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Fluid Balance in the Newborn[1]

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THE NEWBORN INFANT is at that end of the age scale where even small differences in fluid balance may assume great importance. In addition, in this period the child is undergoing rapid physiologic alterations, which by themselves produce significant derangements. A serious drawback to studies in the newborn and infant are the difficulties, even the impossibility, of carrying out those determinations which might serve to increase our knowledge. This may be for either technical or emotional reasons. Unfortunately, much of our information in newborn physiology is limited to inferences, to casual observations, or to experimental results obtained under conditions that do not withstand proper scrutiny. The size and relative inactivity of the newborn and infant offer the prospect for accurate measurement, but these very same factors create serious difficulties.

There are many gaps and many areas of disagreement in our knowledge of neonatal physiology. For example, since blood volume, acid–base balance, etc., are not known with certainty, the neonatal surgeon has adopted principles of fluid balance that vary from the "dilutional"[2,3] approach to the "dehydrational"[4–6] approach. There is frequently a prejudice against the administration of salt water to the newborn before a surgical procedure.[7–9] The tendency is for the infant to arrive in the operating room on the dehydrated side because of a lingering fear of "salt intolerance." That the infant can survive for a week or two without water is certainly no reason for him to be subjected to this dehydration.

Normal Values

The precise dimensions of the various body compartments and their exact composition in the newborn and infant are not known. Table 1 provides some general values in comparing the adult and the neonate.[10] Since body surface area (BSA) is commonly used in the measurement of these values, table 2 establishes the relationship between body weight and surface area.[3] Table 3 serves to define the maximal fluid losses by secretions in the infant and newborn.

Certain of these values deserve special mention. The newborn has more Na^+ and Cl^- per kilogram of body weight than does the adult, presumably because the extracellular fluid (ECF) space is proportionally larger in the former. Serum potassium is also significantly higher in the newborn, perhaps related to the acidemia.[3] Serum phosphorus[11] is characteristically higher in those infants fed cow's milk, which contains a higher concentration of this element than human milk. The high levels of phosphate may in turn act as a diuretic and result in a low urine concentration. The total body water of the infant is greater, whether calculated by body weight or by surface area.[1] However, this does not mean that the infant has an excess volume of water. In fact, water turnover is much greater in the infant than in the adult, and the infant is more susceptible to dehydration. The ratio of ECF to intracellular fluid (ICF) begins to decline soon after birth, and approaches the adult ratio by 2 years of age. An infant deprived of water may deplete his ECF space within five days, whereas the adult may take twice as long (ten days) to reach a similar state.

The fetal kidney clears inulin in amniotic fluid,[12] the inference being that the fetal kidney has excretory capacity. Capacities for clearing inulin, creatinine and urea are the same as or less than those in the adult. Creatinine clearance depends upon muscle mass, and body weight may provide a better basis for its measurement in the newborn.

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The newborn's ability to excrete acid and to produce ammonia suggests that the newborn can cope with the "fixed acids." A greater metabolic rate also implies an increased ability to produce H^+, and it thus follows that use of adult nomograms[13] to assess neonatal base deficits is not satisfactory. Nomograms[13] for use in the newborn have been designed. The infant has less albumin and less globulin than do older children. The resultant lower serum osmotic pressure thus encourages a rapid transfer of fluids into the tissues, including the glomeruli. Sixty-five per cent of the body's albumin is extravascular and available for use. A significant albumin loss is necessary to affect the osmotic pressure gradients, but administration of albumin or other protein solutions should be considered when there is serious albumin deficiency. In other situations, blood can be reconstituted as packed or frozen cells, and administered with lactated Ringer's solution.

TABLE 1. Physiologic Values in Adult Man and the Neonate

	Neonatal	Adult
Extracellular fluid	35 per cent	20 per cent
Water turnover/day	15 per cent	9 per cent
BUN	7–15 mg/100 ml	15–25 mg/100 ml
Urinary Na^+	50 mEq/l	30 mEq/l
Urinary specific gravity	1,005–1,020	1,005–1,035
Serum Na^+	136–143 mEq/l	135–140 mEq/l
Serum HCO_3^-	20 mEq/l	25 mEq/l
Blood volume	60–129 ml/kg	70 ml/kg
Hemoglobin	18–25 g/100 ml	15 g/100 ml
Hematocrit	50–60 per cent	45 per cent
Insensible water	400 ml/m²/day	Variable
Intracellular water	40 per cent	40 per cent
Solutes in urine	10–30 mOsm/kg/day	—

TABLE 2. Body Weight and Surface Area Equivalents

Weight		Surface Area (Sq m)
kg	Pounds	
2	4.4	0.15
5	11.0	0.25
10	22.0	0.45
15	33.0	0.60

Blood Volume

The blood volume of an infant with a normal hemoglobin is estimated to be 80–85 ml/kg.[14] For the premature infant, a higher figure, perhaps equal to 100 ml/kg, has been suggested. In the presence of the common iron-deficiency anemia of infancy, a slightly higher value may also apply. There have been few investigations of blood volume in the normal infant, and figures have not been accurately derived.

The blood volume of the newborn is even more variable. The normal range for blood volume is 60 to 129 ml/kg. Placental transfusion, and the position of the baby at birth relative to the placenta, may also influence blood volume in the newborn.

With the wide range in normal values, any guide to intraoperative blood replacement that is based upon a percentage of blood volume that has been lost can be of only limited usefulness. If the plasma volumes of the newborn and the infant are accepted as 5 per cent of body weight (50 ml/kg), the use of a figure based upon the hematocrit is reasonable. Thus, 50 + Hct as ml/kg offers a good rule of thumb. With this approach, babies with low hematocrits prior to operation will receive blood earlier and at a point of less loss than those with higher hematocrits.

