Fluid and electrolyte balance in children

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Abstract
Fluid therapy in children requires an understanding of certain basic principles to avoid adverse events. Careful consideration needs to be given to both the appropriate rate and composition of the fluids to be administered with frequent re-assessment. Parenteral fluid management is used to meet maintenance requirements, correct any deficit and replace ongoing losses. Non-osmotic secretion of antidiuretic hormone (ADH) may occur, particularly in critically ill children and those in the perioperative period, resulting in an inability to compensate for an inappropriate administration of free water. Excess free water administration may result in cerebral oedema, which is poorly tolerated in children due to the proportionally larger size of the brain within the skull, compared to adults. Hyponatraemic encephalopathy continues to occur in hospitalized children and is associated with severe morbidity and mortality. Early recognition and aggressive management of this condition is required with hypertonic sodium chloride and further care within a paediatric high-dependency/intensive care unit. In the perioperative period concerns over hypoglycaemia have resulted in routine use of dextrose-containing solutions. However for the majority of children the stress response coupled with dextrose supplementation is likely to result in hyperglycaemia. Current recommendations regarding perioperative dextrose management are reviewed.

Keywords Hypoglycaemia; hyponatraemia; intravenous fluids; paediatrics; perioperative fluids

The normal requirement for fluid varies in children of different ages. This is a result of changes in metabolic rate, the ratio of evaporative surface area to body weight, the degree of renal maturity and the amount of total body water at different ages. Intravenous fluids can provide the necessary electrolyte and fluid requirements; however, the appropriate fluid needs to be given and its effects monitored. The glucose content of intravenous fluids is usually only sufficient to prevent ketosis rather than meet the child’s calorific requirement.

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Learning objectives
After reading this article you should be able to:
- prescribe intravenous fluids to children
- understand electrolyte problems that can occur in children
- treat symptomatic acute hyponatraemia

Definitions
Safe fluid prescription depends on an understanding of the following:
- Osmolarity is the concentration of a solution, expressed as the number of solute particles per litre of solution.
- Osmolality is the concentration of a solution, expressed as the number of solute particles per kilogram of solution.
- Tonicity is a measure of effective osmolality or effective osmolality relative to another fluid compartment across a semipermeable membrane.
- Osmoles are solute particles that are capable of exerting an osmotic pressure across a semipermeable membrane. Sodium is the major extracellular osmole and therefore the predominant determinant of extracellular fluid volume. Potassium is the major intracellular ion responsible for determining intracellular fluid volume. Urea and glucose pass freely across all cell membranes and therefore do not contribute to the effective tonicity of body fluid compartments, despite being determinants of plasma osmolality.

As shown in Table 1 the osmolality, sodium content, osmolality compared to plasma and tonicity of available intravenous fluids vary greatly. As can be seen the combined sodium chloride and glucose solutions, where the sodium content is less than 154 mmol/litre, are hypotonic in the body. Glucose passes freely across cell membranes and does not contribute to the effective tonicity.

Antidiuretic hormone (ADH)
Normal plasma osmolality is 280–295 mOsm/litre with tight auto-regulation around each individual’s genetically determined set point. Variations in plasma osmolality are controlled primarily via ADH secretion from the posterior pituitary gland. An increase in plasma osmolality results in an increase in the release of ADH which acts upon the collecting ducts of the renal tubules to increase water re-absorption and therefore lower the plasma osmolality back towards normal. Similarly a fall in plasma osmolality reduces ADH secretion to minimal levels and leads to an increase in water excretion and an increase in plasma osmolality. ADH secretion is also triggered by other non-osmotic factors such as hypovolaemia, hypotension, pain, opioids, volatile anaesthetics, nausea and vomiting.

