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6. Fluid and Electrolytes (Na, Cl and K)

METHODS

Literature Search

Timeframe: publications from 1969 until 2004.

Type of publications: original articles, case series, case-control studies, and overviews.

Key Words: Neonate, Preterm infants, Infants, Children, Fluids, Sodium, Potassium, Chloride.

Language: English, German.

BACKGROUND

Water is an essential carrier for nutrients and metabolites, and it comprises the major part of human body mass at any age. Water and electrolyte requirements per unit body mass are very high after birth and decrease with age until adulthood. Most published studies on the adaptation processes of water and electrolyte metabolism relate to the preterm neonate, while studies on water and electrolyte metabolism in older paediatric patients are limited. Therefore, recommendations for children are often based on extrapolations from data in neonates and adults.

Neonatal Period

The amount of total body water (TBW) decreases markedly from intrauterine life to adulthood: water contributes to 90% of body weight in the 24 weeks old foetus, 75% in term infants, and 50% in adults (1,2). During intrauterine life body water content decreases along with the relative increase of fat mass particularly during the third trimester of gestation (3). Water turnover is high in neonates and decreases with increasing age and the concomitant decreases of metabolic rate and growth velocity (4–6).

Water turnover, like energy turnover, is related to lean body mass (LBM) but has no close relationship to body fat mass (FM). Extremely low birth weight infants (ELBW) and very low birth weight (VLBW) infants have relatively low body fat contents and a higher percentage of LBM and of body water than older infants, which is related to high water turnover.

Total body water is divided into two compartments: intracellular fluid (ICF) and extracellular fluid (ECF). Potassium (K+) is the major ion of the ICF, and its intracellular concentration depends on the Na/K-ATPase activity which is impaired at insufficient supplies of oxygen and energy (7). Premature infants are vulnerable to imbalances between intra- and extracellular compartments. The total volume of intracellular water increases with the number and size of body cells during body growth. ECF is subdivided into intravascular and extravascular components as well as a "third space" which characterises free fluid in preformed body compartments under physiological (like urine in the bladder, cerebral spinal fluid, etc) and pathological conditions (like ascites, or pleural effusions). The major ion of ECF is sodium (Na^+). ECF decreases during growth. Blood volume in neonates is 85–100 ml/kg body weight compared to 60–70 ml blood volume/kg body weight in adolescents and adults (8).

In the assessment of fluid balance, metabolic water production may be of particular importance in paediatric patients because of their high metabolic rates. Endogenous water production equals 0.6 ml H_2O per gram of carbohydrates, 1.0 ml H_2O per gram of fat and 0.4 ml H_2O per gram of protein oxidised (9). A daily weight gain of 15 g/kg in a neonate results in a net storage of about 12 ml of water and approx. 1.0–1.5 mmol Na^+ per kg body weight per day.

Immediate adaptation processes after birth affect the metabolism of water and electrolytes as a result of discontinuation of placental exchange and the onset of considerable insensible water loss and thermoregulation. Subsequent adaptation includes the onset of autonomic renal regulation of fluids and electrolytes, and intake of fluids and other nutrients.

The time course of adaptation may be divided into three major phases:

- Phase I: transition. The immediate postnatal phase is characterised by a relative oliguria (10) followed by a diuretic phase, during which body fluid compartments are rearranged by isotonic or hypertonic (i.e. hypernatraemic and hyperchloremic) contraction (duration hours to days). These changes are caused by considerable evaporative water loss via the immature skin as well as by continuing natriuresis (as present during foetal life) (11). Phase I usually ends when maximum weight loss has occurred. The generally accepted water loss is up to 10% of body weight.
- Phase II: the intermediate phase is characterized by diminished insensible water loss along with increasing cornification of the epidermis, a fall in urine volume to less than 1–2 ml/kg per hour, and a low sodium excretion.
- Phase III: stable growth is characterized by continuous weight gain with a positive net balance for water and sodium.