The Newborn Kidney

The administration of fluids and electrolytes to the neonate has been strongly

TABLE 3. Maximum Losses from Secretions/kg/24 Hours in the Infant

	Water (ml)	Na^+ (mEq)
Sweat	200	36
Saliva	20	2
Gastric juice (tube) (suction)	125	7–18
Pancreatic juice (fistula)	10	2
Intestinal juices (fistula)	40	4
Bile (fistula)	7	2
Vomiting	100	15
Diarrhea	100	15

influenced by the traditional concept that the neonatal kidney is immature, that it is unable to excrete sodium, and that it is unable to concentrate urine.[15–18] Because of these views, and because the neonate normally can exist on a sodium intake of 1–2 mEq/kg/day,[19] several authors have put primary emphasis on the administration of 5–10 per cent dextrose in water, plasma, blood, or even no fluids at all.[20–23] The immaturity of renal function is usually determined by calculations utilizing body weight, height, surface area, renal weight, basal metabolic rate, or the cube root of body weight. However, if other criteria such as extracellular fluid or total body water are used, then there may be no real difference in renal function.

Concentration is mainly a function of solute load. It represents the ability to excrete and conserve water, sodium and urea. Urea forms one of the principal solutes for concentration and is low in the neonate. The ability of the newborn to excrete a dilute urine is thus a normal manifestation. The ability of the neonate to concentrate urine to a specific gravity of more than 1020, representing about 800 mOsm/l when compared with serum, is not usually apparent. However, all the appropriate mechanisms are present. The volume and the concentration of urine are a result of facultative absorption in the distal tubules and the net result of the amounts of solute and solvent presented. The production of concentrated urine depends upon the development of a high concentration of sodium in the interstitial fluid of the renal medulla as a consequence of active transport of sodium out of the ascending limb of Henle's loop to the interstitium, as well as the countercurrent pattern of flow between the loops and the medullary capillaries. Any process that disturbs the function of the medulla produces an early, marked impairment of this concentrating ability. Urine-concentrating ability is further reduced by starvation, by a low-protein diet, or by overhydration. Urea is necessary for the concentration of urine, and the ability of an individual kept on a protein-free diet to excrete hypertonic urine is diminished. It can be restored by giving urea. The newborn, who uses his nitrogen primarily for growth, has a blood urea of 9–15 mg/100 ml. Thus, he does not have the same ability to concentrate urine. Urine concentrating ability may be further lowered by a solute load such as mannitol or saline infusion. The decrease in maximum urinary osmolality that characterizes renal damage is ascribed to a solute diuresis, provoked by the concentration of urea in the glomerular filtrate and the resulting increase in solute load per individual nephron. Urea, in these circumstances, increases its excretion by increasing the blood urea concentration.

The newborn kidney differs from that of the older child. It has fewer nephrons, and

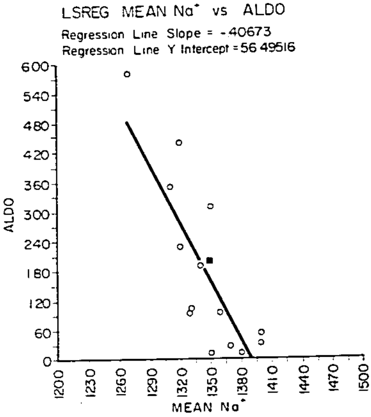

FIG. 1. Least-squares regression line of aldosterone excretion rate and mean serum sodium.

the loops of Henle, the distal convoluted tubules, and the collecting ducts have not yet reached the adult stage. The loops, cortical rather than medullary, are shorter, and there is less convolution of the distal tubules. There is thus less physical ability to concentrate and therefore to conserve. The mechanisms by which these activities are performed, *i.e.*, countercurrent systems and active reabsorption, are compromised. There will be a tendency to develop diuresis, whether water, electrolyte, or osmotic in origin.

Sodium Conservation

Normal neonates may appear to conserve sodium, in that they exist on a sodium intake of less than 1–2 mEq/kg/day. This represents an absolute figure and does not take into account the negative sodium balance of the first few days of life. During this period the 35 per cent extracellular fluid volume, present at birth, is reduced towards the 20 per cent volume of the infant. It is interesting that this figure for sodium intake is about twice that recommended for the adult, with supposedly mature renal function. There is abundant evidence that the neonatal kidney can excrete adequate loads of water, phosphates, chlorides, bicarbonate, urea, and acid.[15–19] However, in the presence of sodium and potassium deficiencies, as in alkalosis, there may be a dilute urine with an alkaline pH, in contrast to the infant who is conserving sodium and therefore excreting acidic urine.

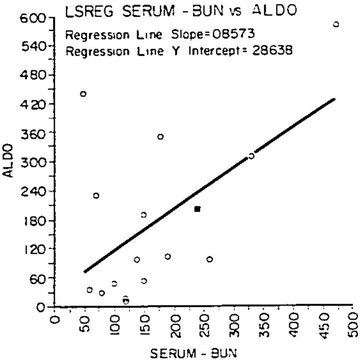

FIG. 2. Least-squares regression line of aldosterone excretion rate and mean BUN.