Water and electrolyte requirements
Water is required to replace obligatory insensible losses via skin and respiratory tract, and that lost via urine and faeces. In 1957 Holliday and Segar published a formula for calculating the maintenance water requirements in children.¹ This easy-to-use formula, or Oh’s later simplification, continues to be widely used

References

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Today (Table 2). To generate this formula Holliday and Segar related the calorific requirements of infants and children to water requirements, with 100 ml of water being lost for every 100 kcal expended. For hospitalized children calorific requirements were defined as being halfway between basal metabolic rate and those estimated for normal activity. In addition daily electrolyte requirements were estimated in relation to the intake of electrolytes from differing types of milk required to meet calorific needs. From this the maintenance electrolyte requirements for sodium were $2\text{ mmol/kg/day}$ and potassium $1\text{ mmol/kg/day}$.

### Maintenance fluids

Where possible fluids should be given enterally. If parenteral fluid therapy is required then maintenance fluid requirements should be calculated using the Holliday and Segar formula based on weight. However this should only be used as a starting point and the individuals’ response to fluid therapy should be monitored closely by clinical observation, fluid balance, weight and a minimum daily electrolyte profile. Fluid composition will vary according to clinical situation. Most children can safely be managed with a solution of 0.45% saline with added glucose (i.e. 0.45% saline with 5% glucose or 0.45% saline with 2.5% glucose) depending on glucose requirements. Sodium chloride 0.18% with glucose 4% should not be used as a maintenance fluid and is restricted to specialist areas to replace ongoing losses of hypotonic fluids. These areas include high dependency, renal, liver and intensive care units.

Certain children are more at risk of developing hyponatraemia and will benefit from the use of isotonic solutions, such as 0.9% saline with or without glucose and Hartmann’s solution. Those at particular risk include children with a low plasma sodium at time of commencing fluids, particularly if below 135, and those in danger of developing non-osmotic ADH secretion. This includes children in the perioperative period who may experience several of the non-osmotic triggers such as hypovolaemia, pain, opiates, nausea or vomiting.

Previously concerns regarding the risk of hypoglycaemia in children undergoing surgery led to the routine use of glucose-containing solutions. However, in the majority of children the stress response to starvation and surgery is more likely to result in hyperglycaemia. Current recommendations are that solutions without additional dextrose may be used intraoperatively in most patients whilst monitoring the blood glucose. Those at risk of hypoglycaemia include:

- neonates in the first 48 hours of life
- preterm and term infants already receiving dextrose-containing solutions
- children on parenteral nutrition
- low body weight (<3rd centile) or undergoing prolonged surgery
- extensive regional blockade with attenuated stress response.

These at-risk groups will require a glucose-containing fluid or regular blood glucose checks intraoperatively. A solution containing 1–2.5% dextrose appears sufficient to prevent hypoglycaemia with a reduced risk of developing hyperglycaemia. However in the postoperative period this may be insufficient to prevent ketosis.

### Deficit

In addition to fluids required to meet maintenance requirements, children may require replacement of a fluid deficit. Fluid deficit sufficient to cause impaired tissue oxygenation, resulting in clinical shock, should be quickly corrected with a bolus of an isotonic fluid. For the majority of patients this bolus is given as 20 ml/kg. However in patients with trauma or diabetic ketoacidosis this should be given in smaller aliquots of 10 ml/kg. Following any fluid bolus clinical re-assessment should guide the need for repeated boluses with consideration to the use of blood after 40 ml/kg (see articles on Transfusion guidelines in children in this issue).
More gradual fluid loss resulting in dehydration can occur due to increased renal losses, such as diabetes insipidus, or from large gastrointestinal (GI) losses, such as gastroenteritis. An assessment of the degree of dehydration requires clinical examination looking at a number of signs (Table 3). However this is often inaccurate and a more accurate figure may be determined from change in body weight, if a recent weight is available. Electrolyte disturbances can also be present depending on the ratio of electrolyte to water loss. Commonly an equal ratio of water to sodium is lost resulting in isonatraemic dehydration, hypernatraemic dehydration from excess water loss or hypotonatraemic dehydration from excess sodium loss can also occur. The aim of treatment should be gradual rehydration over 24–48 hours with frequent electrolyte checks to ensure that the plasma sodium value does not change too rapidly.

