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Review article

Perioperative fluid therapy in pediatrics

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Introduction

Perioperative fluid therapy should be considered as a medical prescription of which both the volume and the composition should be adapted to the patient status, the type of operation and the expected events in the postoperative period. Perioperative fluid therapy is aimed at providing maintenance fluid requirements, at correcting fluid deficit and at providing the volume of fluid needed to maintain adequate tissues perfusion. Recent literature is challenging the old concepts for maintenance fluid requirements described by Holliday and Segar in 1957(1), and the recommendations regarding both volume and content of perioperative solutions have been the subject of recent controversies. Fluid therapy in the neonatal period will not be considered in the present lecture.

Maintenance fluid requirements: facts and controversies

Maintenance fluid therapy represents the fluid and electrolytes requirements needed by the average individual with a normal intracellular (ICF) and extracellular (ECF) fluid volumes over a 24-h period. In 1957, Holliday and Segar (1) estimated metabolic requirements for patients at bed rest. The calorie expenditure was 100 $kcal{\cdot}kg^{-1}$ for infants weighing 3–10 kg, 1000 kcal + 50 $kcal{\cdot}kg^{-1}$ for each kg over 10 kg but <20 kg for children ranging from 10 to 20 kg, and 1500 kcal + 20 $kcal{\cdot}kg^{-1}$ for each kg over 20 kg for children 20 kg and up.

Under normal conditions, 1 ml of water is required to metabolize 1 kcal. This takes into account insensible water losses across the skin and respiratory tract, and urinary water loss. Therefore, in the awake child, calorie and water consumption are considered equal. The corresponding rule for hourly water requirement is well known as the 4/2/1 rule. Hourly water requirements are 4 $ml{\cdot}kg^{-1}{\cdot}h^{-1}$ for infants weighing 3–10 kg, 40 $ml{\cdot}h^{-1}$ plus 2 $ml{\cdot}kg^{-1}{\cdot}h^{-1}$ for each kg over 10 kg for children ranging from 10 to 20 kg, and 60 $ml{\cdot}h^{-1}$ plus 1 $ml{\cdot}kg^{-1}{\cdot}h^{-1}$ for each kg over 20 kg for children 20 kg and up (Table 1).

Example:

Hourly fluid requirements for a child of 15 kg $\rightarrow (4 \times 10) + (2 \times 5) = 50\ ml{\cdot}h^{-1}$.

Daily fluid requirements for a child of 15 kg $\rightarrow (100 \times 10) + (50 \times 5) = 1250\ ml{\cdot}(24\ h)^{-1}$.

In the same study, Holliday and Segar calculated maintenance electrolytes from the amount delivered by the same volume of human milk. Daily sodium and potassium requirements are 3 $mmol{\cdot}kg^{-1}$ and 2 $mmol{\cdot}kg^{-1}$ respectively in children. Thus, the combination of maintenance fluid requirements and electrolyte requirements results in a hypotonic electrolyte solution. Since the publication of this paper, the usual intravenous maintenance fluid given to children by pediatricians for decade was one fourth-to one third-strength saline.

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Table 1
Hourly (4/2/1 rule) and daily maintenance fluids according to child's weight

Weight	*Hourly fluid requirements*	*Daily fluid requirements*
<10 kg	4 ml·kg^{-1}	100 ml·kg^{-1}
10–20 kg	40 ml + 2 ml·kg^{-1} Above 10 kg	1000 ml + 50 ml·kg^{-1} Above 10 kg
>20 kg	60 ml + 1 ml·kg^{-1} Above 20 kg	1500 ml + 25 ml·kg^{-1} Above 20 kg

In 1988, Lindahl (2) found that energy expenditure in anesthetized children was 50% lower than that calculated by Holliday and Segar, but he calculated that 166 ml of water were required to metabolize 100 calories under anesthesia. Thus, there was a good agreement in fluid requirements between the two studies (1,2).

Recently, both the composition and the volume of maintenance fluids were challenged and reevaluated. Briefly, the content of sodium is insufficient in many situations frequently encountered in the hospital setting such as medical emergencies and postoperative period (3–7). Hyponatremia occurs commonly in these clinical situations when Holliday and Segar recommendations (1) are followed. The volume of fluids required in the postoperative period after major surgical procedures has also been re-evaluated recently (8,9). These controversies will be presented below.

