Fluid and electrolyte management in children

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Physiology

The body is comprised of solids and water; the proportion of water changes according to age. Total body water (TBW) is divided between the intracellular fluid (ICF) and the extracellular fluid (ECF), separated by cell membrane. The ECF can be further subdivided into water within the intravascular space (IVS) and the interstitial space (ISS), separated by capillary membrane. The biggest change in water content takes place during intra-uterine gestation and the first 3 years of life (Table 1). At birth, a higher percentage of water is in the ECF, unlike older children and adults where the higher proportion is intracellular.

Despite having a similar osmolality (290–320 mosmoles), the electrolyte content of the ECF and ICF are very different. The ECF contains a high concentration of sodium, bicarbonate and chloride, with a low concentration of potassium, calcium and magnesium. In contrast, the ICF has a high concentration of potassium and magnesium and a low concentration of sodium and bicarbonate. Molecular movement takes place between the various fluid compartments by one of three mechanisms: (i) simple diffusion through the lipid membrane (oxygen, carbon dioxide); (ii) movement through protein channels (sodium, potassium, calcium); and (iii) facilitated diffusion through transmembrane carrier proteins (glucose, amino acids).

Water transport between the ECF and ICF is by osmosis; it will move according to the number of osmotically active particles on each side of the membrane. Water movement between the ISS and the IVS also depends on hydrostatic forces within the capillary which forces water at the arterial end out into the ISS. The high protein content of the IVS exerts a colloid osmotic pressure which pulls fluid back into the IVS at the capillary venous end. The normal functioning of this system depends on the structural integrity of the capillary membrane and the removal of protein from the ISS by the lymphatic system.

Table 1 Changes in body weight, body surface area and fluid composition with age

	Preterm neonate	Neonate	1 yr	3 yr	Adult
Weight (kg)	1.5	3	10	15	70
BSA (m^2)	0.15	0.2	0.5	0.6	1.7
BSA/weight	0.1	0.07	0.05	0.04	0.02
TBW (%)	80	78	65	60	60
ECF (%)	50	45	25	20	20
ICF (%)	30	35	40	40	40

BSA, body surface area; TBW, total body water; ECF, extracellular fluid; ICF, intracellular fluid.

The ECF volume is controlled by manipulation of its major cation, sodium. The sensors in this system are carotid baroreceptors, atrial stretch receptors and the juxtaglomerular apparatus adjacent to afferent renal arterioles. A reduction in ECF volume causes non-osmotic ADH release, stimulation of the sympathetic nervous system to cause vasoconstriction, release of atrial natriuretic peptide and activation of the renin-angiotensin-aldosterone system. Control of osmolality is by varying water intake and excretion. The sensors concerned are osmoreceptors found in the hypothalamus. A rise in ECF osmolality triggers the sensation of thirst and causes release of ADH, which increases water re-absorption at the renal collecting ducts. Young children and debilitated patients may not be able to respond to the sensation of thirst.

At birth, the glomerular filtration rate (GFR) is only 25–30% that of the adult. However, by 4 weeks of age, the kidney achieves 90% maturity. The neonatal kidney has a poor concentrating ability and cannot excrete or conserve sodium as well as an older child, causing an increased obligatory water loss. Neonates can increase their urine

Key points

Children have a more limited capacity to deal with inappropriate water and electrolyte administration than adults.

Body weight is used to calculate water and electrolyte requirements.

Pulse rate and volume are good indicators of dehydration and hypovolaemia.

Fluids administered intra-operatively should have a low dextrose content to avoid hyperglycaemia.

Blood loss in children undergoing major surgery invariably requires replacement.

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Table 2 Daily caloric requirement

0–10 kg	100 kcal kg^{-1}
10–20 kg	1000 kcal + 50 kcal kg^{-1} for each kg over 10
21–70 kg	1500 kcal + 20 kcal kg^{-1} for each kg over 20

Table 3 Maintenance fluid requirements

0–10 kg	4 ml kg^{-1} h^{-1}
10–20 kg	40 ml + 2 ml kg^{-1} h^{-1} for each kg over 10
21–70 kg	60 ml + 1 ml kg^{-1} h^{-1} for each kg over 20

volume following a fluid load but have a reduced ability to concentrate urine. A healthy new-born will tolerate a moderate fluid overload much better than moderate dehydration.

Normal fluid and electrolyte requirements

In 1957, Holliday and Segar developed an easily remembered formula for calculating caloric requirements of hospitalised children from body weight (Table 2). They also showed that the water requirement in millilitres was equal to the total energy expended (*i.e.* 1000 ml of water is required for every 1000 kcal expended). Thus, the formula for caloric requirements can also be used to calculate daily water requirements. In practice, it is often more convenient to calculate the hourly rate of fluid administration using the derived formula shown in Table 3.