Allowing clear oral fluids until 2 hours preoperatively minimizes fluid deficit in children undergoing elective surgery. This approach does not result in an increased aspiration risks, as there is no increase in gastric volumes or decrease in gastric pH. Children with more prolonged fasting times or those undergoing major surgical procedures may experience less postoperative nausea and vomiting if adequately rehydrated intraoperatively. Different approaches to managing this rehydration include a simple 10 ml/kg bolus of isotonic fluid over the first hour or calculating the fluid deficit (hourly maintenance requirements multiplied by the duration of the fluid fast in hours) and replacing it throughout the operation, with 50% being given in the first hour and 25% over the next 2 hours. For either approach to work it must be remembered that this fluid is over and above ongoing maintenance requirements and any ongoing losses.

**Ongoing losses**

Ongoing fluid losses may be easily appreciated and measured, such as high output stoma losses or ongoing blood loss, or more difficult to appreciate and measure, such as transudative losses or evaporative losses. Measurable losses should be replaced ml for ml with an isotonic fluid of similar electrolyte composition to that being lost. This is easiest to achieve by replacing the previous hours measured lost over the subsequent hour. Once urine output is confirmed additional potassium may be added to the replacement fluids. In difficult cases measuring the electrolyte composition of the fluid lost may allow for more accurate replacement and correction of any electrolyte disturbances. Blood loss should be replaced either with crystalloids in a 3:1 ratio or with blood or colloid at a 1:1 ratio. In keeping with adult practice a restrictive transfusion trigger may be applied in children over 3 months of age without cyanotic heart disease. Accepting a haemoglobin level above 7 g/dl will result in fewer transfusions without an apparent increase in adverse incidents (see articles by Hartrey in this issue). Transudative losses, or ‘third-space’ losses, arise due to the redistribution of fluid from the extracellular fluid (ECF) to the interstitium in response to surgical manipulation or stress. Evaporative losses may be increased during surgical exposure, burns or pyrexia. Transudative losses coupled with increased evaporative losses can result in significant effects on the effective circulating plasma volume and eventual haemodynamic compromise. As the amount lost cannot be measured directly close observation of cardiovascular status, acid base status and haematocrit measurement may be beneficial. An estimation of losses can be made dependent on type and site of surgery, ranging from 1–2 ml/kg/hour for minor surgical procedures, 4–7 ml/kg/hour for a thoracotomy to 7–10 ml/kg/hour for abdominal surgery.

**Perioperative fluid management**

Perioperative fluid management can be divided into replacing the preoperative deficit, continuing the maintenance requirements and replacing intraoperative losses. Achieving this with the appropriate fluids maintains adequate circulating blood volume and cardiac output, while preventing electrolyte imbalance.

### Assessment of dehydration

<table>
<thead>
<tr>
<th>Signs/symptoms</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight loss (%)</td>
<td>5</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Volume of deficit (ml/kg)</td>
<td>50</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>Overall appearance</td>
<td>Thirsty, but not unwell</td>
<td>Thirsty, appears unwell or lethargic but rousable</td>
<td>Increasing lethargy or unresponsive, cold peripheries</td>
</tr>
<tr>
<td>Anterior fontanelle</td>
<td>Normal</td>
<td>Decreased</td>
<td>Sunken</td>
</tr>
<tr>
<td>Skin turgor</td>
<td>Normal</td>
<td>Decreased</td>
<td>Very decreased</td>
</tr>
<tr>
<td>Eyes</td>
<td>Normal</td>
<td>Sunken</td>
<td>Very sunken</td>
</tr>
<tr>
<td>Capillary refill time</td>
<td>&lt;2 seconds</td>
<td>2–4 seconds</td>
<td>&gt;4 seconds</td>
</tr>
<tr>
<td>Mucous membranes</td>
<td>Moist</td>
<td>Dry</td>
<td>Very dry</td>
</tr>
<tr>
<td>Pulse volume</td>
<td>Normal</td>
<td>Weak</td>
<td>Very weak</td>
</tr>
<tr>
<td>Respiration</td>
<td>Normal</td>
<td>Increased rate</td>
<td>Increased rate and depth</td>
</tr>
<tr>
<td>Urine output (ml/kg/hour)</td>
<td>&lt;2</td>
<td>&lt;1</td>
<td>&lt;0.5</td>
</tr>
</tbody>
</table>

