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Bernoulli's Principle Applied to Brain Fluids: Intracranial Pressure Does Not Drive Cerebral Perfusion or CSF Flow

Eric Schmidt, Maxime Ros, Emmanuel Moyse, Sylvie Lorthois, and Pascal Swider

Abstract In line with the first law of thermodynamics, Bernoulli's principle states that the total energy in a fluid is the same at all points. We applied Bernoulli's principle to understand the relationship between intracranial pressure (ICP) and intracranial fluids. We analyzed simple fluid physics along a tube to describe the interplay between pressure and velocity. Bernoulli's equation demonstrates that a fluid does not flow along a gradient of pressure or velocity; a fluid flows along a gradient of energy from a high-energy region to a low-energy region. A fluid can even flow against a pressure gradient or a velocity gradient. Pressure and velocity represent part of the total energy. Cerebral blood perfusion is not driven by pressure but by energy: the blood flows from high-energy to lower-energy regions. Hydrocephalus is related to increased cerebrospinal fluid (CSF) resistance (i.e., energy transfer) at various points. Identification of the energy transfer within the CSF circuit is important in understanding and treating CSF-related disorders. Bernoulli's principle is not an abstract concept far from clinical practice. We should be aware that pressure is easy to measure, but it does not induce resumption of fluid flow. Even at the bedside, energy is the key to understanding ICP and fluid dynamics.

Keywords Bernoulli's principle • Fluid mechanics • Intracranial pressure • Velocity • Energy • Hydrocephalus • Cerebrospinal fluid

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Introduction

The first law of thermodynamics states that the conservation of energy, that is, energy of an isolated system, is constant. Resistance is nothing but a transformation of one form of energy to another form: high resistance represents a high-energy transfer and vice versa. In 1738, Daniel Bernoulli published "*Hydrodynamica*" [1], which stated a fundamental principle in line with the first law of thermodynamics: the total energy in a fluid is the same at all points. In other words, the sum of the kinetic energy, gravitational energy, and pressure energy of a fluid particle is constant along a streamline during steady flow, when compressibility and frictional effects are negligible. Despite its simplicity, Bernoulli's principle [2] has proved to be a powerful tool in fluid mechanics.

Kinetic energy. Kinetic energy of an object is the energy it possesses because of its motion. It is defined as the work needed to accelerate a body of a given mass from rest to its stated velocity. Having gained this energy during acceleration, the body maintains this kinetic energy unless its speed changes.

Gravitational energy. Gravitational energy is the simplest to understand: carry a bucket of water up stairs and the work you have done in part goes into the potential energy of the water.

Pressure energy. Energy and pressure are in fact synonyms. Water under high pressure has more energy than water under low pressure. Although water is considered incompressible, water under pressure is stressed by the pressure. To a small extent, the resultant strain is compressing the water and squeezing the bonds and fields in and around the water molecules. Like a bunch of stiff springs, the water absorbs the energy into the springs, which then push back against the container and the surrounding water. The energy stored in the water "springs" is distributed over the mass of the water being squeezed.

The purpose of this paper is to apply in a simple manner Bernoulli's principle to brain fluids to understand the relationship between intracranial pressure (ICP) and intracranial velocity. What is driving brain fluids? Pressure or velocity? Is ICP driving cerebral perfusion and CSF flow?

Materials and Methods

Bernoulli's equation states that the sum of kinetic energy (E_c)+gravitational energy (E_g)+pressure energy (E_p) is constant [3]. Let us consider a fluid flowing steadily (no pulsatility) in a horizontal (no loss in gravitational energy) rigid (no energy storage) tube. The pressure along the tube is measured using vertical piezometer tubes that display local static pressures. We assume that a virtual tap maintains the fluid at a stable level within the tank to keep the flow steady in the horizontal tube. We applied simple fluid physics to describe the interplay between pressure and flow along the tube. Despite the extreme simplicity of this model, it helps us to understand what drives the movement of a fluid.

Results

The results are demonstrated in Figs. 1 and 2.

