Intracranial pressure responses to alterations in arterial carbon dioxide pressure in patients with head injuries

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Cerebral vasomotor responses to alterations in arterial carbon dioxide ($\text{PaCO}_2$), as manifested by intraventricular pressure changes, were studied in a group of patients with head injuries. These patients could be classified into three types based on various degrees of responsiveness thought to reflect the integrity of their cerebral vasomotor reactivity.

Key Words: cerebral vasomotor response, intraventricular pressure, $\text{PaCO}_2$, head injury

Alterations of cerebral vasomotor responses have been implicated as a significant factor in the events leading to the progressive increase in intracranial pressure under various pathological conditions. Langfitt and his colleagues briefly summarize the sequence of events as follows. Cerebral swelling (cerebral masses, etc.) causes an increase in the intracranial contents which ultimately occupies all available space in the intracranial compartment. This results in transient episodes of cerebrovascular dilatation during which cerebral blood flow is increased; the resultant increase in the intracranial vascular compartment causes transient "pressure waves" associated with hypertension (the latter thought to be a compensatory mechanism to maintain adequate cerebral perfusion). This increase in systemic blood pressure is directly transmitted to arterioles and capillaries because autoregulation has been lost, and these vessels are maximally dilated. This causes an egress of fluid into the extracellular space, and cerebral edema results. This series of events ultimately results in progressive loss of cerebral vasomotor responses, cerebral swelling, cerebral ischemia, and finally shock and death.

In addition, Langfitt and his co-workers have shown that hypercapnia may initiate these spontaneous "pressure waves." They consider these pressure waves, associated with hypertension, to indicate impending cerebrovascular and, therefore, neurological decompensation. They emphasize the importance of maintaining optimum ventilation to prevent hypoxia and hypercapnia. The purpose of this report is to document the various types of changes that occur in the cerebral vasomotor responses to alterations in carbon dioxide in severe head-injured humans. The observed changes documented here appear to correspond well with the classification by Langfitt, et al., of stages of vasomotor paresis in experimental animals.
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based on intracranial pressure responses to elevation of systemic arterial pressure. Finally, these experiments further emphasize the necessity of maintaining blood oxygen and carbon dioxide within an ideal therapeutic range in patients with compromised intracranial space.

Method

Patients with severe head injuries adjudged to have little chance of survival were the subjects of these experiments. These patients all had severe brain stem injuries. Some had decerebrate rigidity, fixed dilated pupils, absent vestibulo-ocular reflexes, and absent corneal reflexes; respiratory function and blood pressure were within normal ranges. Other patients had total or almost total absence of brain stem function as manifested by irregular or absent spontaneous respirations and arterial hypotension. All patients, shortly after admission, were subjected to angiography to rule out extra- and intracerebral hematomas. After the hematomas were ruled out or evacuated, intraventricular catheters (No. 9.6 French rubber catheter) were placed through a frontal trephine if surgery was undertaken; or, if surgery was not indicated, through a frontal twist drill hole as described by Kaufmann and Clark. The procedure and instrumentation used to collect these data are used routinely in the treatment of the patients in the Center for the Study of Trauma. However, these procedures were explained to the next of kin and their permission received in accordance with the guidelines provided by the University of Maryland Human Volunteers Committee. Intraventricular catheters are used routinely to assist in diagnosis and therapy of progressive cerebral swelling where the latter is anticipated to be a potential significant problem. Intracranial pressure monitoring has proven to be of great value in the detection and management of increased intracranial pressure. Likewise arterial and venous cannulations are performed routinely on all patients admitted to this center. In addition, moderate artificial hyperventilation is routinely employed as a therapeutic adjunct in the treatment of increased intracranial pressure. Each patient's intracranial pressure response characteristics to alterations in arterial pCO₂ (PaCO₂) are determined in order to provide a more rational basis for hyperventilation as will be discussed in more detail below.

Experiments were conducted on 16 patients, all with craniocerebral trauma. Relatively normal intraventricular pressures were present in seven patients, extremely high-fixed intracranial pressures in five and fluctuating pressures in four. The intraventricular catheter was attached to a P37 Statham transducer with the patient in the horizontal position. The transducer was positioned level with the head. The patients were intubated with cuff tracheal tubes placed transnasally or through a tracheostomy. All were placed on controlled mechanical ventilation using the Engstrom Model 300 ventilator without expired resistance or pressure. All patients were curarized with a dose of tubo-curarine sufficient to eliminate completely diaphragmatic contractions at elevated levels of PaCO₂. Tubo-curarine is thought not to affect cerebral blood flow and, hence, intracranial pressure. No anesthetic agents were used.

Indwelling catheters were placed in the radial artery, at the right atrial superior vena caval junction, and in some cases the pulmonary artery, as confirmed by x-ray and attached to Statham pressure transducers. The following data were recorded simultaneously: intracranial pressure, systolic, diastolic, and mean peripheral arterial pressures, central venous pressure, mean airway pressure, respiratory rate, alveolar pO₂ and pCO₂, and arterial pO₂, pCO₂, and pH.

