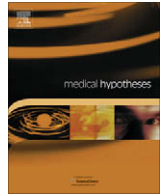


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Hypothesis for lateral ventricular dilatation in communicating hydrocephalus: New understanding of the Monro-Kellie hypothesis in the aspect of cardiac energy transfer through arterial blood flow

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SUMMARY

Many theories have been postulated to date regarding mechanisms involved in non-enlargement of the subarachnoid space and enlargement of the ventricles in patients with communicating hydrocephalus, but none have been proved to be definite. Cerebrospinal fluid (CSF) movement is known not to bulk flow but rather pulsatile flow that develops from the energy of the blood flow ejected from the heart, in an isolated system of the intracranial cavity surrounded by a solid skull, as in the Monro-Kellie hypothesis. The authors attempt to explain the mechanisms involved in selective enlargement of the lateral ventricle in patients with communicating hydrocephalus by re-addressing the Monro-Kellie hypothesis with respect to cardiac energy transfer and dissipation by the Windkessel effect.

The authors present a concept whereby the large energy of blood flow from the heart that is conveyed to the intracranial artery, arteriole, brain parenchyme, ventricle, and CSF within the confined cranial space as in the Monro-Kellie hypothesis, and which ultimately dissipates to maintain an intracranial energy equilibrium. In the same context, if, for some reason the intracranial equilibrium in the energy transfer and dissipation is changed or disrupted, then structural changes would have to occur to achieve and maintain a new intracranial equilibrium. We postulate that the above described mechanisms are those responsible for the development enlarged of lateral ventricles in patients with communicating hydrocephalus.

Structural enlargement of the lateral ventricles in communicating hydrocephalus is a consequence of CSF pathway obstruction and resultant increased CSF absorption function in the lateral ventricle which markedly increases the pulsatile CSF energy flow returning to the lateral ventricles, thus causing collision of pulsatile CSF flow with the brain parenchyme at the ventricular wall, which subsequently leads to structural enlargement of the lateral ventricles. Also, the collision between the CSF pulsation and brain parenchyme pulsation reduces the Windkessel effect of the brain parenchyme which increases the intracranial artery pulse pressure, which in turn is transmitted to the CSF and increases CSF pulse pressure. This vicious circle results in the high pulse pressure within the lateral ventricle structurally dilating the lateral ventricle. Our theory also explains the relationship between ventricle dilatation and idiopathic intracranial hypertension, venous sinus thrombosis, achondroplasia.

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Background

Many theories have been postulated to date regarding the mechanisms involved in the pathogenesis of ventricular dilatation in communicating hydrocephalus, but none have been firmly established yet. First of all, the classical bulk flow theory, which attempts to explain CSF flow, fails to account for ventricular dilatation in patients with communicating hydrocephalus. The reason for this inadequacy is because in the bulk flow theory, CSF is secreted by the choroid plexus and flows to the ventricles and subarachnoid spaces to be subsequently absorbed by the arachnoid

villi. If obstruction of the arachnoid villi occurs and results in hydrocephalus, then subarachnoid space dilatation on the side of the obstructed arachnoid villi would develop. Nevertheless, the lateral ventricles are dilated in many cases [1–4].

Two recent hypotheses have been postulated regarding the mechanisms involved in the formation of dilated lateral ventricles in communicating hydrocephalus. One hypothesis put forward by Bering [5] and further developed by Egnor et al. [6,7] is the hyperdynamic choroid plexus pulsation theory, which suggests that ventricle dilatation is a result of a sequence of hyperdynamic pulsation of choroid plexus: obstruction of the subarachnoid space leads to decrease in artery pulsation, while choroidal artery pulsation is increased and hyperdynamic, which eventually increases the intraventricular pressure to result in ventricle dilatation. However, it

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seems illogical that while subarachnoid space obstruction leads to decreased pulsation in all arteries except choroidal artery, only choroidal artery pulsation is specifically increased, and therefore this theory lacks conviction.