On a body-weight basis, infants have a much higher water requirement than older children and adults. Thus, an adult of 70 kg has a daily water requirement of 2.5 litre or 35 ml kg^{-1}, whereas an infant requires 100 ml kg^{-1}. The greater fluid requirement in infancy reflects a higher rate of metabolism and growth, a greater surface area-to-weight ratio resulting in a higher insensible water loss and a greater urinary obligatory loss due to a reduced renal concentrating ability. Preterm infants have an even greater rate of insensible loss due to thinner, more permeable, vascularised skin. In infants, fluid management may be complicated by low ambient humidity, use of radiant heaters and phototherapy.

Daily requirements of sodium, potassium and chloride are usually quoted as 30, 20 and 20 mol, respectively, for every 1000 kcal expended. However, quantities considerably in excess of these can usually be handled. Bearing in mind that 1000 ml of water is required for every 1000 kcal expended, it is evident that these requirements will be met by giving a solution of 0.18% sodium chloride in 4% dextrose with 20 mmol of added KCl per litre. Any electrolyte deficits can be corrected by using the following formula:

$$\text{Electrolyte deficit (mmol)} = \text{Weight} \times (C_D - C_M) \times 0.3$$

Where C_D = desired plasma concentration and C_M = measured plasma concentration.

The rationale behind providing 4–5% dextrose in paediatric maintenance fluid is to prevent development of ketosis and not to provide adequate calorie intake; this would require a 25% solution of dextrose to keep within normal fluid requirements. In preterm infants and neonates, solutions containing 10% dextrose are used to prevent hypoglycaemia.

Intra-operative fluid management

When a child comes for surgery, the main fluid concerns for the anaesthetist are to replace any pre-operative deficits, provide normal maintenance requirements and replace any intra-operative losses.

Deficit

A healthy child coming for elective surgery will have a deficit consisting of the hourly fluid requirement rate multiplied by the number of hours of starvation. Of this deficit, 50% should be replaced over the first hour of surgery with the other 50% over the next 2 h.

A child coming for emergency surgery may have a further deficit relating to dehydration from existing fever, vomiting or blood loss. The level of dehydration should be assessed and

Table 4 Assessment of dehydration

Signs and symptoms	Mild	Moderate	Severe
Weight loss (%)	5	10	15
Deficit (ml kg^{-1})	50	100	150
Appearance	Thirsty, restless, alert	Thirsty, restless or lethargic but rousable, pale	Drowsy to comatose, limp, cold, sweaty, grey, cyanosed
Skin turgor	Normal	Decreased	Markedly decreased
Mucous membranes	Moist	Dry	Very dry
Anterior fontanelle	Normal	Sunken	Very sunken
Pulse	Normal	Rapid and weak	Rapid and feeble
BP	Normal	Normal/low	Low
Respiration	Normal	Deep	Deep and rapid
Urine output (ml kg^{-1} h^{-1})	< 2	< 1	< 0.5

fluid replaced before surgery. The degree of dehydration can be assessed using a combination of clinical signs and physiological measurements (Table 4). In children, the compensatory response to hypovolaemia is increased heart rate and peripheral vasoconstriction. The ability to increase stroke volume as a means of increasing cardiac output develops with age. Hypotension is a late and ominous sign of hypovolaemia, suggesting imminent decompensation and requiring immediate treatment. Correction of dehydration should be with normal saline or Ringer's lactate. A colloid solution may be needed if the extent of the dehydration is severe.

Maintenance

Maintenance fluid requirements need to be given for the duration of surgery to replace insensible and obligatory losses. It has been shown that using a solution containing 5% dextrose during surgery invariably produces hyperglycaemia, which causes an osmotic diuresis leading to dehydration and electrolyte disturbance. Studies in primates and case reports in the literature show that hyperglycaemia in combination with a hypoxic ischaemic cerebral or spinal cord insult will worsen neurological outcome. The proposed mechanism is that ischaemia occurring in combination with hyperglycaemia results in anaerobic metabolism of the increased brain glucose, with increased formation of lactic acid, which results in a larger acid load and more extensive cellular injury.

During the 1970s, it was found that a high percentage of children < 5 years of age who were starved prior to surgery were apparently hypoglycaemic at induction. However, almost all studies since the 1980s have failed to demonstrate this. Children starved for afternoon surgery tend to have a lower blood sugar that those starved for morning lists; this is thought to be due to the diurnal variation in plasma cortisol concentrations. Pre-operative hypoglycaemia is a very rare event, even in young infants. The current practice of giving liberal amounts of clear fluids in children up to 2 h before surgery reduces this likelihood even further and maintains a better state of hydration.

If dextrose is avoided altogether during anaesthesia, most children will show a rise in blood sugar. Only one-fifth of children will show no change or a fall in blood sugar. Infusion of glucose-free solutions can reduce or abolish the risk of hyperglycaemia, but would not correct a low pre-operative blood sugar. Consequently, lipid mobilisation and ketosis may develop. If dextrose-free solutions are used, an intra-operative check of blood sugar is required. Using an IV solution which contains 1% or 2.5% dextrose will correct any pre-operative hypoglycaemia and not produce intra-operative hyperglycaemia.