Total airway pressure was measured with a pressure transducer or water manometer from a port at the slip joint of the tracheal tube.

Airway gases were sampled at another port at the slip joint of the tracheal tube. Continuous measurement of airway pO₂ and pCO₂ by a mass spectrometer was recorded. Peak expiratory values of pCO₂ and pO₂, maximum and minimum respectively, were recorded as representative of alveolar tensions of these gases, and were corrected for water vapor and barometric pressure. Simultaneously, arterial and mixed venous blood samples were drawn and analyzed for pO₂, pCO₂, and pH using an Instrumentation Laboratory blood gas analyzer.

Alveolar pCO₂ was controlled by combin-
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Results

These data clearly show significant differences in the reactivity of the cerebral vasomotor responses as manifested by changes in intracranial pressure induced by alterations of PaCO₂. These changes appear to correspond well with clinical stability and survival. The subjects could be readily classified into three distinct groups based on these vasomotor responses.

Type 1: Rapid Response Curves

As reported by Hayes and Tindall and confirmed in these studies, changes in some patients with head injury are readily induced by alterations in PaCO₂; however, significant reduction in intracranial pressure does not occur below 30 mm Hg. A typical “response profile” curve is illustrated in Fig. 1. These types of responses are seen in severely brain stem injured patients who do not usually have elevated intracranial pressure. Furthermore, the intracranial pressure changes in response to alterations in PaCO₂ are very rapid: the delay between PaCO₂ change and the pressure change is very small; both occur almost simultaneously. The data from Fig. 1 are replotted in Fig. 2 to demonstrate the relationship of the intracranial pressure response to alterations in PaCO₂ relative to time. The two curves in Fig. 2 are derived from the same patient, the only difference being that the curve on the right (B) represents a more rapid sequence than that seen on the left (A). Note that the intracranial pressure response in both the ascending and descending limbs occurs almost simultaneously.

Fig. 1. Profile curve demonstrating the normal relationship between intracranial pressure and alteration in arterial pCO₂. This normal curve shows that a PaCO₂ below 30 mm Hg results in very little further reduction in intraventricular pressure (IVP).

Fig. 2. Profile curves demonstrating the temporal relationship between alterations in PaCO₂ and resultant changes in intracranial pressure (IVP) characteristic of the Type 1 patient. Note that the IVP follows the PaCO₂ very closely. The changes in each occur almost simultaneously in each curve.
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with the changes in PaCO₂. This type of response curve was typical of all Type 1 patients.

Despite the fact that these patients had suffered severe brain stem injuries, as manifested by fixed dilated pupils, decerebrate rigidity, and in some cases absence of vestibulo-ocular reflexes, their clinical status remained relatively stable. They did not have marked fluctuations in intracranial pressure or systemic blood pressure. Specifically, they did not have spontaneous intracranial "pressure waves." Some of these patients remained clinically stable throughout their period of observation; however, others deteriorated neurologically and developed clear changes in their cerebral vasomotor reactivity.

Type 2: Attenuated Response Profile Curves

Intracranial pressure could also be changed in this type of patient by altering the PaCO₂; however, the response patterns were significantly different from those of Type 1 in that: 1) reduction in intracranial pressure became less prompt, i.e., the interval between the onset of PaCO₂ reduction and pressure reduction was significantly increased; 2) intracranial pressure at times appeared to fluctuate independently of PaCO₂ changes; and 3) "pressure waves" could be induced by elevation of PaCO₂.

Patients usually but not always had elevations of resting intracranial pressure. The patients tended to be unstable neurologically and frequently had episodes of spontaneous "pressure waves" associated with systemic arterial hypertension. Their clinical status tended to vacillate, but not necessarily progressively deteriorate.
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Progression from Type 1 (Stage I of Langfitt, et al.) to Type 2 (Stage II of Langfitt, et al.) probably occurs frequently, clinically, as manifested by the development of spontaneous intermittent episodes of hypertension after several days. The coincident evolution of the response “profile curve” in a given individual has been difficult to document because of a reluctance to leave intraventricular catheters in place longer than about 4 days. However, this progression has been documented in a subject in which serial studies were conducted. The rapid response “profile curve” illustrated in Fig. 2 was taken from the patient 5 hours after removal of an acute subdural hematoma. The repeat response “profile curve” obtained 6 days later is shown in Fig. 7. One can now see that the response type has changed to a typical Type 2 response “profile curve”; notably, a pressure wave has been induced by an increase in the PaCO₂ as manifested by a spontaneous increase in intracranial pressure independent of the PaCO₂ (point A). Although the downward pressure curve occurs virtually simultaneously with the initiation of lowering the PaCO₂ (point B), the initial downward slope is shallow and does not follow the PaCO₂ curve very closely (cf. Fig. 4). At point (C) despite the fact that the PaCO₂ has been lowered to 30 mm Hg, the intraventricular pressure still remains at 75 mm Hg. The downward pressure curve then begins to fall rather precipitously and is similar to that in Fig. 4. Therefore, one can see

Type 3: No Response “Profile Curves”

In this subject the intracranial pressure could not be altered by even extreme changes in PaCO₂ (Fig. 6). These patients were usually in a moribund state as manifested by total absence of brain stem reflexes, irregular or absent spontaneous respirations, and hypotension.