Discussion

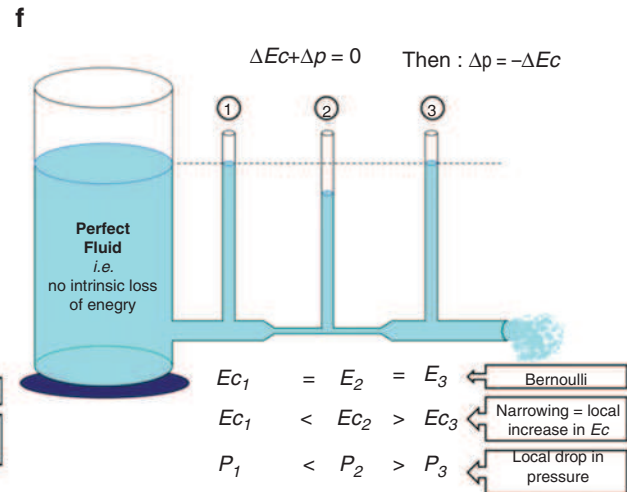
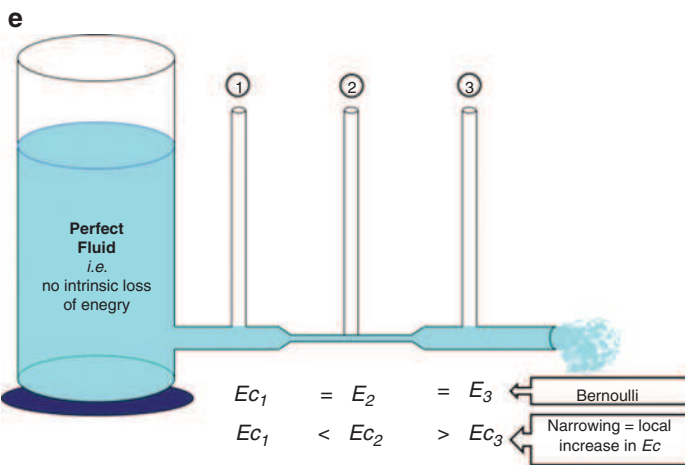
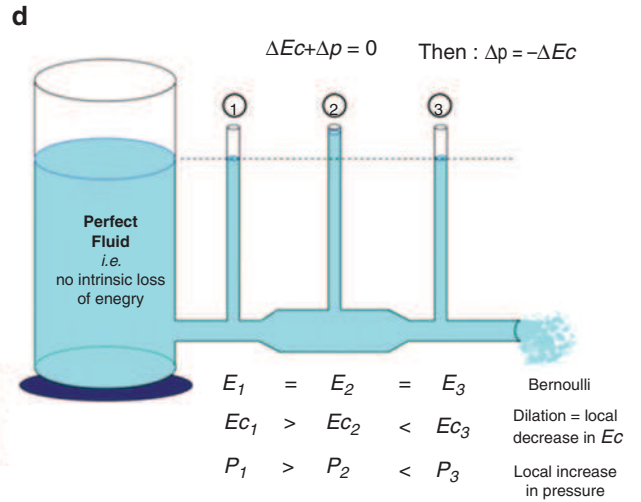
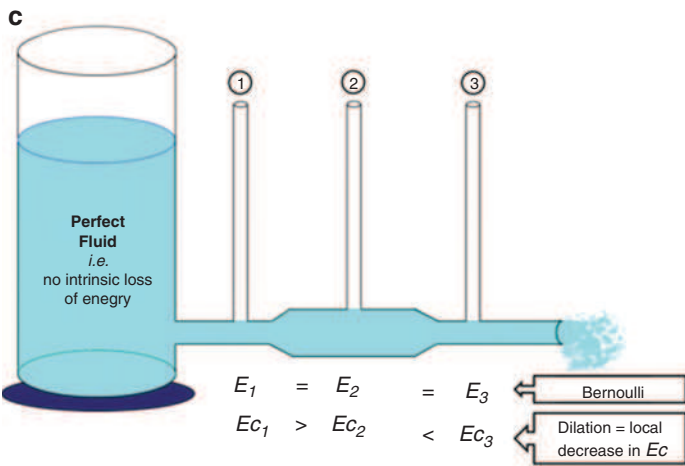
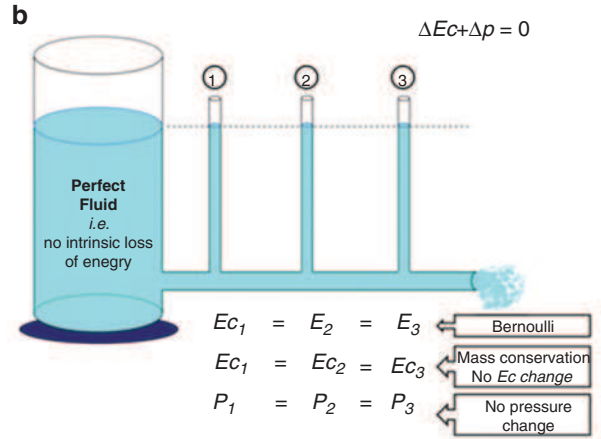
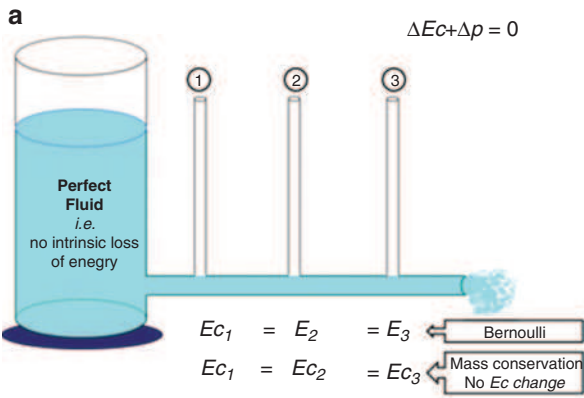
Thanks to Bernoulli, we demonstrate that pressure does not drive flow. A fluid does not flow along a gradient of pressure or a gradient of velocity. In physics and physiol-