A second theory for lateral ventricle dilatation in communicating hydrocephalus as proposed by Greitz [8–10] is the hydrodynamic theory (impaired Windkessel effect hypothesis), in which hydrocephalus is considered to be an effect of decreased intracranial compliance. When intracranial pressure is increased due to the presence of hydrocephalus, arterial expansion, and blood flow is restricted, which is transmitted to arterioles and capillaries with increased arterial pulse pressure. The resulting event is increased brain pulsation and intraventricular pulse pressure, and thus ventricle dilatation. This theory may be adequate to explain the occurrence of ventricular dilatation as a consequence of decreased intracranial compliance, but is deficient in expounding how the lateral ventricular pulsation derived from the parenchymal pulsation dilate in turn the lateral ventricle to overcome parenchymal pressure that is arguing in a circle. In other words, the above theory fails to elucidate how increased brain pulsation results in increased intraventricular pulse pressure that is higher than parenchymal pressure.

We, the authors, attempt to determine the precise mechanisms that are present in the formation of lateral ventricle dilatation in communicating hydrocephalus by re-analyzing the Monro-Kellie hypothesis in terms of energy transfer and dissipation in the confined cranial space. In the Monro-Kellie hypothesis the skull is a rigid compartment housing three components – the brain, blood, and CSF – and if the volume one of these components become enlarged, then the volume of the other components will have to decrease accordingly [11]. In other words, the existing three components have to compensate with each other in the restricted space of the cranium.

To explain the transfer and dissipation of the blood flow energy generated from the heart to the arteries, brain parenchyme, and CSF, the Windkessel effect concept is essential. The Windkessel effect was first described in the 19th century in order to utilize more effectively fire hoses. In this concept, the water in the water pump contained in the fire engine compression chamber is transferred in a pulsatile flow manner via a distensible air-filled chamber, providing a more constant flow of water from the fire hose. In terms of human physiology, the water pump is likened to the heart, the distensible air-filled chamber to the artery and arteriole wall capacitance, the fire hose to the arteriole, thus explaining the recoiling effect of the artery. In other words, according to the Windkessel effect prevents detrimental over-increase of the arterial pulse pressure due to the pulsatile blood flow from the contraction of the heart, thus providing a more constant and effective blood flow to the arterioles and capillaries. The Windkessel effect also reduces the load on the heart by the same physiologic mechanisms [12].

Re-interpretation of the above energy transfer and dissipation concept of the Windkessel effect in respect of the confined spatial concept of Monro-Kellie hypothesis, for the energy that is contained in the blood flow which is 15% of the cardiac output, that is transmitted to the cranium to be dissipated, a well organized system of energy transfer from the intracranial artery to the arterioles, brain parenchyme, ventricles, and CSF is necessary as the intracranial space is surrounded by a solid non-expansile skull with limited space. In addition, each of the intracranial structures needs to maintain good compliance for effective energy transfer and dissipation. But the dispersion of the Windkessel effect for each structure, i.e., decreased compliance of the intracranial structures and thus increased pulse pressure leads to ineffective transfer and dissipation of the blood flow energy from the heart to the cranium. Such defective energy transfer and dissipation and subsequent upset of the intracranial energy equilibrium is presumed to re-establish a new equilibrium that changes the intracranial

structural interrelationship. It is on this basis that the authors attempt to construe the phenomenon of lateral ventricle dilatation in communicating hydrocephalus.

Hypothesis

The authors postulate a hypothesis that the lateral ventricle dilatation in communicating hydrocephalus is a consequence of defective blood flow energy transfer and dissipation from the heart to the confined intracranial space as in the Monro-Kellie hypothesis.

