DERLEME/REVIEW

Pediatric Intraoperative Fluid Therapy in Anesthesiology

Anesteziyolojide Pediatrik İntraoperatif Sıvı Tedavisi

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ABSTRACT

Pediatric anesthesia requires careful consideration of fluid and electrolyte management due to the distinct physiological properties of children. Knowledge of postnatal adaptations is critical in avoiding complications from dehydration or overhydration. Children have a higher percentage of total body water, which makes them more vulnerable to imbalances in fluids. Insensible losses depend on respiratory rates and environmental conditions; otherwise, loss would result in dehydration if not corrected promptly. The neonatal renal physiology affects the filtration of fluids and the management of electrolytes, thus requiring individualized fluid therapy for neonates. Hormonal control, crossed capillary hydrodynamics, metabolic factors, and electrolyte equilibrium complicate pediatric fluid therapy further. Clinical evaluation measures aided by high-tech monitoring and multimodal methods will help assess children's fluid status. Isotonic solutions with adequate electrolyte composition are to be used as pediatric intravenous fluid therapy according to the recent guidelines. Crystalloids are preferred over colloids in the initial management of most pediatric patients. Recent evidence supports the use of isotonic balanced crystalloids to minimize iatrogenic complications such as hyponatremia and hyperchloremic acidosis, with ongoing monitoring tailored to individual patient needs.
Keywords: Anesthesia, fluid therapy, ıntravenous ınfusions, pediatrics, perioperative care.

ÖZET

Pediatrik anestezi, çocukların farklı fizyolojik özellikleri nedeniyle sıvı ve elektrolit yönetiminin dikkatle değerlendirilmesini gerektirir. Doğum sonrası adaptasyonların bilinmesi, dehidrasyon veya aşırı hidrasyondan kaynaklanan komplikasyonların önlenmesinde kritik öneme sahiptir. Çocukların toplam vücut suyu yüzdesi daha yüksektir, bu da onları sıvı dengesizliklerine karşı daha savunmasız hale getirir. Hissedilmeyen kayıplar solunum hızına ve çevresel koşullara bağlıdır; aksi takdirde, kayıp derhal düzeltilmezse dehidrasyona neden olur. Yenidoğan böbrek fizyolojisi sıvıların filtrasyonunu ve elektrolitlerin yönetimini etkiler, bu nedenle yenidoğanlar için bireyselleştirilmiş sıvı tedavisi gerektirir. Hormonal kontrol, kapiller hidrodinamik, metabolik faktörler ve elektrolit dengesi pediatrik sıvı tedavisini daha da karmaşık hale getirir. Yüksek teknolojili monitörizasyon ve multimodal yöntemlerle desteklenen klinik değerlendirme ölçütleri, çocukların sıvı durumunun değerlendirilmesine yardımcı olacaktır. Son kılavuzlara göre pediatrik intravenöz sıvı tedavisi olarak yeterli elektrolit bileşimine sahip izotonik solüsyonlar kullanılmalıdır. Çoğu pediatrik hastanın başlangıç yönetiminde kristalloidler kolloidlere tercih edilir, ancak sıvı yönetimi her bir hasta faktörüne göre uyarlanmalı ve perioperatif dönem boyunca sürekli izlenmelidir.
Anahtar kelimeler: Anestezi, sıvı tedavisi, intravenöz infüzyonlar, pediatri, perioperatif bakım.

Introduction

Perioperative fluid and electrolyte management is an essential component of pediatric anesthesia. The unique features of children's physiology, particularly their low reserve capacity and vulnerability to electrolyte imbalances, underscore the relevance of these issues to anesthesiologists. This article presents a review of the principles, problems, and evidence-based approaches to fluid and electrolyte management in pediatric surgical patients.