ogy a fluid flows along a gradient of energy [4]. The qualitative behavior, termed "Bernoulli effect" [5], is rather counterintuitive, with a lowering of fluid pressure in regions where the velocity is increased. An even more surprising fact is that a fluid can flow against a pressure gradient, from high-pressure region to low-pressure region. For example, in Fig. d the fluid flows from P_1 to P_2 and $P_1 < P_2$, in Fig. f it flows from P_2 to P_3 and $P_2 < P_3$. Also, a fluid can flow against a velocity gradient from low-velocity region to higher-velocity region (e.g., Fig. d: $E_{c2} < E_{c3}$). A fluid does not flow along a gradient of pressure or velocity; a fluid can even flow against a gradient of pressure or velocity. A fluid flows along a gradient of energy, from high-energy region to low-energy region. Pressure and velocity represent a part of the total energy. Measurement of a sole pressure or velocity cannot induce resumption of fluid flow. In what way can Bernoulli's principle be applied to brain fluid?

Intracranial pressure (ICP) is the pressure within the rigid skull. ICP is used to calculate the cerebral perfusion pressure (CPP) as the difference between mean arterial blood pressure (ABP) and mean ICP. In this CPP approach, pulsatile blood flows from the high-energy arterial region (ABP) to the lower-energy venous region (ICP). CPP is easy to explain, calculate, and process at the bedside. However, we should take into account the fact that gauging pressure is an approximation of energy measurement. Using Shepard's approach to hemodynamic energy calculations [6], instead of CPP we should compute an energy-equivalent cerebral perfusion pressure (EECPP) from phasic flow and pressure measurements. The hemodynamic energy delivered to the brain by the pulsatile cardiac blood flow should be calculated using the following formula: $EECPP \text{ (mmHg)} = (\int p dt) / (\int f dt)$, where f is the cerebral blood flow (ml/min), p is the internal carotid pressure (mmHg), and dt is the change in time at the end of the flow and pressure cycle. Thanks to Bernoulli,

Fig. 1 Behavior of a perfect fluid in a horizontal line system and the changes in local pressure (measured using a piezometer tube) depending on the narrowing or dilation of the tube. We explain the local pressure changes using Bernoulli's principle. (a) A perfect fluid is flowing in a horizontal tube; hence, there is no gravitational gradient along the tube. A perfect fluid has no intrinsic loss of energy owing to friction. Bernoulli's principle states that the total energy of the fluid is constant; the net change in kinetic and pressure energy is therefore null: $\Delta E_c + \Delta P = 0$. In accordance with Bernoulli's principle, the total energy is constant ($E_1 = E_2 = E_3$). Owing to mass conservation and the stability of the tube diameter, the mass per unit time is unchanged, and there is no variation in kinetic energy ($E_{c1} = E_{c2} = E_{c3}$). (b) As $\Delta E_c = 0$, then $\Delta P = 0$; in other words, there is no change in pressure along the tube. The static pressure head measured using a piezometer tube is stable: $P_1 = P_2 = P_3$. (c) A perfect fluid is flowing in a horizontal tube with local dilation. Owing to Bernoulli's principle, the total energy is constant ($E_1 = E_2 = E_3$), $\Delta E_c + \Delta P = 0$ or $\Delta E_c = -\Delta P$. Where the tube is dilated, because of mass

