markedly high pressure (Type III) and those of moderately high pressure with marked regularity (Type IV). The consciousness of patients with these continuous B-waves was usually impaired, and normal sleep cycles that included REM were never observed. However, a better clinical picture regarding the level of consciousness in association with better reactivity on EEG findings was found in patients with type III. On the other hand, severely impaired consciousness was seen when B-waves continued with marked regularity for a long period. The characteristic EEG pattern during overnight recordings in patients with continuous high pressure B-waves is the alternating appearance of EEG activities indicative of light sleep and waking, which coincide with cyclic oscillations of B-waves appearing at the rate of 1/2 to 2 per minute in accordance with periodic, apneic breathing rhythm; i. e., the period of apnea coincides with troughs of B-waves which are followed by a gradual elevation of ICP. When ICP reaches the crest of the B-wave, a light sleep EEG pattern turns to one of arousal and hyperpnea occurs at the same time (Ingvar & Lundberg, 1961). Consequently, the patients in this group are not able to attain deep sleep and REM sleep. This phasic relationship between sleep, breathing and ICP simulates that observed in sleep apnea syndrome (Sugita *et al.*, 1985). CO₂ retention is considered to be responsible for the elevation of ICP in obstructive sleep apnea syndrome, while, the origin of B-waves under other conditions is a matter of dispute. Many attempts have failed to verify the causal relationship between the level of PCO₂ tension and B-waves, and a lack of relationship was deduced by the fact that B-waves appear in constant PCO₂ tension under controlled ventilation (Børgesen & Espersen, 1986; Lundberg, 1960; Venes, 1979). At present, both the periodic respiratory rhythm and B-waves are considered to be regulated at the same time by an intrinsic neurogenic mechanism, the genesis of which remains unknown (Børgesen & Espersen, 1986; Venes, 1979). Furthermore, the question whether these continuous B-waves are identical to those of episodic appearance in their genesis and

Table 1. Pressure waves and their clinical correlations

Pressure waves (Type)	Pressure range (mmHg)		Apneic breathing synchronized	EEG		Patients	
	Resting	Peak		Sleep stage	No.	Consciousness	Intracranial pathology
I. A-(plateau) waves	10–40	40–100	rare	I – IV, REM	15	alert	Brain tumor (preop.) Progressive hydrocephalus Benign intracranial hypertension
II. Episodic B-waves	5–25	25–75	usually	I – IV, REM	22	alert	Chronic hydrocephalus, Brain tumor (postop.)
III. Persistent, high pressure B-waves	40–100		always	Awake/Sleep alternate	15	drowsy to stupor	SAH, ICH: more in acute stage Brain tumor with impending herniation
IV. Continuous, regular B-waves	10–30		always	not scored	12	stupor to comatose	SAH, ICH; mostly in subacute stage
V. None	0–10		rare	may be scored with REM	21	alert to comatose	Non-specific

mechanism remains unresolved.

Conclusion

Intracranial pressure waves were classified into five types with an introduction of sub-classification of B-waves according to their pattern of appearance. It was proven that these newly defined pressure waves represented the consciousness and sleep conditions of patients as well as the stage and nature of the intracranial hypertension better than those of the traditional classification defined by Lundberg (Table 1). The continuous recording of ICP provides useful informations to decide therapeutic modalities for patients with intracranial hypertension by evaluating the tightness of the intracranial compartment and may serve to predict the prognosis of patients when studied simultaneously with EEG recordings.

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脳神経外科疾患における睡眠時頭蓋内圧波の分析 そのⅠ．頭蓋内圧波の分類とその臨床的意義

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要 旨： 頭蓋内圧亢進症状あるいは画像上脳室拡大を示した 85 人の患者について、頭蓋内圧・脳波および関連生体現象を夜間 8－12 時間にわたって連続記録した。頭蓋内圧連続記録によって得られた圧波をその出現様式に従って 5 型に分類し、それぞれの圧波型と睡眠および臨床病態との相関を検討した。突発性に出現する A 波（Ⅰ型）と episodic B 波（Ⅱ型）は慢性期の頭蓋内圧亢進状態あるいは慢性期水頭症に主として出現し、これらの患者は意識が保たれ、脳波上も REM 期を含む睡眠周期がよく観察された。一方、B 波が高圧域で持続出現する場合（Ⅲ型）あるいは中圧域で規則性・連続性に出現する場合（Ⅳ型）は、頭蓋内出血の急性期・亜急性期患者にみられ、種々の程度の意識障害を示し、脳波上も正常の睡眠周期を欠いた。頭蓋内圧が正常圧の範囲にとどまり、圧波を欠く場合（Ⅴ型）の臨床的意義は見いだせなかった。突発性および連続性圧波の形成機序に関して臨床的観点から考察した。

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