We hypothesize that in normal human conditions, the blood flow energy that is initiated from the heart is sequentially transferred as intracranial arterial pulsation, arteriole pulsation, brain parenchyme pulsation, and CSF pulsation, and which thereafter dissipates, finally to pass through the arachnoid villi and exiting via the venous system (Figure 1a). However, in communicating hydrocephalus conditions with CSF pathway obstruction, the CSF pulsation energy passes through the arachnoid villi but does not exit the venous system, and returns to the lateral ventricle. Furthermore, in communicating hydrocephalus conditions, the CSF absorption is increased through the lateral ventricle and that contributes additional force to the CSF pulsatile flow returning to the lateral ventricle. Subsequently, the returning CSF pulsatile flow is of a higher energy status than normal conditions and come into collision with the brain parenchyme at the lateral ventricle wall, inducing new high energy equilibrium within the lateral ventricle wall, and finally structural changes such as lateral ventricle dilatation confined intracranial space as in the Monro-Kellie hypothesis. Also, the collision at the lateral ventricle wall between the CSF pulsation and brain parenchyme pulsation reduced the Windkessel effect in the brain parenchyme, and thus decreased compliance of the brain parenchyme. The decreased compliance of the brain parenchyme from the reduced Windkessel effect of the brain parenchyme causes increased brain parenchyme pulse pressure and decreased Windkessel effect of intracranial arteriole and artery. Ultimately, arterial pulse pressure also increases and the high pulse pressure is in turn transferred to the CSF, that is, CSF pathway obstruction and the ensuing decreased Windkessel effect of the intracranial artery, arterioles, and brain parenchyme causes defective energy transfer and dissipation within the cranium. Hence, the pulse pressure transmitted to the CSF increases and the energy also becomes greater. We therefore hypothesize that this vicious cycle leads to the formation of a new high energy equilibrium status within the lateral ventricle and lateral ventricle dilatation (Figure 1b).

Testing the hypothesis

The human brain comprises approximately 2% of the total body weight, but almost 15% of the total cardiac output is transmitted to the brain. The normal cerebral blood flow is 45–50 ml 100 g⁻¹ min⁻¹ and is therefore the organ which receives one of the highest blood flow per unit volume [13]. In terms of kinetic energy that is generated by the systolic and diastolic blood pulsation of the heart, the small and confined intracranial space consumes a relatively large quantity of this energy. Therefore the energy generated by the cardiac output is transferred to the limited and confined spaced cranium, and defective dissipation of this energy which leads to upsetting of and formation of a new energy equilibrium can only result in intracranial structural changes.

Another reason for intracranial structural changes as a consequence of abnormalities in the energy transfer and dissipation system is the final energy dissipation step. The CSF flow is not only a bulk flow that follows the CSF pathway, but rather a pulsatile flow