conservation, the mass per unit time is reduced, i.e., reduced velocity. There is a local drop in kinetic energy, which is not evenly distributed along the line ($E_{c1} > E_{c2} < E_{c3}$). (d) As $\Delta E_c = -\Delta P$, every reduction in kinetic energy is associated with an inverse change in pressure. $E_{c1} > E_{c2} < E_{c3}$ yields $P_1 < P_2 > P_3$. At \bullet there is a local drop in velocity with a counterintuitive increase in pressure. The static pressure head, measured using a piezometer tube, demonstrates the local pressure augmentation ($P_1 < P_2 > P_3$). (e) A perfect fluid is flowing in a horizontal tube with local constriction. Bernoulli's principle states that the total energy is constant ($E_1 = E_2 = E_3$), $\Delta E_c + \Delta P = 0$ or $\Delta E_c = -\Delta P$. Where the tube is constricted, owing to mass conservation, the mass per unit time is increased, i.e., increased velocity, and there is a local increase in kinetic energy that is not evenly distributed along the line ($E_{c1} < E_{c2} > E_{c3}$). (f) As $\Delta E_c = -\Delta P$, every increase in kinetic E is associated with an inverse change in pressure. $E_{c1} < E_{c2} > E_{c3}$ yields $P_1 > P_2 < P_3$ with a local counterintuitive drop in pressure. The static pressure head, measured using a piezometer tube, demonstrates the local pressure reduction ($P_1 > P_2 < P_3$)