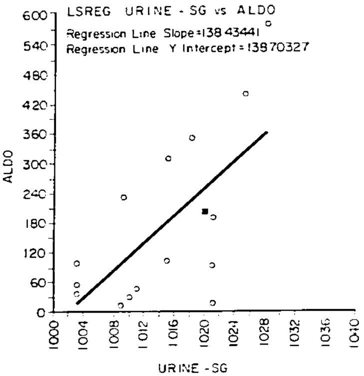

FIG. 3. Least-squares regression line of aldosterone excretion rate and mean urinary specific gravity.

Excretion appears to be an adequate function, but there is a tendency to hyponatremia in the presence of a sodium deficiency. Balance studies of 57 newborns have demonstrated that revised concepts of neonatal renal function and administration of fluids to the neonatal surgical patient are in order. These studies have shown that the functional capacity of the neonatal kidney is limited by factors such as solvent quantities and solute loads.

The neonatal kidney is capable of concentrating urine, and the failure is that of conserving rather than a failure to excrete sodium.[25–27] In these studies, aldosterone excretion rate (AER) was measured and related to mean serum sodium, blood urea, and urinary specific gravity. The least-squares regression line in figure 1 indicates that as mean serum sodium decreased from 140 to 125 mEq/l aldosterone (AER) increased. This would indicate a response of the newborn to a low serum sodium with an increase in aldosterone in an attempt to retain sodium. This line is statistically significant (correlation coefficient −0.808). Similarly, in figure 2, as blood urea nitrogen (BUN) increased from 5 to 50 mg/100 ml, aldosterone increased (correlation coefficient +.562). This may be an indication of the value of the BUN as a measure of hydration or renal blood flow.

The urinary specific gravity is also reflected in the aldosterone level (fig. 3). This could be an index of a decrease in the renal blood flow, dehydration, or sodium loss (correlation coefficient +.652). These three regression lines are all measures of the stimuli that physiologically increase the production of aldosterone, namely, flow, osmolality, and volume.

From the above study, it may be concluded that the newborn can produce aldosterone, and there appears to be an effective action in that sodium/potassium exchange occurs with sodium deficiency. There is also a correlation between aldosterone and serum sodium. There is further correlation between the state of hydration as evidenced by BUN and urinary specific gravity and the level of aldosterone as measured by the AER.

Recently, Weldon *et al.*[28] studied the effects of surgery upon sodium metabolism and the aldosterone secretion rate (ASR) in children. In the herniorrhaphy group, there was no change in ASR, suggesting that no sodium retention occurs in the young infant. However, in a further group of five patients, these investigators found a significant increase in ASR and a tendency to retain sodium. Four of these five operations were Duhamel procedures, requiring extensive bowel preparations, and it is quite possible that sodium was needed to a greater extent, in that postoperative urinary losses actually increased in three infants. Irvin[29] and Brevik[30] have confirmed a similar sodium need in adults. Bryan[31] has shown that serum sodium is the significant independent variable with the ASR in neonates. Corroborative work by Siegel,[32] studying serum aldosterone levels, showed a definitive correlation with the serum sodium ion in the newborn.

The general conclusions are that the neonate require water and electrolytes during operation and in the postoperative period, and that there is no difficulty in excreting sodium within wide limits. The urine-concentrating ability and the ability to excrete a dilute urine are relatively normal. Recognizing that surgery is a major stress, further stress should not be added to the patient by the withholding of fluids or electrolytes. All abnormal losses, for example from the stomach, should be replaced with equal volumes of isotonic saline solution. The newborn can respond to a sodium deficiency with an increase in aldosterone secretion rate. The neonate can also respond to this hormone by reabsorption of sodium from the urine, depending upon the quantities available. The low concentration of sodium in the urine may in some cases result from the hypotonic quality of the fluids administered and the large quantity of urine resulting. An osmotic diuresis, from the characteristic low newborn renal threshold for glucose, is also possible, and may occur as a result of an excess amount of 10 per cent glucose solution. However, if the newborn is given only small amounts of fluid, then the free water from metabolism is utilized as a maintenance solution. Both of these offer cogent reasons for the administration of balanced salt solutions.

Potassium replacement is necessary in the postoperative period, especially if an aldosterone mechanism is indicated. There is no correlation of the weight, and presumably the maturity, of the newborn with the range of aldosterone. There is also no distinction between the mature and the premature neonate. The apparent sodium retention is one of interpretation. In the absence of sufficient water, renal blood flow (RBF) decreases, glomerular filtration rate (GFR) becomes low, and a relative renal shutdown occurs. Due to continued hypotonic fluid losses, serum sodium will increase and relative hypernatremia occurs. In reality this represents hypertonic dehydration.

Postoperative Fluid Requirements

Swenson,[33] in studying the minimal postoperative fluid requirements of the newborn, recommended 765 ml/m^2/day. This, however, is a minimum. The usual recommended level is 1–1.5 l/m^2/day. He added that a loss of effective blood volume resulting from internal fluid shifts indicates the need for additional fluid for volume expansion. For proper therapy, one must have an estimate of body compartments by volume, the specific total electrolyte changes, the changes in water and electrolyte distribution, the alterations in acid–base status, and the caloric needs.