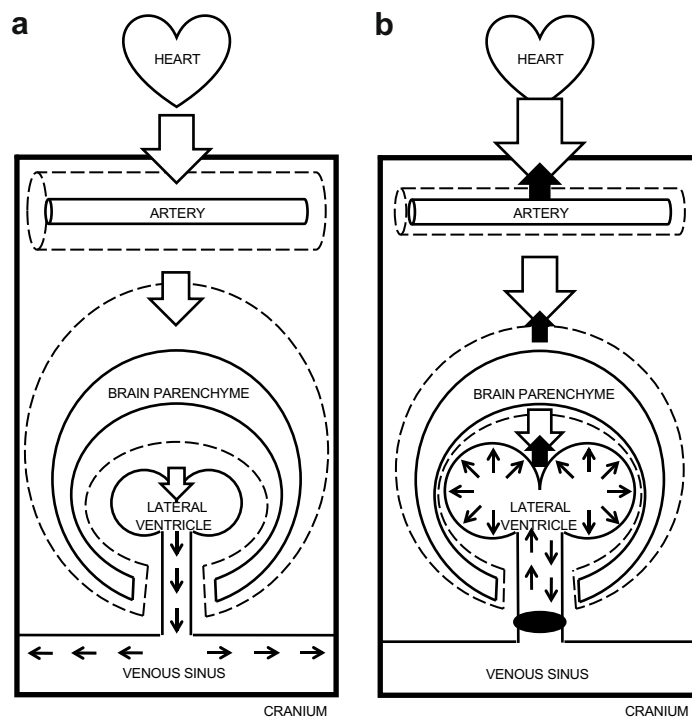


Figure 1. (a) The blood flow energy that is initiated in the heart is transferred sequentially as intracranial arterial pulsation, brain parenchyma pulsation, and CSF pulsation, and which finally dissipates. The remaining energy exits as CSF pulsation via the arachnoid villi to the venous system, maintaining the energy equilibrium within the confined intracranial space as in the Monro-Kellie hypothesis (dash lines indicate the pulsation of each structure). (b) Activation of CSF absorption function in the lateral ventricles and CSF pathway obstruction of communicating hydrocephalus leads to high energy CSF pulsatile flow that is returning to the lateral ventricles. This high energy CSF pulsatile flow come into collision with the brain parenchyma at the lateral ventricle wall, producing a high energy equilibrium in the lateral ventricles, and the loss of the Windkessel effect results in reduced brain parenchyma compliance and increased pulse pressure. The increased brain parenchyma pulse pressure reduces the Windkessel effect of the energy transferring intracranial artery and increased pulse pressure ensues. The increased pulse pressure of the two intracranial components within the confined intracranial space increase the CSF pulse pressure, the last step in the energy transfer and dissipation system, and the lateral ventricles gradually change into a higher energy status. New energy equilibrium forms due to this vicious cycle, and finally structural change in the form of lateral ventricle dilatation is the end point as in the Monro-Kellie hypothesis.

pattern along the CSF pathway [14], and which can be confirmed by flow sensitive MRI. The net position change of the craniospinal CSF bulk flow is 0.004% (0.006 ml/150 ml) of the total CSF volume per 1 cardiac cycle as demonstrated by flow sensitive MRI [8,15]. In the aqueduct where the CSF bulk flow velocity is the highest, the bulk flow velocity is only 1/10th of the pulsatile CSF flow [8]. In other words, considering the fact that CSF flow is not bulk flow but pulsatile flow, the energy contained within the CSF is substantial. Moreover, in many previous studies, investigations utilizing flow sensitive MRI have revealed that pulsatile CSF flow is significantly higher in the aqueduct in communicating hydrocephalus conditions [15–17]. This observation partly supports our theory that defective energy transfer and dissipation leads to high CSF pulsation energy in communicating hydrocephalus to cause lateral ventricle dilatation.

One of the important aspects in the formation of lateral ventricle dilatation in communicating hydrocephalus is the increased reverse pulsatile CSF flow to the lateral ventricle and the increased absorption of CSF by the lateral ventricle, and which has been proven by radioisotope cisternography techniques [18–20]. Larsson et al. [20] performed radioisotope cisternography in normal pressure hydrocephalus patients by lumbar injection of 200MBq^{99m}Tc DTPA (diethylene-triamin-penta-acetic acid), and observed that the increased ratio between ventricular and total intracranial activity which suggested increased CSF reflux into the ventricles, and that ratio between ventricular and total intracranial activity was maintained at a steady level according to progression of time, suggesting that CSF absorption occurs at the ventricular wall to the periventricular tissues. Thereafter, the energy of the reflux pulsatile CSF flow into the ventricle exits via the ventricle wall into the brain parenchyma, resulting in collision with the brain paren-

chyma pulsation, reduced brain parenchyma compliance, and increased brain parenchyma pulse pressure. The increased pulse pressure is thought to be transmitted to the ventricles to induce a high energy equilibrium and finally ventricle dilatation.

Several previous studies have shown that cerebral blood flow is decreased in patients with communicating hydrocephalus [21,22]. This can be explained by the theory that in communicating hydrocephalus, there is a defect in the blood flow energy transfer and dissipation system to the cranium. In communicating hydrocephalus this defect results in the abnormal Windkessel effect of the intracranial artery and arterioles, leading to increased pulse pressure and thus inconstant blood flow transfer to the capillaries. While the constant blood flow delivers blood most effectively to the capillaries, the blood flow with increased pulse pressure from the decreased Windkessel effect reduces cerebral blood flow per unit volume and time.