Pediatric intraoperative fluid management faces specific challenges due to their physiological traits, which are different from those of adults. which are high metabolic rates, high surface area to weight ratio, and immature renal function wherein all these factors significantly influence the fluid and electrolyte balance

during a surgical procedure. Such differences in physiology are key to the success of anesthesiologists in administering fluids and maintaining electrolyte balance in pediatric patients. Postnatal physiology changes dynamically and greatly impact the clinical strategy of managing fluid in newborns. These changes include adaptations of the total body water (TBW) shift and an evolving kidney function. It is of prime importance that these postnatal adaptations be understood, because from that understanding comes the opportunity to apply the most adequate therapy in avoiding either dehydration or fluid overload complications. The next sections will describe these physiological changes and their practice-based implications.

Total Body Water Dynamics

The dynamics of TBW are core to neonatal fluid therapy. TBW serves as a key indicator of hydration status in neonates, directly influencing their fluid requirements. Preterm neonates have increased TBW because their skin barriers are not fully developed and their renal systems are too immature; they are more in the range of 80-90% of their body weight versus 75% for term neonates[1]. This higher TBW makes them very labile concerning fluids, which necessitates very slow and careful titration of fluid intake to avoid either overload or dehydration. The extracellular (ECF) and intracellular fluid (ICF) distribution changes markedly with age. Preterm infants may have up to almost 80% of the TBW as extracellular, decreasing to about 60% by six months of age[2]. The fall in fluid as the child grows predominantly falls within the extracellular compartment and thus leads to the gradual hike of the ECF to ICF ratio until it approaches the adult ratio of 1:2 between the ages of about one and three years[1]. Younger children, with a higher proportion of ECF, pose greater challenges for anesthesiologists due to their altered responses to fluid administration and loss. On average, a 9-year-old child weighing 30 kg possesses about 60% of their body weight as TBW with ICF and ECF accounting for roughly 50% each. On the other hand, a neonate aged one month and weighing 4.5 kg possesses around 70% of their body weight as TBW with ICF constituting two-thirds and ECF one-third of TBW[1]. The TBW distribution by age is summarized in Figure 1. Such variations are important for fluid management, as they affect the volumes of fluids that need to be administered and the ease of redistribution of fluids between compartments throughout the perioperative period. Adults and children may use similar electrolyte-rich fluids if the renal function is adequate because the composition of ECF (plasma inclusive) is relatively constant across age groups[1]. The higher percentage of ECF to total body weight in younger children makes them much more vulnerable to dehydration and fluid imbalance than adults. Elevated vulnerability must be taken into account when evaluating fluid requirements and the probable effects of starvation as well as surgical stress on fluid balance in young children.

Figure 1. Age-related total body water distribution.

Insensible Water Losses

Compared to adults, children have a relatively larger body surface area in relation to weight, heightened insensible water loss mainly due to the respiratory system and the skin, and hence have increased fluid

requirements with a higher tendency for dehydration. The greater part of insensible water losses is through the lungs and skin in infants and younger children[2]. Neonates and particularly preterm neonates have very high insensible losses, which can account for a considerable percentage of their total water needs and, if not rapidly corrected, may lead to dehydration. The respiratory rate in children is also higher; therefore, there is an increase in insensible water loss by the respiratory route. These can become very high, particularly during mechanical ventilation with dry gases in the operating room. While present-day anesthesia machines are now available with humidification capabilities, the contribution of respiratory water loss should still be considered, especially in prolonged procedures or in pediatric patients with respiratory pathology that warrant elevated minute ventilation. Environmental factors in the operating room, such as temperature, humidity, and active warming devices, significantly affect insensible water loss in pediatric patients. High ambient temperatures and adequate levels of humidity can decrease these losses, and unreasonably dry or cooler conditions require the fluid to reach an even higher level. All these factors are to be taken into consideration by an anesthesiologist in developing a fluid management plan for pediatric patients, particularly neonates and infants because of the incomplete mechanism for temperature regulation at their age.