Volume changes may involve all compartments, or may be selective. The changes may be those of contraction or expansion, and may be hypertonic, isotonic, or hypotonic. *Isotonic expansion* results from administration of an excess of isotonic fluid, probably a physiologic salt solution. This does not lead to osmolar gradients between the interior and the exterior of the cell, and thus there is no shift of water between the compartments. *Isotonic contraction* is the reverse situation. Again, there is no change in extracellular osmolality, and no shift of water in relation to the cell. However, both the blood and the interstitial volumes contract. Serum sodium remains normal. *Hypertonic expansion* results from the intravenous administration of a hypertonic salt solution. The volume and osmolality of the extracellular fluid are increased and result in a water shift from the cells until both compartments are isoosmolar. *Hypertonic contraction* occurs from a loss of water with a relatively smaller loss of salt. The osmolality of the extracellular water increases, water flows from the cells, and cellular dehydration occurs. *Hypotonic expansion* occurs when the gain in volume in the extracellular space is predominantly water. Water, being freely diffusible, enters the cells, and all compartments are increased in volume. *Hypotonic contraction* is due to the loss of both salt and water, but relatively more of the former. There is a diminution in extracellular osmolality, and a water shift into the cells. While the extracellular compartment has decreased, the intracellular water content has also increased until osmolality has been equilibrated.

Sodium Deficiency or Decrease in Extracellular Water Volume

This deficiency can be clinically divided into two groups: 1) the concentration of extracellular sodium is low but total body sodium is normal or high; 2) the total body stores of Na^+ are low. Hyponatremia reflects a relative or absolute increase in the ratio of water to sodium ions and indicates that the intracellular water is expanded and diluted.[34] This is a common deficiency, not only because losses of sodium via sweat and kidney are commonly unreplaced, but because all the secretions of the gastrointestinal tract contain sodium in significant quantities. The sodium content of these fluids is influenced by aldosterone, but the volume of fluid secreted is not affected. Regulation is thus not necessarily according to body's needs. Tubes and suction devices frequently augment the losses. In sodium depletion, the cause is usually loss of the body's own electrolyte-containing solutions, rather than a lack of intake. The clinical syndrome is that of an infant with a large, rapid weight loss. Thirst is not a feature.

Information derived from a small portion of a small compartment, such as serum sodium, can be projected only in terms of the contents of other compartments, or the concentrations of electrolytes contained therein. The interpretation of laboratory values for serum sodium may be complex. A decrease in serum sodium may be absolute or relative, or it may represent displacement by fat, glucose, or urea. Hyponatremia, or for that matter, hypernatremia, may thus be real or relative. A change in the serum sodium may represent distribution or concentration. It is the ratio of sodium ions to water molecules that is important. This determines the osmolality of the extracellular fluid. Thus, hyponatremia indicates a relative or an absolute increase in the ratio of water to solutes. Hypernatremia reflects a relative or an absolute deficit of water. Sodium concentration, by itself, cannot be used to determine the state of hydration, since expanded or contracted volumes of total body water can be accompanied by high, normal, or low levels of serum sodium. A normal serum sodium concentration indicates a normal ratio between solutes and water, whether volume is high, normal, or low. The osmolality in the extracellular fluid is normal, and therefore, the volume of the intracellular water is normal. Hyponatremia, on the other hand, indicates an expanded and hypotonic intracellular fluid. Hypernatremia reflects a contracted and hypertonic intracellular fluid. Both may be associated with variable states of hydration.

The interpretation that a normal ratio of sodium ions to water molecules in the extracellular fluid indicates a normal intracellular volume has important implications. The production of antidiuretic hormone (ADH) and aldosterone is increased or decreased by changes in intracellular osmolality and volume, and aldosterone is influenced also by extracellular osmolality and volume. The newborn and the small infant do not follow the adult patterns of salt losses,[1] and the newborn continues to secrete a dilute urine containing sodium. The gastric secretion rate does not diminish, and the newborn has the ability to produce a gastric secretion that contains as much as 165 mEq/l sodium. This loss of fluid will produce a hypo-osmotic state. When other losses occur, *e.g.*, insensible losses that are normally hypotonic, the newborn may have an iso-osmotic contraction of the extracellular space. Since the usual influences on ADH and aldosterone are absent, the newborn continues to excrete urine of normal volume and content. This is in sharp contrast to the adult, whose gastric secretion contains less sodium, 60–90 mEq/l, and in whom a hypotonic loss results in hypertonic dehydration and appropriate hormonal production.

Osmolality

The two osmolalities most easily measured are those of serum and urine.[3] With proper intake of foods and fluids, the normal ratio between serum and urinary osmolality is approximately 1:1.5. Serum osmolality is 285–310 mOsm/l of serum, but if proteins and fat are removed, the osmolality increases to 320–350 mOsm/l of plasma water. Extracellular osmolality is important as it is the determinant of intracellular water.

Potentially deleterious effects can follow a sudden increase in osmolality, especially if the change is more than 40 mOsm/l within a few hours.[35] Even smaller changes may have serious effects. Among the dangers recognized with sudden increases in osmolality are cerebral hemorrhage, metabolic changes, and renal damage. Pressure and volume changes in the cerebrospinal fluid follow rapid changes in osmolality produced by the administration of hyperosmolal solutions containing obligatory extracellular fluid solute. These effects are followed by capillary dilatation and congestion. The desiccated cells can then release H^+ and produce acidemia. If hyperosmolal sodium bicarbonate has been the hyperosmolal substance, its administration has been self-defeating if in the process it has produced acidemia.

Renal damage may be seen in infants with severe salt poisoning. The sequence of events following a sudden increase in osmolality from any solute injected intravenously that remains extracellular includes expansion of the extravascular volume, shrinkage of cells, reduced pressure and volume of the cerebrospinal fluid, capillary dilatation and congestion, physical, chemical, and/or metabolic damage to the cells. These effects are seen with all hyperosmolal solutions, *i.e.*, hypertonic saline, hypertonic glucose, sodium bicarbonate, and THAM.[36] The rate of increase in osmolality tolerated by a normally hydrated infant is about 5–8 mOsm/l/hour.