Many of the regulatory processes involved have limitations in paediatric patients because of immaturity or limited efficacy in infants and children. The renal glomerular surface area available for filtration is small in preterm and term neonates compared to that in older infants and adults (12). In term infants, GFR increases significantly during the first week of life (13) and continues to rise over the first two years of life (14). Immaturity of the distal nephron with an anatomically shortened loop of Henle lead to reduced ability to concentrate urine (15). Maximum urinary concentrations are up to 550 mosm/l in preterm infants, and 700 mosm/l in term infants, compared to 1200 mosm/l in adults (16). Neonates may be placed at risk for volume depletion when a high renal solute load cannot be compensated for by the ability to produce concentrated urine. Although hormonal factors i.e. renin-angiotensin-aldosterone system (RAAS), and arginine-vasopressin (AVP) are mature early in gestation, the effects are limited by renal immaturity (17). A lower plasma oncotic pressure and higher permeability of the capillary wall in preterm infants compared to term infants and adults (18) enhances the shift of water from the intravascular to the interstitial compartment, with an increased risk of oedema especially under pathologic conditions such as sepsis (19).

Sodium (Na^+) is the principal cation of the extracellular fluid and modulates the maintenance of the intravascular and interstitial volumes. Sodium intake can influence the ECF volume. Sodium excretion occurs primarily through urine, but also through sweat and faeces.

Chloride (Cl^-) is the major anion of the extracellular fluid occurring in plasma, lymph, connective tissue, cartilage and bone. The exchangeable chloride remains relatively constant per unit of body weight at different ages. The intake and output of chloride usually parallels that of sodium, but external losses and excretion can occur independently, mainly in equilibrium with bicarbonate status. The daily turnover of chloride is high. Renal conservation occurs with tubular reabsorption of 60–70% of the filtrated chloride.

Potassium (K^+) is the major intracellular cation, and the potassium pool correlates well with the lean body mass. Ten percent of the potassium body pools are not exchangeable (bone, connective tissue, cartilage). The potassium intake varies widely. Extracellular potassium concentration is not always related to intracellular concentration.

In neonates, faecal sodium losses depend on gestational age and amount to about 0.1 mmol/kg body weight per day in premature infants and 0.02 mmol/kg per day in term infants. Faecal potassium losses are about twice as high as sodium losses, but show no relation with gestational age (20). Additional losses may occur under pathological conditions e.g. bowel obstruction, ileostomy, pleural effusions, peritoneal drainage, and external cerebrospinal fluid drainage. In these circumstances the electrolyte content of lost fluids cannot be predicted precisely. In the clinical setting it is a good routine to measure at least once the sodium concentrations of such fluid losses in order to replace them (chloride usually correlates with sodium losses). Potassium losses are usually much smaller because of the mainly intracellular distribution.

Extra needs for accretion of body mass during growth periods require an adequate supply of electrolytes. A mean growth rate of 15 g/kg body weight per day results in a net storage of about 1.0–1.5 mmol Na^+/kg body weight per day in neonates. It has been shown that restricted administration of sodium impairs longitudinal growth and weight gain in otherwise healthy preterm infants (21). The growth rate decreases with age. There are limited experimental data about the water and electrolyte needs in older children. In a balance study, Fusch et al. estimated a sodium requirement of 2.7 mmol/kg body weight per day. The authors expected an overestimation of sodium requirement in the investigated paediatric patients and assumed an even lower requirement (22). It may be of importance that some drugs (benzylpenicillin) and mineral salts (phosphates) may contain considerable amounts of cations because they are prepared as the sodium or potassium salts.

Phase I/Transition

The goals for fluid and electrolyte administration during this period are to:

- allow contraction of ECF (without compromising intravascular fluid volume and cardiovascular function) with negative water balance of not more than 10%.
- allow a negative net balance for sodium of 2–5 mmol/kg per day for the first postnatal days, to maintain normal serum electrolyte concentrations.
- secure a sufficient urinary output and avoid oliguria (<0.5–1.0 ml/kg per hour) for longer than twelve hours,
- ensure regulation of body temperature by providing enough fluid for transepidermal evaporation.