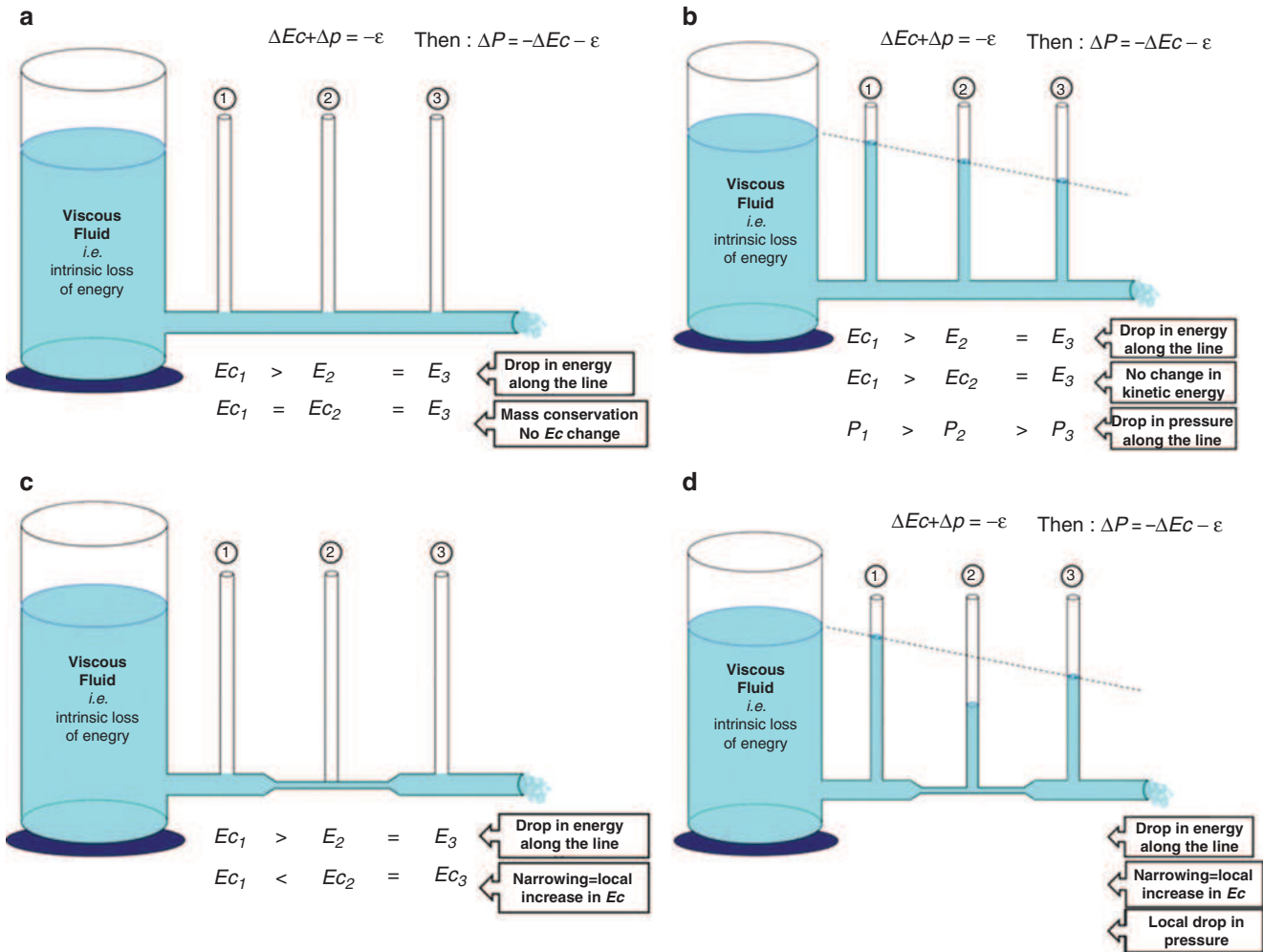


Fig. 2 Behavior of a viscous fluid in the same system. (a) A viscous fluid is flowing in a horizontal tube. A viscous fluid transfers energy to heat because of intrinsic friction. Bernoulli's principle states that the total energy of the fluid is constant, but the friction yields an energy loss with a drop in energy along the line ($E_1 > E_2 > E_3$). Therefore, the net change in kinetic and pressure energy is negative: $\Delta Ec + \Delta P = -\epsilon$. Owing to mass conservation and the stability of the tube diameter, the mass per unit time is stable, and there is no change in kinetic energy ($Ec_1 = Ec_2 = Ec_3$). (b) As $\Delta Ec + \Delta P = -\epsilon$ and $\Delta Ec = 0$, then $\Delta P = -\epsilon$, that is, a drop in pressure along the tube. The static pressure head, measured

using a piezometer tube, is reduced along the line with $P_1 > P_2 > P_3$. (c) A viscous fluid is flowing in a horizontal tube with local constriction. We know that $E_1 > E_2 > E_3$. Where the tube is constricted, owing to mass conservation, the mass per unit of time is increased, i.e., increased velocity. At ② there is a local increase in kinetic energy ($Ec_1 < Ec_2 > Ec_3$). (d) As $\Delta P = -\Delta Ec - \epsilon$, every increase in kinetic energy is associated with a greater inverse reduction in pressure. $Ec_1 < Ec_2 > Ec_3$ yields $P_1 > P_2 < P_3$ with a pressure drop at ②. The static pressure head, measured using a piezometer tube, demonstrates the local pressure drop ($P_1 > P_2 < P_3$)

energy is a key to understanding fluid dynamics and should be applied to understand and characterize cerebral perfusion.

Intracranial pressure is the pressure in the cerebrospinal fluid (CSF) within the rigid skull. CSF is produced by the choroid plexus and is drained down to the venous system by the arachnoid granulations [7]. Consequently, CSF flows along a gradient of energy, from high-energy choroid plexus, through the ventricles, the subarachnoid space, and arachnoid granulations to reach the lower-

energy venous blood. Hydrocephalus is supposed to be related to the derangement of CSF flow and increased resistance at various points has been proposed [8]. The total resistance of CSF flow is the sum of all resistance at various locations, in succession: the foramen of Monro, the aqueduct of Sylvius, the foramina of Luschka and Magendie, the posterior fossa subarachnoid space, the tentorial notch, the subarachnoid space, and finally, resistance at the level of the arachnoid granulations. As mentioned above, resistance is nothing but energy transfer.

Consequently, CSF transfers energy at various points (see above). To better understand ICP, we should keep in mind Bernoulli's principle and identify the location of energy transfer within the CSF circuit. Interestingly, manipulation of intraventricular pulsatility could lead to hydrocephalus [9, 10]. Indeed, an experimental increase in the pressure pulse wave with an intraventricular balloon yielded enlargement of the manipulated ventricle compared with the contralateral ventricle [10]. One can consider how important CSF pulsatility is with regard to ventricular dilation. On the other hand, the artificial increase in pulse wave is produced by adding external energy to the ventricular system. In other words, this experimental setting artificially augments the energy gradient along the CSF circulation; hence, greater energy transfer is required for CSF to flow. Greater energy transfer is greater resistance, isn't it? Then is this experimental hydrocephalus without obstruction of flow related to an increase in pulse pressure or an underlying increase in CSF resistance? Probably both. There is a growing body of evidence that the "pulsatile energy" is important in understanding and treating hydrocephalus and CSF-related disorders [11]. ICP should be considered as dual-purpose, with static and dynamic components.

Intracranial pressure is a complex modality that contains combined information about the brain and heart, and about cerebral compensatory and blood flow regulation mechanisms [12]. Bernoulli's principle is not an abstract concept that is far from clinical practice. We should be aware and teach that pressure does not drive flow. Pressure is one of the easiest physical properties to measure, but pressure does not induce a resumption of fluid flow. Thanks to Daniel Bernoulli, energy is the key to understanding cerebral fluid dynamics and helping to decipher ICP.

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Conflict of Interest Statement No conflict of interest to declare.

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