Osmolality has been suggested as the index for water and electrolyte needs in the postoperative period.[37] It is proposed that urinary and serum osmolalities be followed and the ratio be kept in the vicinity of 1.5:1. Urinary osmolality is approximately 450 mOsm/l. These calculations may be based upon the following formulas:

Total fluid requirements

$$= \text{basic fluid requirements} \times \frac{U_{osm}}{228} \quad (1)$$

where U_{osm} is the urinary osmolality; *or*

$$(TBW_1 \times Osm_1) + L_{osm} = TBW_2 \times Osm_2 \quad (2)$$

where TBW_1 and $_2$, and Osm_1 and $_2$, refer to total body water and osmolality before and after the solute load (L_{osm}).

When any therapeutic measure is applied to the newborn or small infant,[37,38] a failure to respond may be due to the failure to protect the infant against hypothermia, hypoglycemia, hypoxia, acidosis, aspiration, and infection. The entire therapeutic procedure may be rendered futile by neglect of these common features. While examination and deliberation are being carried out, the newborn and the small infant should be kept warm. Infrared lights, warm-water mattresses, warm blankets, and elevation of ambient room temperature are all useful, but are often neglected.[39,40]

Gastric distention or dilatation is a very common problem in the newborn and infant. It may be caused by a pathologic process, such as intestinal obstruction, or result from the simple physiologic process of feeding. It may also be the consequence of partial airway obstruction due to the particular anatomy of the upper airway in the newborn. Acidosis, respiratory or metabolic, hypoxemia, and obtunded cerebration may be implicated as predisposing causes. Apart from increasing the risks associated with elevation of the diaphragm and basal atelectasis, gastric distention is the most common cause of postoperative nausea and vomiting, which may result in aspiration. Every effort, then, should be made to reduce gaseous distention and to keep the stomach as empty as possible. The pernicious habit of clamping a nasogastric tube, when transporting a patient, is to be condemned, and anesthesia should never be induced with this clamp applied.

Glucose

The metabolic rate of the infant, his oxygen consumption, and his ability to produce hydrogen ion are almost double those of the adult.[41,42] Because of the greater metabolic rate, almost all solutions administered to the infant should contain 5 per cent dextrose. Exceptions would include the replacement of abnormal losses and drainage and interstitial fluid replacements of deficiencies where large volumes are involved. They also would include certain forms of hyperalimentation (rebound hypoglycemia occurs frequently after hyperalimentation and may necessitate administration of glucose), and the use of blood and blood substitutes. The advantages of administering glucose are that it prevents hypoglycemia and supplies metabolic needs. It encourages neoglucogenesis and is protein-sparing; and it limits glycogenolysis. The limitation of glycogenolysis and the effect on protein-sparing reduce potassium loss in the infant subjected to a surgical procedure. Since the infant's water requirement is approximately 100 ml/kg/day, it is obvious that 5 per cent glucose should be added, at least to all maintenance fluids, as the metabolic requirement of glucose for this age is 5 g/kg/day.

Lactated Ringer's Solution

The intraoperative use of a solution such as lactated Ringer's solution† has many effects.[30,34,43] These include the maintenance of renal hemodynamics, as opposed to the depression of renal blood flow and glomerular filtration rates of 40–80 per cent without salt infusion; the prevention of postoperative acute renal shutdown (a complication that carries a high mortality rate of 70 per cent in surgical patients); the avoidance of postoperative acute water retention; a marked decrease in the incidence of significant intra- and postoperative hypotension; a decrease in the morbidity associated with vascular surgery; a decrease in the need for blood transfusion; and the use of a physiologic solution similar in composition to the fluid in the interstitial space. This solution, however, does lack the buffering capacity of interstitial water, which has a buffering capacity somewhere about one fifth that of plasma, and it has an oncotic pressure of 5 torr. Therefore, where relatively large volumes of electrolyte (and noncolloid) solutions are administered, the addition of colloid as albumin or plasma may be appropriate. Albumin as a 5 per cent solution in lactated Ringer's solution has been suggested.

Intraoperative Fluids

The important considerations here is normal fluid maintenance, which amounts to

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†A "physiologic" salt solution is here used synonymously with a "balanced" salt solution, the components of which approximate the components of the fluid that surrounds the cell, the interstitial fluid. While there are slight variations in the various commercially prepared solutions, for practical purposes, they are not significant.

1–1.5 l/m^2/day for the hospitalized neonate and infant.[1,38] This figure is based upon a minimum water loss of 700–800 ml/m^2/day, to which must be added solvent water for the urinary excretion of waste products. This figure of 1–1.5 l/m^2/day would be reduced in the hospitalized patient through inactivity associated with illness. However, the catabolism of the stress response, and the increased requirements from fever, hyperventilation, or acidosis, will all increase the amount necessary for maintenance. Visible sweating, such as that associated with fever, would also increase water and electrolyte needs. The normal maintenance requirement of the neonate during anesthesia may be summarized as: 1–1.5 l/m^2/day = 70–100 ml/kg/day = 3–4 ml/kg/hour of a solution of 5 per cent dextrose in water, with one fifth of the amount as dextrose, 5 per cent, in lactated Ringer's solution. This is approximately twice the maintenance volume for the normal adult patient. Since during operation it is not convenient to change the type of solution constantly, and since the other losses are of a more concentrated nature, the recommended maintenance during anesthesia is 5 per cent dextrose in lactated Ringer's solution.