Preoperative assessment: estimation of fluid deficit

The preoperative assessment of fluid volume and state of hydration varies from elective surgery patients with no or slowly developing fluid deficit to the severely traumatized patient who is undergoing a dynamic deficit in blood and interstitial volume and in whom it is more difficult to evaluate fluid balance. Only some specific pediatric situations will be reviewed.

Preoperative fasting has been a prerequisite for elective surgery as the demonstration by Mendelson of a link between feeding and pulmonary aspiration of gastric contents in parturients. However, recent work has shown that prolonged fasting does not reduce the risk of aspiration during anesthesia. This has led to a reduction in fasting times and a greater appreciation of the several risk factors for regurgitation and aspiration (10–12). There is now a large body of evidence that free intake of clear fluids up to 2 h preoperatively does not affect the pH or volume of gastric contents at induction of anesthesia in children or adults. In addition, reduced fasting time increases patient comfort and hydration, which is of utmost importance in infants and young children. Current guidelines of preoperative fasting for elective surgery are indicated on Table 2.

Table 2
Fasting guidelines for elective surgery (11)

Ingested material	*Minimum fasting period (h)*
Clear liquids	2
Breast milk	4
Infant formula	4 (<3 month)–6 (>3 month)
Nonhuman milk	6
Light meal	6

Dehydration is observed in many common clinical situations such as vomiting, diarrhea, fever. Estimation of the degree of dehydration is based on classical clinical signs. In an acute clinical situation, the weight loss of the child is usually a very good indication of total water loss. It should be kept in mind that the most important sign of normal hydration status is kidney function. Thus, monitoring of urinary output is essential for evaluating and treating any fluid deficit. Correction of 1% of dehydration requires about 10 ml·kg^{-1} of fluids. Rate of fluid administration depends on seriousness and on rapidity of dehydration.

The ultimate goal of perioperative fluid therapy is to maintain a correct fluid and electrolyte balance and, as a consequence, normal cardiovascular stability. Indeed, dehydration and some medical conditions associated with third space sequestration of fluids (e.g. intestinal occlusion) will in turn affect vascular fluid volume. Restoration of an adequate vascular fluid volume is essential to maintain cardiovascular stability, organ perfusion and adequate tissue oxygenation. Isotonic transfer of fluid from the extracellular compartment to a nonfunctional interstitial space forms third space volume. Replacement of intravascular volume losses should be performed by administration of normotonic and normo-osmolar solution. Crystalloid solutions such as Ringer lactate or normal saline, or even a colloid solution, can be used. The prognosis of some medical conditions such as septic shock depends on the quantity and the rapidity of vascular loading: the younger the child, the greater the volume of fluid loading related to body weight (13).

Intraoperative fluid management

Volume of intraoperative fluids

Intraoperative fluid therapy is aimed at providing basal metabolic requirements (maintenance fluids), at compensating for preoperative fasting deficit and at replacing losses from surgical field.

When new NPO guidelines are followed, fasting fluid deficit is expected to be minimal. However, this is not always applicable or followed, and some children are fasting for several hours prior to surgery. Fasting deficit is calculated by multiplying the hourly maintenance fluid requirement by the number of hours of restriction. In 1975, Furman *et al.*(14) proposed to replace 50% of the fasting deficit in the first hour and 25% in the second and third hours. In 1986, Berry (15) proposed simplified guidelines for fluid administration according to child's age and to the severity of surgical trauma (Table 3). The amount of hydrating solutions required during the first hour of anesthesia was greater in infants and young children than in older children to take into account the larger deficit because of larger losses of extracellular fluid volume. These guidelines are adapted to children fasted for 6–8 h following the classical recommendation 'NPO after midnight'. The amount of fluid given during the first hour should be reduced if children are fasting for a shorter period of time or if the child is already receiving intravenous fluid prior to surgery.

Table 3
Guidelines for fluid administration of balanced salt solution in children according to the age and to the severity of tissue trauma(15)

1. First hour: plus item 3 below
   25 $ml\cdot kg^{-1}$ in children aged 3 years and under
   15 $ml\cdot kg^{-1}$ in children aged 4 years and over
2. All other hours (plus item 3 below)
   Maintenance + trauma = basic hourly fluid
   Maintenance volume = 4 $ml\cdot kg^{-1}\cdot h^{-1}$
   Maintenance + mild trauma = 6 $ml\cdot kg^{-1}\cdot h^{-1}$
   Maintenance + moderate trauma = 8 $ml\cdot kg^{-1}\cdot h^{-1}$
   Maintenance + severe trauma = 10 $ml\cdot kg^{-1}\cdot h^{-1}$
3. Blood replacement 1 : 1 with blood or colloid or 3 : 1 with crystalloids

These guidelines are only guidelines and should be adapted to clinical situations.