Fig. 5. Profile curves demonstrating a spontaneous “pressure wave” seen in a Type 2 patient which occurred independent of any significant alteration in the PaCO₂. Intraventricular fluid was aspirated at the arrow.

Fig. 6. Profile curves demonstrating the total lack of response of the intraventricular pressure (IVP) to alteration of PaCO₂, typical of the Type 3 patient. Note the high fixed intracranial pressure characteristic of the type.
In 1965 Langfitt and his coworkers described stages of progressive cerebral vasomotor paresis caused by progressive increase in intracranial pressure. Normally, the intracranial space contains compressible tissue, displacement of which by mass lesions, edema, etc., can compensate for increases in the intracranial contents. However, a point is reached where all excess available space has been occupied, and, at that point, any small increment in the intracranial contents can cause a sudden rise in intracranial pressure. During this compensatory phase (Stage I of Langfitt et al.) intracranial pressure is normal, and, if the intracranial contents have not been significantly displaced, increases in PaCO₂ will produce only a slow gradual increase in intracranial pressure in response to an increase in the intracranial blood volume. However, if a significant amount of CSF has been displaced, and despite a normal resting pressure, elevation of the PaCO₂ may produce a rather dramatic increase in intracranial pressure, because additional intracranial volume cannot be accommodated. The Type 1 responses presented in this report probably represent the late Stage I of Langfitt, et al., since prompt elevation of intracranial pressure occurred as a result of hypercapnia, indicating, as one might expect, that these severely injured patients had some cerebral swelling, but not enough to raise the resting intracranial pressure. However, it should be emphasized that in this type of patient spontaneous “pressure waves” were not seen, and there was no evidence of vasomotor instability.

Type 2 response “profile curves” had two salient features. First, a “pressure wave” was generated by an increase in PaCO₂ and, second, a delay is seen between the initial decrease in PaCO₂ and the onset of a decrease in the intracranial pressure. The initial increase in the intracranial pressure followed closely the increase in the PaCO₂ similar to that seen in Type 1. This clearly indicates that vasomotor responsiveness is retained in Type 2; however, it is also apparent that a certain vasomotor instability exists. The initial increase in PaCO₂ causes an initial abrupt simultaneous increase in intracranial pressure; however, a spontaneous pressure wave develops when a certain threshold is reached. The latter is presumably the result of transient vasomotor paresis induced by maximal displacement of intracranial tissues as the result of cerebral edema, swelling, or mass lesion. That the vasomotor paresis can recover is demonstrated by the coincident, albeit delayed, decrease in intracranial pressure as a result of lowering the PaCO₂. It should be reemphasized that spontaneous “pressure waves” occur in this type of patient independent of fluctuation in the PaCO₂, and are not solely produced by hypercapnia. The characteristics of the Stage II paresis of Langfitt, et al., corresponds closely to the Type 2 described here. They emphasize that spontaneous pressure waves occur frequently and could be initiated by hypercapnia, and that the duration of the peaks of a “pressure wave” could be shortened by hyperventilation and decreasing the intracerebral mass by other means. In short, this stage is characterized predominantly by vasomotor instability. It is apparent that Type 3 response curves have lost all vasomotor responsiveness to PaCO₂. Langfitt, et al., have described Stages III and IV, in both of which vasomotor responses to alterations in...
PaCO2 are lost. This common characteristic fits well the Type 3 reported here and, presumably, both Stages III and IV of Langfitt, et al., fall into this category. This type of patient characteristically had a high resting intracranial pressure, was hypotensive, and clearly moribund.

Clinical Implications

Adequate ventilation during the acute phases of severe head injuries is obviously critical.1,6,10,14 That intracranial pressure waves can be initiated by hypercapnia is now well documented.8 Furthermore, these pressure waves associated with hypertension probably indicate impending cerebrovasomotor collapse.8 Therefore, all efforts should be directed toward prevention of progression of this series of events by lowering intracranial pressure by removal of CSF, osmotic diuretics, and hyperventilation. The advantages of monitoring intracranial pressure are apparent in that these physiological aberrations can be observed and corrected before frank clinical deterioration occurs.

In a previous study,10 we analyzed the response "profile curves" of the Type 1 patient. We concluded that lowering the PaCO2 below 30 mm Hg was unnecessary and probably not desirable because a lower PaCO2 effected little further reduction in intracranial pressure and, furthermore, an extremely low PaCO2 may reduce cerebral blood flow to dangerous levels.1,3,11-13 Additional studies presented in this report confirm 30 mm Hg as being an ideal PaCO2 to be maintained in this situation. The spontaneous pressure waves have not been produced with levels of 30 mm Hg or less; maintaining a PaCO2 in this range would still be adequate to prevent the initiation of spontaneous "pressure waves." This will not insure, however, that spontaneous pressure waves will not occur, since it has been demonstrated in this report that they occur in the absence of hypercapnia. Nevertheless, the magnitude and frequency may be kept at a minimum.

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References


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