There are also special considerations relating to the anesthesia system employed. Although Ayre's T-piece is frequently used, closed or semiclosed (semiopen) systems are also in vogue. No matter which system is employed, dry cold gases leaving the anesthesia machine will be warmed and humdified before reaching the alveoli. If this occurs in the infant's respiratory tract, it represents an obligatory water loss. If an ultrasonic nebulizer within the circuit[44] is not employed, as much as 1 ml/l of minute ventilation/hour with a closed circuit, and as much as 2.5 ml/l of minute ventilation/hour with a nonrebreathing system, may be needed. This water loss contains no electrolytes, but does represent a quantity that cannot be ignored.

Translocation of Fluids at the Site of Operation

This broad category includes changes related to chemical reactions, trauma, surgical manipulation at the operative site; and those that occur at the cellular level, *i.e.*, the Cooke's effect, with its intracellular sodium and water shifts.[29,30,45]

If there is a relative reduction in the extracellular fluid, it must be replaced. At the cellular level, it may reflect alterations in the circulation, the effects of hydrostatic pressure, stress responses, stagnation of tissue perfusion, or even regional tissue hypoxia or acidosis. This ionic shift will be accompanied by a net water shift into the cells. The effect will last several days, and serves to remove available fluid from the extracellular fluid compartment. The amounts involved are extremely variable, and depend upon the severity of the injury, the site, the time element, and the compensation possible. There is presently no way to determine the amount with accuracy. Obviously, the amount will be less for limited superficial procedures than for those procedures involving the upper part of the peritoneal cavity. The usual estimates range from 1 to 10 ml/kg/hour. The highest amount is associated with upper peritoneal "burns." Translocation is considerably diminished after 2–3 hours and, therefore, the amount suggested for this third space defect is 1–10 ml/kg for the first 2–3 hours of the surgical procedure.

Changes in extracellular fluid volume may also be associated with blood loss as the net result of hydrostatic–oncotic pressure gradients (conventional Starling forces). Hypotension may result, independent of whether there is a real or a relative decrease in the effective blood volume. There is no known sensor of the vascular capacity. If blood loss continues without replacement until shock supervenes, the interstitial fluid will be utilized for the replacement of blood volume. To regain the proper volume status for the various compartments, more fluid will obviously be needed if blood is given later than if it is replaced earlier. One suggested method of administration is to allow 0.5–2.0 ml of salt solution/ml of the blood given, depending upon the timing of blood replacement.

Changes in fluid requirement may be associated with the anesthetic agent or method. All anesthetic agents are cardiac depressants and will generate a compensatory response by the body if circulatory function remains unaltered. The use of hypothermia is associated with internal water and electrolyte shifts into the cell and may produce a cold diuresis. The shift is towards a hypovolemic effect. Hyperthermia requires large volumes of fluid to replace increased losses from the lungs and skin. Hypercarbia is associated with a transfer of HCO_3^- for Cl^- across vascular and cellular membranes and, with this, water. The endothelium of the capillary allows a greater transfer of fluid to the interstitial compartment. This is a Bohr type of effect. While there has been no external loss of fluids, large quantities of an isoosmolar electrolyte solution may be necessary to maintain blood pressure.

There may also be changes associated with the pathophysiology of the disease or the preparation of the patient. At some time in the perioperative period, all deficiencies of fluids and electrolytes have to be replaced, for proper care of the infant. If this is not done prior to operation, it may have to be done as a matter of urgency during the procedure. Losses that occur due to the disease, those resulting from intestinal obstruction, vomiting, diarrhea, fistulous drainages, exudations, or protein or blood losses of infarcted bowel, should be replaced by equal volumes of fluid of similar composition. In most instances this is impractical. If the fluid lost contains a high proportion of H^+, isotonic saline solution should be used; otherwise, lactated Ringer's solution is employed. There is frequently an order for "nothing by mouth" for some hours before operation in an endeavor to empty the stomach and to reduce the risk of vomiting and aspiration. This ritual is followed by most individuals associated with surgery and anesthesia. Unfortunately, the infant or the newborn may come to the operating suite without having had fluids for 12–18 hours. "Pathologic dehydration" may be present. In some instances, such as cyanotic heart disease associated with a high hematocrit, this may be especially hazardous. It would be better if all *NPO* (nothing by mouth) orders for infants were made very specific. For example, for an 8:00 AM operation, "clear fluids from midnight to 4:00 AM; feed clear fluids at 4:00 AM; then NPO." Clear fluids refer to any fluid of a glucose nature without sediment. When glucose is given as a 5 per cent solution orally, gastric effects related to its osmotic pressure are minimal.

Blood Replacement

Whether the infant has anemia or hypovolemia, the oxygen-carrying capacity should be restored preoperatively. If the problem is anemia, packed erythrocytes are preferred. If hypovolemia is present, whole blood is preferable. There are, of course, risks in the administration of blood and blood products that may weigh against this decision.

If packed erythrocytes are used (hematocrit approximately 70 per cent) a guide to the quantity of cells needed can be obtained by use of the calculation: packed cells needed = 1.5 ml for each percentage point the hematocrit needs to be raised per kilogram of body weight = 1.5 ml/%Hct/kg.[38] For whole blood, the factor would be 2.5, as the hematocrit of whole blood is approximately 40 per cent. One and one-tenth milliliter of frozen erythrocytes should increase the hematocrit 1 per cent/kg, the cells being resuspended in a small amount of either crystalloid or colloid solution. In exchange transfusion the newborn is given packed (or frozen) erythrocytes with the addition of 20–30 ml of 25 per cent salt-poor albumin, because of its ability to bind bilirubin.