Third-space losses may vary from 1 $ml\cdot kg^{-1}\cdot h^{-1}$ for a minor surgical procedure to as much as 15–20 $ml\cdot kg^{-1}\cdot h^{-1}$ for major abdominal procedures, or even up to 50 $ml\cdot kg^{-1}\cdot h^{-1}$ for surgery of necrotizing enterocolitis in premature infants. The younger the child, the greater the relative proportion of losses because of the large extracellular fluid volume in young infants compared with older children and adults. Indeed, ECF volume represents 45% of body weight in term neonates, 30% by the age of 1 year compared with 20% in adults. Third-space losses should be replaced with crystalloids (normal saline or Ringer lactate). Large amounts of normal saline are responsible for hyperchloremic metabolic acidosis, whereas this does not occur after Ringer lactate administration (16). Although no define morbidity has been yet associated with postoperative hyperchloremic metabolic acidosis in adult patients, Ringer lactate is probably the best crystalloid during major surgery such as spinal fusion or renal transplantation (16,17).

The rationale for avoiding both hyper- and hypoglycemia

The next question is whether or not administration of dextrose is necessary during surgery. In the last 20 years, there has been a complete reevaluation of the place of glucose in routine intraoperative solutions. As already discussed above, energy requirements during anesthesia are close to basal metabolic rate. Administration of dextrose was deemed mandatory in the early days to avoid perioperative hypoglycemia which may be difficult to diagnose in an anesthetized child, but the risk of hyperglycemia was at that time underestimated.

Hypoglycemia is known to induce brain damage especially in newborn infant. However, the risk of preoperative hypoglycemia has been demonstrated to be low in normal healthy infants and children (1–2%), despite prolonged fasting periods (18–25). Thus, it would appear that in the vast majority of patients there is no need to administer glucose in the perioperative period nor there is a need to monitor blood glucose in these patients.

Conversely, the danger of hyperglycemia in the perioperative period is a real clinical issue that has been extensively reviewed (26,27). Hyperglycemia can induce osmotic diuresis and consequently dehydration and electrolyte disturbances. Several animal studies have also demonstrated that hyperglycemia will increase the risk of hypoxic-ischemic brain or spinal cord damage (28–30). In infants subjected to profound hypothermic circulatory arrest for cardiac surgery, high prearrest blood glucose levels are associated with postoperative neurological deficits (31). Thus, intraoperative hyperglycemia should be avoided.

The rationale for choosing isotonic hydrating solutions

Most of the fluids required during surgery are needed for replacing either fasting deficit or third-space losses. Both losses consist mainly of extracellular fluids as discussed previously. Thus hydrating solutions should contain high sodium and chloride and a low concentration of bicarbonate, calcium and potassium. Lactated Ringer is quickly degraded into bicarbonate in the liver and behaves as a buffer. As discussed below, polyionique B66 (32) presents only minor differences from standard Ringer-lactate solutions. Its sodium concentration is slightly lower at 120 instead of 130 $mmol \cdot l^{-1}$. This difference allows maintenance of the osmolarity of the solution close to that of the plasma, despite the presence of 0.9% dextrose.

The history of manufacturing polyionique B66 comes from a series of clinical studies done in the early nineties. As discussed above, most of the pediatric anesthesiologists were mainly concerned with the risk of hypoglycemia in those days, not with the potential dangers of hyperglycemia. The first study (20) compared two hydrating solutions containing either 5% dextrose (D5), the reference, or 2.5% dextrose (D2.5). With both solutions, hyperglycemia was observed in the early postoperative period, but mean blood glucose levels were higher in the D5 group compared with D2.5. The second study (19) compared not only blood glucose but also plasma sodium values after administration of three different hydrating solutions: a mixture in equal part of LR and D5 (LR½ D2.5), LR and LR with 1% dextrose (LRD1). As expected, blood glucose values were maintained within acceptable values with the two LR solutions. Plasma sodium values were also maintained within normal values with the two LR solutions, but a significant decrease in plasma sodium values was observed when LR½ D2.5 was administered. This led us to promote the use of isotonic solutions during surgery in order to maintain normal plasma sodium values (33).