Table 3
Several years ago concerns about hyponatraemic deaths in children prompted the National Patient Safety Agency to issue an alert on the use of hyponatraemic solutions, particularly in children undergoing surgical procedures. It is recommended to use an isotonic maintenance fluid intraoperatively and for the first 48 hours postoperatively. Fluid restriction of maintenance fluids should also be considered in the postoperative period. Concerns regarding the development of iatrogenic hypernatraemia when using isotonic solutions appear to be unfounded, with studies in both critical care and patients with gastroenteritis showing no significant increased risk in developing hypernatraemia compared to patients receiving hypotonic solutions.6,7

Management of intravenous fluid administration

Fluid prescription requires the same consideration as other medicines with reference to indications, contraindications, monitoring and, particularly, volume. The need for intravenous fluids should be regularly assessed with the aim of changing over to the enteral route as soon as possible. Whichever intravenous fluid is chosen, the optimal way of avoiding dangerous hypo- or hypernatraemia is to observe fluid balance and monitor the plasma sodium concentration regularly. Hyponatraemia can develop within a short timescale and a robust monitoring regime is essential. Weight should be measured, if possible, prior to commencing fluid therapy, and daily thereafter. Fluid balance, including oral intake, should be recorded using a fluid balance chart. Plasma sodium, potassium, urea and creatinine should be measured at baseline and at least once a day. Consider measuring every 4–6 hours if an abnormal reading is found. Electrolyte abnormalities may be managed as shown in Table 4. More frequent sampling should definitely be undertaken if the plasma sodium is below 130 mmol/litre. Ideally, use the same sample technique; either capillary or venous blood sampling, and analytical method on each occasion. This can avoid potentially misleading changes in serial sodium measurements. Urine chemistry may be useful in a small number of high-risk cases. If clinical features suggestive of developing hyponatraemia occur, plasma electrolytes must be checked urgently.

Hyponatraemic encephalopathy

Despite numerous case reports highlighting the dangers associ-ated with intravenous fluid therapy,8 previously well children in hospital continue to suffer morbidity and mortality from acute hyponatraemia and hyponatraemic encephalopathy. This is a result of a combination of factors. Maintenance fluid requirements as calculated by Holliday and Segar’s formula may be an overestimate in hospitalized children resulting in excess free water administration. In addition, the use of hypotonic fluid solutions leads to increased free water administration. Finally

Management of electrolyte abnormalities4

<table>
<thead>
<tr>
<th>Hypokalaemia</th>
<th>Hyperkalaemia</th>
<th>Hypocalcaemia correct total</th>
</tr>
</thead>
<tbody>
<tr>
<td>[K⁺] &lt; 3.5 mmol/litre</td>
<td>[K⁺] &gt; 5.5 mmol/litre</td>
<td>[Ca²⁺] &lt; 2.0 mmol/litre or 1.5 mmol/litre in neonates</td>
</tr>
</tbody>
</table>

**Effects**

- Symptoms unusual
- Muscle weakness, ileus, cramps, arrhythmias, decreased cardiac contractility and cardiac arrest.

**Treatment**

- Mild ([K⁺] < 3.5 mmol/litre): Increase oral K+ supplementation (0–5 mmol/kg/day).
- Severe ([K⁺] < 3 mmol/litre): IV correction no faster than 0.25 mmol/kg/hour.
- Maximum 40 mmol/litre fluids given peripherally. Higher concentrations may be given via central line in a monitored critical care area.

- Treatment aimed at:
  1. Reduce K⁺ intake
  2. Antagonizing membrane effects by giving 100 µg/kg 10% calcium gluconate IV (0.5 ml/kg)
  3. Increase intracellular shift with 1–2 mmol/kg sodium bicarbonate, 0.3–0.5 g/kg/hour of glucose with 1 unit insulin for every 5 g of glucose and/or 2.5–5 mg nebulized salbutamol
  4. Remove K⁺ with 125–250 mg/kg calcium resonium PO or PR, furosemide 1 mg/kg or dialysis/hemofiltration

- Correction with either:
  0.5 ml/kg 10% calcium gluconate slow IV (maximum 20 ml over 10 minutes) or:
  0.2 ml/kg 10% calcium chloride slow IV (maximum 10 ml over 10 minutes).
  Cautious IV injection will cause severe tissue damage if extravasation occurs. Use central access if available.