Several facets are involved in intraoperative blood replacement. The accurate measurement of blood loss is vital to any replacement regime. The volumes to be measured may be small, and yet should be measured as accurately as possible. A number of approaches have been advocated: weighing sponges, hemoglobinometry, calibrated suction bottles, and visual estimation. Most people, realizing the outcome when estimation is poor, will err on the high side. Some add an arbitrary 25 per cent. There is no substitute for experience and judgment.

"Davenport's" law is popular for the calculation of intraoperative blood replacement.[46] That is: less than 10 per cent loss, no replacement necessary; more than 20 per cent loss, blood must be replaced. Between these two figures, blood replacement will vary with clinical circumstances and the type of operation. Once a decision to replace blood has been made, it should be completely replaced, milliliter for milliliter. Some would even add 5 ml/kg. The infant is at a disadvantage if earlier in the operation blood has been replaced with an electrolyte solution. With the latter, two to three times the volume of blood lost are needed because of its intra- and extravascular distribution. Electrolyte solutions instead of blood are therefore not recommended for the infant. If frozen erythrocytes are used intraoperatively, it should be kept in mind that they contain no protein when reconstituted with an electrolyte solution, and no clotting factors. These must be added whenever relatively large volumes of blood are given. For the acute replacement of a large blood loss, the infant's trachea should be intubated, with controlled ventilation and supplemental oxygen supplied. The blood should be warmed (a microwave oven appears most efficient when units of blood are constant in size). Fresh blood is preferable, and a syringe should be used for accurate measurement. The blood should be filtered, especially if it is old. The addition of sodium bicarbonate, calcium ions, etc., is a matter of individual preference. Physiologic salt solution, lactated Ringer's solution, Normosol-R, Hartman's solution, etc., may be added, 0.5–2.0 ml/ml blood. This reduces the incidence of postoperative pulmonary complications and corrects for the extracellular fluid loss due to the initial hypotension.

Albumin/Dextran

Substitute blood therapy is also useful in treatment of the neonate and infant.[38] Albumin may be given in unlimited amounts, and there is no problem with cross-matching. It is not allergenic, but it is costly and the supply is limited.

Some specific indications for the use of albumin include conditions where the serum albumin is low due to loss or low production (renal or hepatic disease), in emergency situations, or to replace a specific loss, to reconstitute packed or frozen cells, in exchange transfusions, for plasmapheresis, for cardiac surgery, or for the restoration of colloid in the interstitial fluid (roughly equivalent to a 1 per cent solution of albumin). Dextran may be preferred where rheology has been compromised by a high hematocrit, "sludging," or shock, in cyanotic heart disease, or where the reduction of agglutination, rouleaux formation, and microthrombi is beneficial, for example, in sickle-cell states. The amount of albumin used as a 5 per cent solution in lactated Ringer's solution is 10–20 ml/kg. This equals 0.5–1.0 g albumin/kg body weight. Dextran, molecular weight 8,000, + low-molecular-weight dextran, molecular weight 75,000, is administered as a 6 per cent solution, with or without saline solution. This is 7–15 ml/kg.

Volumes of Intraoperative Fluids

Since it is impossible to derive a fluid that meets the exact requirements of every infant, a solution of general composition is frequently used. For most surgical procedures, it is not necessary to provide more than normal maintenance requirements, *i.e.*, 3–4 ml/kg/hour of dextrose, 5 per cent, in lactated Ringer's solution. Those who prefer to be more precise may use a 1/5-strength salt solution. For major abdominal operations, the amounts of fluids needed will vary according to the site and extent of the operation, usually ranging from 5 to 15 ml/kg/hour of dextrose, 5 per cent, in lactated Ringer's solution for 2–3 hours, after which a smaller amount is given according to the physical condition of the infant. It is commonly recommended to be 8–10 ml/kg/hour of dextrose, 5 per cent, in lactated Ringer's solution.

There are several acute situations in the neonate in which there is a need to replace or to maintain the intravascular volume, due to a sudden translocation of fluid from the vascular compartment.[38] Such conditions include acute respiratory acidosis, congenital diaphragmatic hernia, congenital lobar emphysysema, and intraoperative bowel washouts such as occur with meconium ileus. If a balanced salt solution is to be used, it would distribute in this age group in a ratio of 3:1 or 4:1, interstitial compartment to intravascular compartment. An overwhelming amount of fluid might then be needed. If colloid is also given (albumin as a 5 per cent solution in lactated Ringer's solution), a much smaller volume will achieve the same effect. In cardiac surgery, when salt solution is used for replacement of blood loss associated with a high hematocrit, two to three times as much solution may be necessary as would be needed with judicious use of a colloid solution. There are certain conditions where lactate (bicarbonate, acetate, or other alkali-containing fluid) is not recommended for replacement.[38] These include infant metabolic alkalosis, where the bicarbonate in plasma is already high and the need is for H^+. Saline solution acts as an H^+ donor and does not contribute to the bicarbonate load, and is the preferable solution. A second situation is cardiac surgery where excessive amounts of sodium may be administered. This is usually in an attempt to correct metabolic acidosis, frequently associated with a period of cardiac arrest. When this can be anticipated, it may be preferable to use a non-sodium solution, dextrose and water, rather than complete the operation with an extracellular hyperosmolar sodium state due to the large amount of sodium bicarbonate administered during the procedure. In chronic respiratory disease, where the bicarbonate of the plasma is already high, a chloride solution such as saline solution is preferable. Finally, in those conditions where chloride is specifically indicated, *e.g.*, when hypochloremia requires saline solution rather than a lactate solution.