Clinical guidelines for intraoperative fluid therapy

Intraoperative administration of glucose-free isotonic hydrating solutions should be the routine practice for most procedures in children over 4–5 years of age. In infants and young children, 5% dextrose solutions should be avoided, but 1% or 2% dextrose in lactated Ringer is appropriate (19,20,24). Glucose infusion at a rate of 120–300 $mg \cdot kg^{-1} \cdot h^{-1}$ is sufficient to maintain an acceptable blood glucose level and to prevent lipid mobilization in infants and children (34,35). Polyionique B66 contains 0.9% dextrose that is adequate to maintain normal blood glucose values in infants and young children during surgery. (Table 4) This 'golden compromise solution' (36) has been used in France for more than 15 years and marketing authorization was granted in 2001 by the French authorities.

Although, there is a rationale for using these hydrating solutions with higher sodium concentration and low or no dextrose, the current practice in some European countries is antiquated. In a survey of current prescribing practices in UK, Way *et al.*(37) reported that 60% of anesthesiologists were still prescribing hypotonic dextrose saline solutions in the intraoperative period and 75% did so in the postoperative period. Several cases of morbidity and even mortality because of severe iatrogenic hyponatremia have been reported in UK and other countries (4–6,9,38,39): it is time to change these practices (36).

Volume replacement during infancy: indications and choice of crystalloids and colloids

Crystalloids (normal saline or Ringer lactate) are first administered to treat absolute or relative blood volume deficits frequently observed during surgery in children. Their advantages include low cost, lack

Table 4
Composition and clinical use of Lactated Ringer, polyionique B66 (32,33) and polyionique B26

Composition mmol·l^{-1}	*Lactated ringer*	*Polyionique B66*	*Polyionique B26*
Sodium	130	120	68
Potassium	4	4	27
Calcium	1.4	2.2	–
Chloride	109	108	95
Lactate	28	20	–
Dextrose	0	50.5	277
Indications	Maintenance fluid therapy during surgery in children over 3–4 years of age Replacement of extra losses (third space, gastric fluid…)	Maintenance fluid therapy during surgery in infants and young children	Maintenance fluid therapy in the postoperative period in normovolemic children

of effect on coagulation, no risk of anaphylactic reaction and no risk of transmission of any known or unknown infectious agent. Normally, 15–20 ml·kg^{-1} of Ringer lactate solution over 15–20 min will re-establish cardiovascular stability. After administration of a total of 30–50 ml·kg^{-1} of crystalloid solution, the administration of a colloid solution (albumin or synthetic colloid) to maintain intravascular osmotic pressure is indicated (40).

Gelatins have been used for many years in children but also in early infancy to treat intravascular fluid deficits. Hydroxyethylstach (HES) preparations are becoming very popular for vascular loading in adults and children (41). However, the number of pediatric studies aimed at evaluating HES efficacy and tolerance is limited. Three studies compared HES preparations with 5% or 20% albumin during general surgery or cardiac surgery in infants and children (42–44). In these three studies, HES was as effective as albumin, and no undesirable side effects were reported. However, short term and long term side-effects were recently reevaluated after HES administration (45–47). In most countries, both daily allowed quantity and duration of HES administration have been limited by health authorities. The better knowledge of undesirable effects of HES has led most pediatric anesthesiologists and pediatricians to avoid the use of HES in premature and newborn infants. In the latter, the choice of colloid will therefore be restricted to gelatins or albumin.

Although the use of albumin has been challenged owing to its high cost and to its uncertain risk of transmission of nonconventional agents, it remains the main colloid used in the neonatal period and early infancy for volume expansion (48,49). In hypotensive premature infants, 4.5% albumin was demonstrated to be more effective than 20% albumin (50). This suggests that the volume of albumin administered is more important that its concentration to maintain or restore cardiovascular stability. Thus 5% albumin remains the preferred colloid in young infants as it is iso-oncotic to plasma and very effective to maintain blood pressure and plasma colloid perfusion pressure.

Postoperative fluid therapy: consensus and controversies

Consensus

Oral fluid intake is usually allowed within the first three postoperative hours in most pediatric patients. Early oral fluid intake was required in most institutions before discharging the patient from hospital. This view is now challenged as it has been reported that withholding oral fluids postoperatively from children undergoing day surgery reduces the incidence of vomiting (51,52). For minor surgical procedures, the intraoperative administration of large volumes of crystalloids ('superhydration') is associated with a reduced incidence of postoperative nausea and vomiting after anesthesia in pediatric and adult patients (53). Thus in the author's opinion, Berry's guidelines are appropriate for minor surgical cases provided that either LR or polyionique B66 is administered during surgery. This is the common practice in our department.

