Physiology of human fluid balance

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Abstract

The physiology of fluid balance in humans should be understood and applied in clinical practice. Fluid balance, when managed accurately and safely, can prevent significant morbidity and mortality. Anaesthesia and critical care patients are often fasted and under physiological stress. Therefore, homoeostatic regulation of fluid balance is impaired. A disturbance in normal fluid balance induces a physiological 'stress' response via metabolic, neuroendocrine and immune-mediated systems. Critically unwell patients may suffer morbidity secondary to high-volume fluid losses or oedema. There are three fluid compartments discussed in relation to human fluid balance. The intracellular space is surrounded by extracellular fluid, separated by the water permeable cell membrane. Extracellular fluid (ECF) compartment volume and electrolyte concentration, majorly sodium, must be tightly regulated to avoid osmosis and cell damage. The renal system maintains ECF volume by regulating sodium and osmotic concentration by retaining or excreting water.

Keywords Aldosterone; anti-diuretic hormone; arginine vasopressin; fluid balance; osmolality; osmolarity; physiology; renin-angiotensin-aldosterone system; sodium

Royal College of Anaesthetists CPD Matrix: 1A01, 1A02, 2C04

Learning objectives

After reading this article, you should be able to:

- understand the regulation of water and electrolyte balance
- understand fluid compartments and capillary dynamics
- define the terms osmosis, osmotic concentration (formerly osmolarity) and osmolality and tonicity
- describe barriers to fluid movement between compartments
- define the role of arginine vasopressin in fluid balance

Water

In physiology, water (H_2O) can be distinguished from the term 'fluid' because water does not contain solutes. Water is vital for cell metabolism, thermoregulation and lubrication of tissues. The lean human body is composed of approximately 60% water.

Water intake occurs by eating and drinking (approximately 2200 ml), and through metabolic water production (350 ml). Metabolic water is generated as a by-product of carbohydrate, protein and fat oxidation. The daily requirement of water in health is estimated to be 20–60 ml/kg/day. Water is lost via urine, faeces and also insensible losses. Insensible water loss is the loss of water through respiration. Burns disturb the natural waterproof barrier of the skin and those patients with extensive burns lose higher volumes of fluid. Insensible losses are increased in patients under physiological stress, for example in sepsis.

Water is reabsorbed in the nephron following osmosis. Approximately two-thirds of water presented to the proximal convoluted tubule is reabsorbed secondary to sodium active transport, with water following the movement of sodium. The descending limb of the loop of Henlé is permeable to water whereas the ascending limb is impermeable. There is no water reabsorption at the distal tubule, but due to electrolyte reabsorption the fluid remains dilute. Dilute urine leaves the distal tubule and enters the collecting duct where arginine vasopressin (AVP), otherwise known as antidiuretic hormone (ADH), is the main hormone that regulates water balance. Daily output of urine is approximately 0.5 ml/kg/hour.

Total body water and fluid compartments

Total body water (TBW) varies between individuals of different sex and age and is dependent on lean body mass (Table 1). In a 70 kg man TBW is approximately 60% of body weight, 42 l. Tissues differ in their water composition. For example muscle is composed of 75% water, bone 22% and adipose tissue 10%.

Total body water is distributed between two fluid compartments; two-thirds of water is in the intracellular fluid compartment (ICF) and one-third is in the extracellular fluid compartment (ECF). Extracellular fluid is further sub-divided into intravascular and interstitial compartments but these are considered to be in equilibrium (Figure 1).

Water must move from the ICF compartment back to the intravascular compartment in order to be excreted. The fluid composition of the plasma in the intravascular compartment is then regulated by metabolism in body organs.

Lymph describes the interstitial fluid that is transported and filtered in the lymphatic system back into the intravascular space. There are additional transcellular fluid compartments in the ECF compartment regulated by secretory cells: sweat, gastrointestinal, cerebrospinal fluid, ocular, peritoneal, pericardial, pleural and synovial. These use water as a lubricant.

Measuring compartments

The approximate volume of a compartment can be measured by intravenous injection of an indicator that cannot move between compartments. The amount of this indicator lost by elimination and excretion must be known.