**Table 4**

ECG, electrocardiography; IV, intravenous; PO, orally; PR, rectally.
children who are acutely unwell or recovering from surgery are likely to have several reasons for non-osmotic secretion of ADH and therefore an impaired ability to excrete free water. This imbalance between water intake and excretion can result initially in a dilution of the ECF and eventual redistribution into the intracellular compartment. Children are particularly at risk of developing hypernatraemic encephalopathy as they have a relatively large brain to skull vault, so changes in brain volume are less well tolerated. Clinically hypernatraemic encephalopathy is a medical emergency that requires rapid recognition and treatment to prevent poor outcomes. Initially there may be an insidious onset of non-specific symptoms such as lethargy or nausea and vomiting which are common in postoperative patients. This may then progress to headache, decreasing consciousness, seizures, respiratory arrest and death, although some children may present initially with these more serious signs. Seizures associated with hypernatraemic encephalopathy may show a poor response to conventional anticonvulsive therapy and hypertonic sodium should be administered, with the aim of raising the serum sodium above the seizure threshold.

Treatment of hyponatraemia

As part of the general resuscitative measures repeated boluses of 1–2 ml/kg of 2.7% sodium chloride should be administered until either seizures stop or serum sodium concentration is greater than 125 mmol/litre. It should be expected that 1 ml/kg of 2.7% sodium chloride will raise the serum sodium concentration by 1 mmol/litre. A formula to estimate amount of sodium required to correct plasma sodium concentration is shown in Box 1. Subsequent care of these children should occur in a high-dependency environment to allow repeated clinical assessment and a gradual serum sodium correction at a rate no greater than 0.5 mmol/litre/hour to prevent osmotic demyelination syndrome. Patients with asymptomatic hyponatraemia do not require 2.7% sodium chloride treatment and if dehydrated may be managed with either oral fluids or intravenous rehydration with 0.9% sodium chloride. Patients who are hyponatraemic and have a normal or raised volume status should be managed with fluid restriction.\(^4\)

Treatment of hypernatraemia

Hypernatraemia is defined as a serum sodium concentration greater than 145 mmol/litre and may occur due to a loss of water relative to sodium or, less commonly, due to excess sodium intake (e.g. salt poisoning). Hypernatraemia will result in fluid shift from the intracellular fluid compartment to the ECF and the clinical manifestations of dehydration may not be present due to the relatively well-preserved circulating volume. In the brain this fluid shift may cause structural change with eventual haemorrhage or venous sinus thrombosis. Treatment of hypernatraemia requires an assessment of cause and duration with long-standing hypernatraemia increasing the risk of cerebral oedema during correction. Gradual rehydration with replacement of calculated fluid deficit over 48 hours is achieved using a hypotonic solution such as 0.45% saline with 5% dextrose. As for hyponatraemia the change in serum sodium concentration should be no faster than 0.5 mmol/litre/hour.

**REFERENCES**

1. Holliday MA, Segar WE. The maintenance need for water in parenteral fluid therapy. *Pediatrics* 1957 May 1; **19**:823–32.
2. Oh TH. Formulas for calculating fluid maintenance requirements. *Anesthesiology* 1980; **53**:351.

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**Calculating sodium correction in acute hyponatraemia**

An estimation of sodium requirements can be made using the formula below:

\[
\text{mmol of sodium required} = (130 - \text{present sodium concentration}) \times 0.6 \times \text{body weight (kg)}
\]

The calculated requirements can then be given from the following solutions depending on availability and hydration status:

- 0.9% sodium chloride contains 154 mmol/litre
- 1.8% sodium chloride contains 308 mmol/litre
- 2.7% sodium chloride contains 462 mmol/litre

**Box 1**