If oral intake should be delayed (e.g. after abdominal surgery), fluid therapy should be administered usually on a peripheral venous access if duration of intravenous infusion is not expected to exceed 5 days or on a central venous access when long term parenteral nutrition is necessary. Fluid therapy should provide basic metabolic requirements, and compensate for gastrointestinal losses (e.g. gastric suctioning) and additional losses (e.g. fever).

Postoperative hyponatremia is the most frequent electrolyte disorder in the postoperative period. Severe hyponatremia (<120–125 mmol·l^{-1}) may result in transient or permanent brain damage (54,55). Most postoperative hyponatremia observed in ASA 1 children are due to the administration of hypotonic fluids when capacities of free water elimination are impaired. Other causes of hyponatremia include pituitary or adrenal insufficiency, brain injuries or brain tumors associated with salt losses, and inappropriate secretion of ADH. Plasma ADH is often increased in postoperative period as a result of hypovolemia, stress, pain, or traction of dura mater. The combination of ADH secretion and infusion of hypotonic fluids will produce dilutional hyponatremia. Profound hyponatremia promotes cerebral edema which clinical signs include decreasing level of consciousness, disorientation, vomiting, and in severe cases seizure activity. Acute symptomatic hyponatremia is a medical emergency which requires immediate therapy. Hypertonic NaCl should be administered to increase plasma sodium up to 125 mmol·l^{-1}, as the risk of seizure decreases above this value. Water restriction may be sufficient only in normovolemic patients without clinical signs. Diuretic may be used in patients with normal or high vascular volume.

Postoperative hyponatremia should be prevented by avoiding hypotonic solutions during surgery and in the early postoperative period.

Controversies

Two opposite attitudes have emerged in the recent literature regarding both the volume and the composition of postoperative fluid therapy after the report of numerous cases of severe hyponatremia in children.

Some are defending the use of isotonic saline in 5% dextrose in hospitalized children except those with plasma sodium values above 140 mmol·l^{-1} (5,56,57). The maintenance rate should be reduced only in children with plasma sodium concentration <138 mmol·l^{-1} and in those at risk for nonosmotic secretion of ADH.

Conversely, Holliday and Segar have changed their recommendations for maintenance fluid therapy especially for surgical patients (8,9,58). They recommend to correct first fluid deficit with 20–40 ml·kg^{-1} normal saline, then to give half of the average maintenance fluid for the first 24 h and to monitor daily plasma sodium concentration.

Clinical guidelines

Basically, combining the two approaches, these simple recommendations could be proposed.

- Hypovolemia should be treated rapidly;
- After major surgery in patients at risk of high ADH secretion, daily maintenance fluids are to be reduced by one third during the first postoperative day provided the child is normovolemic;
- Composition of fluids is a compromise between high sodium requirements, energy requirements and osmolarity of the solution. 5% dextrose is usually adequate to provide energy needs in the early postoperative period. In order to limit the osmolarity of the solution, our choice is to give a ready-to-use D5 salted hydrating solution containing NaCl 4 g·l^{-1}, and KCl 2 g·l^{-1} (polyionique B26, Table 4). All extra losses (gastric tube, chest tubes…) are to be replaced with Lactated Ringer;
- Plasma sodium and glucose concentrations should be monitored at least once daily in acute patients;
- Hidden fluid administration such as fluids used to dilute antibiotics or analgesics, should be taken into account. Drugs have to be diluted in normal saline whenever possible to avoid the administration of large volumes of electrolyte-free solutions especially in infants;
- Finally, one should keep in mind that recommendations are just a framework and that it is of critical importance to individualize fluid therapy in unstable children.

Conclusion

Old concepts such as age-related changes in body composition explain the necessity to provide larger volumes of fluid during infancy as maintenance requirements are higher than later in life, but also to administer larger quantity of fluids to compensate for third space losses and to restore effective vascular volume. Recent studies have reevaluated the risk of hyperglycemia especially in children at risk of hypoxic-ischemic episodes, and that of hyponatremia, the most frequent postoperative electrolyte disorder, both of them being likely to promote or to aggravate permanent or transient brain damage. Finally, the choice of colloid during infancy is a nonsolved question owing the on-going adult literature which questions the potential short term and long term effects of HES and of albumin.

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