Volume of distribution in a compartment = dose of indicator/concentration in compartment

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Total body water (TBW) composition

	TBW as % of body weight
Neonates	75%
Infants	70%
Adult male	60%
Adult female	55%
Elderly	45%

Table 1

Fluid compartments for 70 kg adult male

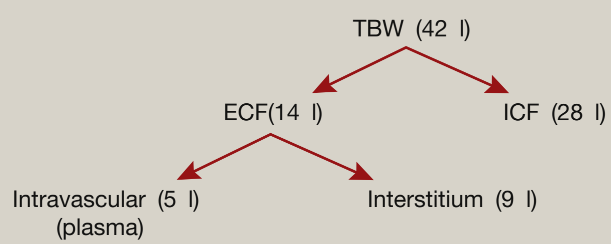

Figure 1

Total body water can be measured using deuterium oxide and the principle of dilution. Plasma can be measured with radiolabeled albumin, as this large molecule remains within the intravascular space. Total blood volume within plasma can also be calculated.

$$\text{Total blood volume} = \text{plasma volume x 100/100-haematocrit}$$

Extracellular fluid is difficult to measure due to the constant movement of water between intravascular and interstitial fluid. Intracellular fluid volume can only be calculated if ECF volume and TBW are known.

$$ICF = TBW - ECF$$

Composition of fluid compartments

A solute is a substance dissolved in a medium, the solvent. When a solute is added to a solvent it is called a solution. A solution has a greater overall volume and, therefore, a lower concentration of the solute.

The ECF compartment is considered a reservoir of nutrients and oxygen required for cellular metabolism. This fluid compartment can be added to through enteral or parenteral intake and from products of metabolism. The ECF compartment can also be depleted by metabolism and excretion. The major solute and electrolyte present in ECF is sodium.

The ECF and ICF compartments have an imbalance of sodium (Na^+) and potassium (K^+) ions. The Na^+/K^+ ATPase pump regulates this imbalance to maintain a high concentration of Na^+ and K^+ within the ECF and ICF, respectively. This mechanism determines cell membrane potential, thus playing a crucial role in neuronal cell action potential initiation and propagation.

In order to balance electrical charge across a cell membrane certain anions and cations are associated with each other. Sodium is paired with chloride (Cl^-) and bicarbonate (HCO_3^-). Phosphate (PO_4^{3-}) is a major intracellular anion balancing the opposing charge of K^+. In addition to electrolytes, negatively charged proteins also remain intracellular to maintain electrochemical neutrality.

Barriers to movement of fluid

The plasma cell membrane is composed of a lipid bilayer with a hydrophilic phospholipid head exterior and a hydrophobic interior. The main functions of this lipid bilayer are to maintain the cell structure, prevent water molecules passing through the hydrophobic interior and to keep fluidity of membranous proteins. Small water molecules can move freely through the plasma membrane as the fluid structure of the membrane changes. Water can also pass through specifically designed water pores, called aquaporin channels.

The plasma membrane barrier between interstitial and intracellular compartments allows passive and active transport by carrier proteins, compared to majorly passive movement across the capillary wall. Interstitial and intravascular fluid compartments are similar in composition compared to the ICF compartment.

Capillary blood, which makes up 5% of circulating volume, provides an important source of water and nutrients for cellular metabolism. Blood flows very slowly through capillary beds due to extensive branching and resistance remains lower than other blood vessels.

The intravascular and interstitial fluid compartments are divided by a fenestrated, 1 micrometre thick capillary wall. This thin wall is supported by a basement membrane and extracellular matrix. Fenestrations are large holes between the endothelial cells which allow faster fluid movement. Water and hydrophilic substances can also pass through the pores between capillary endothelial cells. The movement of water is therefore controlled by presence of pores and pore size. In the brain, tight junctions do not allow pores to exist, keeping the integrity of the blood—brain barrier and preventing water influx.

The composition of the intravascular and interstitial compartments is broadly similar. Starling's forces exist between capillary blood and the interstitium across the capillary membrane. In health, there are limitations on the ability of certain plasma proteins to cross the capillary wall.

Intracellular volume is determined by water moving through the plasma cell membrane by osmosis. Therefore, cells can shrink or expand if water balance and ECF solute concentration is not strictly controlled. The ECF compartment has a similar osmotic concentration to the ICF compartment to prevent net movement of water into a cell (around 300 mosmol/L).

Starling's forces

Hydrostatic pressure (P) is the driving force for capillary fluid (C) filtration across the capillary membrane into the interstitial fluid compartment (IF). The ability of fluid to cross this membrane is also dependent on the permeability and surface area of the membrane. The capillary filtration coefficient takes these variables into account (K). The capillary membrane is impermeable

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