The hypothesis forwarded by the authors also assists in understanding other problems associated with lateral ventricular dilatation. First, we believe that our hypothesis helps in explaining why lateral ventricular dilatation does not occur in patients with idiopathic intracranial hypertension. In studies which have employed flow sensitive MRI, it was shown that while pulsatile CSF flow is markedly increased in the aqueduct of patients with hydrocephalus, there was no significant difference with respect to aqueduct pulsatile CSF flow between idiopathic intracranial hypertension patients and normal patients [23,24]. These results indicate that although intracranial pressure is increased in idiopathic intracranial hypertension, there are no returning CSF movement and no defect in the intracranial energy transfer system, and therefore the CSF pulsation energy is not increased and lateral ventricular dilatation does not occur.

We also propose that our hypothesis helps in understanding the mechanisms in ventricular size change when venous sinus thrombosis occurs, in which CSF obstruction is present. The reduced venous drainage in venous sinus thrombosis usually decreases the CSF drainage and results in ventricular dilatation [25,26]. In some cases, the venous sinus thrombosis causes increased intracranial pressure without manifest ventricular enlargement, while in other cases of venous sinus thrombosis ventricular dilatation is observed in the initial stages but which gradually returns to normal dimensions as time passes [27]. This may be due to the degree of drainage from the obstructed venous sinus to the CSF and the extracellular fluid (ECF) of the brain parenchyme. If CSF drainage is mainly via the brain parenchyme ECF and the drainage via the venous sinus thrombosis pathway is minimal, then there would be no CSF pathway obstruction and therefore no disruption of the energy transfer and dissipation system, and hence no ventricular dilatation. Conversely, if brain parenchyme ECF drainage is minimal and CSF drainage is mainly by the venous sinus thrombosis route, disruption of the energy transfer and dissipation system occurs with ensuing ventricular dilatation. If there exists a venous sinus thrombosis that nonspecifically drains the ECF and CSF, a portion of the CSF would not be adequately drained, and the resulting disruption of the energy transfer and dissipation system would lead to mild lateral ventricular dilatation. However, compensatory collateral circulation formation via the capillaries would increase the CSF drainage to the brain parenchyme ECF as time passes [27]. Therefore, the disruption of the energy transfer and dissipation system that is caused by the decreased CSF drainage is compensated by the CSF drainage to the ECF. In fact, collateral circulation to the capillaries is formed in venous sinus thrombosis and sometimes the ventricular size may decrease. We propose that our hypothesis explains the reason for ventricular dilatation in patients with venous sinus thrombosis, which is the disruption of the intracranial energy transfer and dissipation system that occurs as a consequence of CSF pathway obstruction.

Similarly, we suggest that our theory is again able to explain the mechanisms for the mild ventricular dilatation and later stabilization in achondroplasia patients. Achondroplasia is the condition whereby suppressed endochondral bone formation leads to reduction in skull base size and therefore stenosis of the jugular foramen and venous narrowing [28]. This event obstructs nonspecifically the brain parenchyme ECF drainage vein and the CSF drainage vein, resulting in disruption of the energy transfer and dissipation system, and hence ventricular dilatation. However, as mentioned above, there is compensation by formation of collateral circulation and increased drainage to the ECF and increased CSF drainage, and thus decreased ventricular dilatation, as in venous sinus thrombosis. Magnetic resonance venography studies have demonstrated a correlation between the extent of venous narrowing at the jugular foramen and ventricle size of patients with achondroplasia, and this may be explained by the disruption of the intracranial energy transfer and dissipation system due to the CSF pathway obstruction. In the same context, the formation of collateral circulation and subsequent decrease in ventricle size is also attributable to the disruption of the energy transfer and dissipation system theory [29].

Conclusion

This hypothesis offers a better elucidation for lateral ventricular dilatation in communicating hydrocephalus that has not been available in the past: disruption of the energy transfer and dissipation system that disrupts the intracranial energy equilibrium in the confined intracranial space as in the Monro-Kellie hypothesis. We also envisage that the same hypothesis will contribute to a better understanding of the formation of ventricular dilatation in other

conditions such as idiopathic intracranial hypertension, venous sinus thrombosis, and achondroplasia.

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