Postoperative Fluid and Electrolyte Requirements

Excluding cardiac and other specific procedures in the newborn and infant, the general recommendations for postoperative fluid therapy include maintenance fluid therapy for the postoperative period that closely parallels the guidelines previously described for fluid maintenance during operative therapy (table 3). Swenson[33] has investigated the minimal fluid requirements of infants in the postoperative period and found the volume of fluid necessary to maintain a stable body weight to be 765 $ml/m^2/24$ hours (±154 ml). He stresses that this requirement is minimal, "since a loss of effective blood volume as a consequence of internal fluid shifts would indicate the need for additional fluid for plasma volume expansion." The value of humidification or nebulization of the environment to reduce the fluid needs has been mentioned. It has been suggested that the absence of humidity in the atmosphere surrounding the infant may be a significant factor in his daily water requirement. This may be especially so when the infant is in an Isolette. However, the current trend is to use the microenvironment provided by infrared heat. Insensible water loss for the normal neonate has been found to be 335 $ml/m^2/24$ hours.[1] The ill neonate may lose as much as 80 ml/kg/day from insensible losses. This fluid has an electrolyte composition approximately that of N/5 saline, consisting of sweat (approximately N/3 saline) and respiratory losses of water without electrolyte. The composition of sweat is influenced by aldosterone, which reduces the sodium and increases the potassium concentration present. Fluid requirement increases with fever, sweating, hyperventilation, acidosis, and the use of infrared heaters for neonatal warmth. The sodium losses from this fluid are also increased. The postoperative fluid requirements therefore approximate 1–1.5 $l/m^2/day$ = 70–100 ml/kg/day = 3–4 ml/kg/hour of dextrose, 5 per cent, in water, one-fifth of the daily volume to be given as dextrose, 5 per cent, in lactated Ringer's solution. In the presence of fever, hyperventilation, sweating, acidosis, etc., two fifths of the daily volume should be dextrose, 5 per cent, in lactated Ringer's solution. Postoperative requirements include the correction of all laboratory-measured deficits of sodium, potassium, and acidemia, etc. They also involve calculation of fluids present in secretions, discharges, and exudates, which are normal losses in the postoperative period. These are not usually measured, but include urine, feces, gastric aspirations, effusions, etc. The losses of fluids that are isotonic with the interstitial compartment should be replaced with equal volumes of isotonic saline solution. Hypotonic saline solution is not recommended, as the extra water may compound the renal losses of both water and electrolyte. The correction of specific defects should be accomplished with calculated volumes of appropriate fluids. If the losses are abnormally great,[47,48] with large volumes of gastric aspiration, effusions, fistulous drainage, diarrheas, discharges, etc., they may result in serious depletion of water and electrolytes. In the newborn with a nasogastric tube in place, the volume of gastric secretion may reach 125 ml/kg/day (normally 20–40 ml/kg/day). The Na^+ content can reach 165 mEq/l (usually 115–165 mEq/l), and the H^+ content reaches adult proportions within 24 hours of birth. Such quantities of water and electrolytes would rapidly deplete the neonate and infant. Careful attention should thus be paid to these factors, and the lost volume promptly replaced with an equal volume of isotonic saline solution, unless the sodium content has been measured and found to be other than that estimated. Gastric secretion is under the influence of aldosterone, but the effects of ADH or aldosterone may be minimized by the presence of mechanical or pathologic stimuli, *e.g.*, nasogastric tubes. Potassium losses or requirements[49] are increased in the postoperative period as a result of stress, steroids, aldosterone, or ADH, from the potassium content of gastric and intestinal secretions, from catabolism, glycogenolysis, neoglucogenesis, etc. The amount of replacement required is varied. Normally the figure is based on caloric/water needs of the newborn surgical patient as with other electrolyte demands. The newborn needs are: metabolic, 100 cal/kg/day; water, 55 ml/100/cal; Na^+, K^+, Cl^-, 1–3 mEq/100 cal/24 hours. These amounts will provide for the insensible losses and for excretion of urine with an osmolality of 400–500 mOsm/l.[37] In the presence of large losses of hydrogen ion, alkalosis (respiratory or metabolic), large sodium deficits, or diuretic action (whether water or chemical), potassium requirements may increase five to six times. The amounts of potassium supplementation necessary postoperatively in newborns and infants may range from 4 to 20 mEq K^+ (as KCl) for each liter of solution administered. The larger amounts would be given as compensation for gastric secretions or for alkalosis. Rarely should potassium be given at a rate greater than 3 mEq/kg/24 hours, and preferably it should be administered by a slow intravenous drip, with adequate urine formation or ECG control.

Exudates, transudates, and discharges all contain protein, and this loss may also have to be replaced to maintain serum oncotic pressure. Albumin, being the main contributor, is the preferable replacement, but plasma is equally satisfactory. If other variables can be controlled, the volume of urine that is considered adequate to reflect proper hydration is 0.3 to 0.5 ml/kg/hour.

Conclusion

The administration of fluids and electrolytes during anesthesia is obviously as critically important in the newborn and infant as it is in the adult. The two most common causes of death in pediatric cases, where anesthesia is contributory, remain hypoxia and inaccurate fluid loss measurement and replacement. The incidence of cardiac arrest during anesthesia in infants is 1:600, compared with an adult rate of 1:2,300.[50] At least one factor in this increased incidence is undoubtedly hypovolemia, even though this particular age group is supposed to have a well developed cardiovascular compensatory capacity. Many infants actually do not receive the fluids that are needed. Thus, a reduction in surgical mortality probably could be achieved by the elimination of fluid and electrolyte deficiency as a source of error.

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