Care must be taken in children receiving propranolol or regional anaesthesia as part of their anaesthetic technique. Propranolol-related hypoglycaemia was first reported in 1967. Since then, further reports have been published. Propranolol has the double danger of precipitating hypoglycaemia and of concealing an important clinical sign of this disorder. The effects of regional anaesthesia on blood glucose and stress responses during surgery in children have been investigated. Caudal, epidural and spinal anaesthesia have been shown to attenuate the stress response to surgery. Blood glucose concentrations in children receiving combined general and regional anaesthesia are significantly lower than those receiving general anaesthesia alone. Spinal is more effective than epidural anaesthesia in blocking the stress response. Use of high doses of opioids (fentanyl 50 $\mu g\ kg^{-1}$) may also have the same effect. All these patients should have glucose-containing maintenance fluids and intra-operative checks of blood sugar.

Intra-operative losses

Intra-operative fluid loss relates to third-space loss and blood loss. Third-space loss is an isotonic transfer of fluid from the ECF to a non-functional interstitial compartment. Surgical trauma, infection and burns are some of the causes. If such sequestration of fluid continues without replacement, the plasma volume will become depleted. The volume lost is impossible to measure, but is estimated by the extent of surgery and the clinical response to appropriate fluid replacement. It should be replaced with an isotonic fluid such as normal saline or Ringer's lactate. The clinical response to replacement should be sustained and consist of an adequate blood pressure and heart rate, adequate tissue perfusion and a urine output of 1–2 ml $kg^{-1}\ h^{-1}$. Third-space loss will be greatest in a young infant undergoing major intra-abdominal surgery and will be least in those undergoing superficial surgery or neurosurgery (Table 5).

Blood loss should always be replaced in young children undergoing major surgery. Initial replacement should be with crystalloid in a ratio of 3:1 or with colloid in a ratio of 1:1. Pure glucose solution should never be used for plasma volume expansion. It is rapidly metabolised and behaves as free water, quickly

Table 5 Estimate of normal third-space losses

Intra-abdominal surgery	6–10 ml $kg^{-1}\ h^{-1}$
Intrathoracic surgery	4–7 ml $kg^{-1}\ h^{-1}$
Eye surgery/superficial/neurosurgery	1–2 ml $kg^{-1}\ h^{-1}$

Table 6 Normal and acceptable haematocrit

Age	Normal HCT	Acceptable HCT
Preterm infant	0.40–0.45	0.35
Term neonate	0.45–0.65	0.30–0.35
3 month	0.30–0.42	0.25
1 yr	0.34–0.42	0.20–0.25
6 yr	0.35–0.43	0.20–0.25

Table 7 Estimate of blood volume

Preterm neonate	90–100 ml kg^{-1}
Term neonate	80–90 ml kg^{-1}
Infant	75–80 ml kg^{-1}
Older children	70–75 ml kg^{-1}

equilibrating between the ICF and ECF compartments. For every 100 ml infused, only 7.5 ml will remain within the IVS. The colloid solution used may be human albumin solution (HAS) or an artificial colloid such as gelatin or starch solution. There is little evidence that one colloid is better than another in most children but there are few studies in the literature. In neonates, HAS is a superior plasma expander; it maintains the colloid osmotic pressure and serum albumin concentration better than artificial solutions.

It is important to have a plan for blood-loss replacement based on the child's pre-operative condition, haematocrit and nature of the surgery. Allowable blood loss (ABL), which depends on the patient's pre-operative haematocrit and lowest acceptable haematocrit, is a useful concept. The lowest acceptable haematocrit was described by Berry and denotes the lowest haematocrit tolerated without needing transfusion (Table 6). We also need to work out the child's estimated blood volume (EBV) which depends on body weight (Table 7). Allowable blood loss can then be calculated according to the following equation:

$$\text{ABL} = \text{weight} \times \text{EBV} \times (H_0 - H_1)/H_a$$

Where H_0 = patient's original haematocrit, H_1 = lowest acceptable haematocrit, and H_a = the average haematocrit = $(H_0 + H_1)/2$

Care should be taken in children given large amounts of blood intra-operatively. The glucose content in stored blood has been measured at 15–20 mmol $litre^{-1}$ and may cause hyperglycaemia if given in large amounts with maintenance fluids which contain dextrose.

Postoperatively, normal volumes of maintenance fluid should be given, including any on-going third-space loss. After most types of surgery, third-space loss will be minimal. However, after a gastroschisis repair, it may be as high as 35 ml kg^{-1} h^{-1} for the first 24–48 h. In addition, losses due to naso-gastric tube drainage, gut fistuli, peritoneal drainage, chest drain loss and on-going blood loss also need to be replaced with an appropriate fluid. Gut losses are normally replaced in a 1:1 ratio with normal saline. On-going blood loss will need to be replaced with crystalloid, colloid or blood in adequate volume, depending on the child's current haematocrit.

Key references

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See multiple choice questions 1–4.