The range of fluid load neonates can deal with during phase I in healthy preterm infants (29–34 weeks gestational age), range from 96 to 200 ml/kg per day from the third day of life ((23) (LOE 2+)) but rarely exceed 130 ml/kg per day. The needs for fluid intake are dependent on birth weight and increase daily (see Table 6.1). Electrolyte administration during the first 3–5 days also depends on maturity and birth weight.

Sodium intake should be restricted in VLBW infants during the period of ECF contraction until a weight loss of approximately 6–10% has occurred. A restricted sodium intake has positive effects on oxygen requirements and the risk of later bronchopulmonary dysplasia ((24) (LOE 2++)). However, there is also evidence that sodium restriction induces higher risk to develop hyponatraemia ((25) (LOE 2−)), which has been associated with brain pathology (pontine myelinolyosis) ((26) (LOE 3)).

TABLE 6.1. *Parenteral fluid and electrolyte intake during the first postnatal week*

	Recommended fluid intake (ml/kg body weight per day)					
Days after birth	1st day	2nd day	3rd day	4th day	5th day	6th day
Term neonate	60–120	80–120	100–130	120–150	140–160	140–180
Preterm neonate >1500 g	60–80	80–100	100–120	120–150	140–160	140–160
Preterm neonate <1500 g	80–90	100–110	120 –130	130–150	140–160	160–180
Recommended Na^+, K^+, Cl^- supply (mmol/kg body weight per day)						
*Na^+	0–3 (5)					
**K^+	0–2					
Cl^-	0–5					

The expected weight loss is depends on treatment conditions (fluid intake) and environmental factors (humidity etc.).
*Careful adjustment of water and electrolyte administration is needed in ELBW infants at onset of diuresis and in polyuric patients.
**K^+ supplementation should usually start after onset of diuresis.

A review of four randomized clinical studies with different levels of fluid intake during the first week of life concluded that fluid restriction reduces the risk of patent ductus arteriosus, necrotising enterocolitis, and death, and tended to reduce the risk of bronchopulmonary dysplasia (n.s.) and to increase the risk of dehydration (n.s.) ((27) (LOE 1+)).

Phase II: The Intermediate Phase

The goals for fluid and electrolyte administration during phase II are to:

- replete the body for electrolyte losses, replace actual water and electrolytes.
- augment oral feedings.

Phase III: Stable Growth

The goals for fluid and electrolyte administration during phase III are to:

- replace losses of water and electrolytes (maintain water and electrolyte homeostasis).
- provide enough extra water and electrolytes to build up new tissue at intrauterine growth rates.

The recommended fluid intakes in phase II (Table 6.2) are based on studies suggesting that a daily fluid intake equal to or higher than 170 ml/kg body weight per day is accompanied by high urinary sodium excretion with negative sodium balance, even if Na^+ intake is as high as 10 mmol/kg body weight per day ((28) (LOE 3)). Fluid therapy in ELBW in excess of 200 ml/kg/d does not maintain Na^+ balance, regardless of the amount of NaCl provided. It is important to note that ELBW infants require more fluids than recommended during the first week of life for term infants, because of high insensible water loses ((29) (LOE 3)). Evaporation of water from upper respiratory passages accounts for approximately one third of net insensible water loss (30) and reaches the level of 0.8–0.9 ml/kg body weight per hour in premature infants, 0.5 ml/kg body weight per hour in term neonates ((31) (LOE 3)), 0.4 ml/kg body weight per day in older children and 0.3 ml/kg body weight per day in adolescents ((32) (LOE 3)).

Urinary output may be as high as 6.0 ml/kg per hour of free water in the presence of a total urine production of 9.8 ml/kg per hour in preterm infants with birth weight 2000 g (33). Fluid requirements during the phase III (Table 6.3) are related to the expected weight gain.

Water loss from stool is negligible in early life prior to establishing enteral feeding in premature infants. When full enteral feeding is achieved, faecal losses of 5–10 ml/kg per day are usually assumed to balance metabolic water production (34). Plasma Na^+ concentrations are normal in infants with sodium intakes of 1.1–3.0 mmol/kg body weight per day and fluid intakes of 140–170 ml/kg body weight per day with no relation of growth rates to sodium intake within these ranges ((35–38) (LOE 2–3)).

TABLE 6.2. *Parenteral fluid and electrolyte intake for newborn infants during the intermediate phase prior to the establishment of stable growth*

Birth weight	Fluid intake (ml/kg body weight per day)	Na^+ intake (mmol/kg body weight per day)	K^+ intake (mmol/kg body weight per day)	Cl^- intake (mmol/kg body weight per day)
Term neonate	140–170	2.0–5.0	1.0–3.0	2.0–3.0
>1500 g	140–160	3.0–5.0	1.0–3.0	3.0–5.0
<1500 g	140–180	2.0–3.0 (5)	1.0–2.0	2.0–3.0

TABLE 6.3. *Parenteral fluid and electrolyte intake for infants during the first month of life with stable growth*

	Fluid intake (ml/kg body weight per day)	Na^+ intake (mmol/kg body weight per day)	K^+ intake (mmol/kg body weight per day)
Term neonate	140–160	2.0–3.0	1.5–3.0
Preterm neonate	140–160	3.0–5.0 (7.0)	2.0–5.0

There is evidence that fluid intake lower than 140 ml/kg body weight day, together with Na^+ intake of about 1 mmol/kg body weight per day, is adequate to maintain sodium balance in ELBW neonates ((39–44) (LOE 2–3)). There is no increase in morbidity among infants given less Na^+ and less fluid. There was a non significant trend to higher incidences of patent ductus arteriosus and bronchopulmonary dysplasia in infants given more Na^+ and a higher fluid intake ((45,46) (LOE 2–3)).

Breast-fed term infants need as little as 0.35 to 0.7 mmol/kg body weight per day of Na^+ during the first 4 months of life to achieve adequate growth ((47) (LOE 3)). A recommendation to provide 1.0 to 2.0 mmol/kg per day of NaCl should counter-balance incidental losses from skin or gastrointestinal tract. In preterm infants, a higher growth rate explains a higher sodium requirement.

Preterm infants retain about 1.0 to 1.5 mmol/kg body weight per day K^+, which is about the same as foetal accretion ((48) (LOE 3)). The amount of potassium usually recommended is similar to the amount provided in human milk, about 2 to 3 mmol/kg per day (49).

Environmental factors influence insensible fluid loss:

- Double wall incubators reduce insensible water loss in VLBW neonates by about 30% when a humidity of 90% is used at thermo-neutral temperature. With maturation of the epidermal barrier it is possible to reduce ambient humidity step by step commonly after the first 5 days of life (50).
- The use of waterproof coverings (such as plastic films, plastic blankets, and bubble blankets) in addition to treatment in a double wall incubator leads to further reduction of insensible water loss by 30–60% (51).
- The use of radiant warmers or single wall incubators for VLBW care may increase water loss and impair thermoregulation (52).
- The use of emollient ointments decreases insensible water loss of up to 50% in open care conditions (53,54).
- Endotracheal intubation and mechanical ventilation using warmed and humidified air significantly reduce insensible respiratory water (55) and the needs for fluids are reduced by 20 ml/kg body weight per day.

In summary the treatment strategy during the adaptation of neonates to extrauterine life is:

- to expect decrease of body weight during the first 3–5 (max. 7) days after birth.
- to maintain normal serum electrolyte concentrations.
- to avoid oliguria $<0{,}5$ ml/kg body weight per hour for 8–12 h.

INFANTS BEYOND NEONATAL PERIOD AND CHILDREN

Recommendations for sodium intake range from 1 to 4 mmol/kg body weight per day ((56–58) (LOE 3)).

Requirements on electrolytes for infants and children are based on empirical evidences and are set on the level of 1–3 mmol for sodium and 1–3 mmol of potassium required per intake of 100 kcal ((59) (LOE 3)). The lower limit of intravenous sodium and potassium intake is in agreement with the Codex Standard for Infant Formula (60). The empirical recommendations for sodium and potassium intake in children do not exceed 3 mmol/kg body weight per day (LOE 4) (Table 6.4).

Electrolytes, urea and other substances constitute urine osmotic load. High nitrogen and energy supply with parenteral nutrition require sufficient water supply as the vehicle for nutrient delivery. Recommended fluid volume for paediatric patients beyond the neonatal period is provided in Table 6.5.

Water requirements in infants and young children depend on the rate of exchange of total body water which is more rapid than later in life and influence maintenance water requirements. Daily maintenance fluid requirement is a function of total caloric expenditure at rest; for infants below 10 kg of body weight it equals about 100 ml/kg body weight per day. Children with a body weight of 11–20 kg should receive 1000 ml + 50 ml/kg for each kg body weight above 10 kg, and children with a body weight above 20 kg 1500 ml + 20 ml/kg for each kg above 20 kg ((59) (LOE 3)).

Total water requirements consist of the maintenance needs, replacement of ongoing losses (insensible water loss, urinary losses, and stool losses) and, in particular situations, replacement of deficits. Insensible water loss from the skin and lungs is an energy costly procedure and

TABLE 6.4. *Parenteral electrolyte intake for infants after the first month of life and for children*

Electrolyte	Infants	Children >1 year
Na^+ (mmol/kg body weight per day)	2.0–3.0	1.0–3.0
*K^+ (mmol/kg body weight per day)	1.0–3.0	1.0–3.0

**K^+ supplementation should usually start after onset of diuresis.

TABLE 6.5. *Parental fluid intake for term infants after the first month of life and for children*

Age	Fluid intake (ml/kg body weight per day) (maximal volumes in brackets)
Term infants from the second month of life	120–150 (180)
1–2 years	80–120 (150)
3–5 years	80–100
6–12 years	60–80
13–18 years	50–70

consumes one fourth of the overall caloric expenditure, with loss of 1 ml of water related to energy needs of 0.5 kcal.

Urine osmotic load results from protein catabolism and electrolyte excretion, but is little affected by carbohydrate and fat metabolism which produce metabolic water and CO2. Water requirements increase with fever, hyperventilation, hypermetabolism and gastrointestinal losses and decrease in renal failure and congestive heart failure.

MONITORING OF PARENTERAL FLUID AND ELECTROLYTE TREATMENT

A monitoring protocol should be adapted to the individual patient's needs. Monitoring intervals depend on clinical status, underlying pathophysiology, medications and treatment modalities. Indications of changes of hydration and electrolyte status may include:

- clinical status of the patient
- body weight and body composition
- fluid balance
- blood electrolyte concentrations and acid base status
- haematocrit and blood urea nitrogen
- urine specific gravity, urine electrolytes
- water intake and excretion

In parenterally fed infants and children, serum electrolyte concentrations and weight are usually monitored daily for the first days of treatment; then the monitoring intervals are adapted depending on the clinical status and the stability of the patient's condition.

Recommendations

It is emphasized here that needs of individual patients may deviate markedly from the ranges of intakes recommended here, depending on clinical circumstances such as fluid retention, dehydration or excessive water losses.

Preterm and Term Infants During the Transition Phase

A gradual increase of fluid volume in preterm and term neonates is recommended. Sodium, chloride and potassium should be supplemented in the first 3–6 days after birth, i.e. in phase I (transition) when contraction of extracellular fluid compartment occurs. Na^+ supplementation may start after the first 2 days under monitoring of serum electrolytes levels has shown in Table 1. **GOR D**

Preterm and Term Infants During the Stabilisation Phase

Phase II (stabilisation) when extracellular fluid compartment contraction is completed may vary in duration from about 5–15 days and is completed when birth weight is regained and the kidneys produce more concentrated urine. Expected weight gain is 10–20 g/kg body weight per day (Table 2). **GOR D**

Preterm and Term Infants During the Phase of Established Growth

During phase III (established stable growth) the aim is to match physiological growth rates. Chloride supplementation follows sodium and potassium. Expected weight gain is 10–20 g/kg body weight per day (Table 3). **GOR D**

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