Renal Physiology and Development

The development of renal function is very important during infancy and early childhood because it plays a role in the regulation of fluid and electrolytes. The glomerular filtration rate (GFR) in full-term newborns is substantially less than adult levels and does not reach adult values until approximately one year of age[3]. The reduced filtrate delivery is related to the smaller surface area of capillaries for filtration, low systemic arterial pressure, and high resistance of the renal vasculature. Therefore, there is a low ultrafiltration pressure. The kidneys at birth have limited capacity to reabsorb water, with maximal urinary dilution being only 600 $mOsm/kgH_2O$ as against 1200 $mOsm/kgH_2O$ in adults. The decreased ability to concentrate urine is due to the hypotonic environment of the renal medulla and decreased response to antidiuretic hormone (ADH). Consequently, in neonates and young children, the ability to preserve water in states of deprivation or when there is increased loss of fluids is diminished. This makes them particularly at risk to the development of dehydration during the period of preoperative fasting. Tubular function develops slowly in early life. The reduced GFR in neonates not only impacts their filtration capacity but also has implications for electrolyte management, notably sodium. Newborns can have a high sodium excretion in the urine because the proximal tubule does not have a sufficient capacity to reabsorb sodium. Postnatally enhanced activity of the renin-angiotensin-aldosterone system increases distal tubular sodium reabsorption, which may decrease or not allow the excretion of substantial or rapid sodium loads. In this contradictory interplay between potential sodium loss and retention, the choice of maintenance fluid formulation should be taken with caution.

After surgery, the ability of newborns and young infants to balance acid and base in the body, which is crucial for their overall health, is influenced by how fluids are managed and the stress of surgery. The deficiency of hydrogen ion excretion and bicarbonate-generating capabilities place these patients at high risk of metabolic acidosis, particularly when there is inadequate tissue perfusion or increased metabolic needs and if large volumes of chloride-rich fluid are given, this may result in hyperchloremic metabolic acidosis of a severity that cannot be well-tolerated by infants due to their limited compensatory mechanisms.

Preterm neonates are structurally immature in terms of renal function. Postnatal diuresis, a normal phenomenon in newborns though very frequent in preterm neonates, is the outflow of excessive ECF and does not represent pathological fluid loss.

Recognition of such physiological processes is important to avoid unnecessary fluid input which can cause fluid overload with attendant consequences.

Hormonal Regulation of Fluid Balance

The important consequences of variations in hormonal control of fluid balance between children and adult populations are related to fluid management in the perioperative environment. More susceptible to several perioperative stresses in children, arginine vasopressin (AVP), another name for ADH, is essential for fluid

balance control. Following birth, serum ADH concentrations elevate and may rise significantly due to stressors such as surgical interventions, pain, nausea, and hypovolemia.

Increased ADH response in children during surgery can lead to temporary challenges in excreting free water, raising the risk of fluid retention and dilutional hyponatremia. This is quite important while evaluating perioperative fluid maintenance. Although hypotonic fluids were formerly used depending on metabolic demands, the awareness of non-osmotic ADH triggers in the perioperative phase has resulted in a movement towards isotonic solutions.

 During the first week of newborn life, the renin-angiotensin-aldosterone system shows notable activity which raises aldosterone levels and causes more vascular tone[4]. These raised aldosterone levels improve the reabsorption of sodium in the distal tubules, therefore perhaps compromising the capacity to excrete significant or acute sodium loads. While it affects the responsiveness to fluid and electrolyte therapies, this higher aldosterone activity helps newborns to preserve blood pressure and vascular tone.

Atrial natriuretic peptide (ANP) is involved in the regulation of fluid balance in children, especially during instances of volume expansion. ANP facilitates natriuresis and diuresis, which helps to mitigate the sodium-retaining actions of the renin-angiotensin-aldosterone system[5]. Nonetheless, the functionality of this system may be underdeveloped in neonates and young infants, which could restrict their capacity to effectively manage volume expansion.

Exchanged Transcapillary Fluid

The Starling hypothesis describes transcapillary fluid exchange for both children and adults, with the equation detailing how pressure gradients affect fluid flow across capillary walls. Typically, fluid filtration at capillary arterial ends balances with reabsorption at venous ends. In children, increased capillary permeability in neonates and infants can lead to more fluid and protein moving into the interstitial space. Increased permeability can contribute to edema, especially in inflammatory diseases or with high-volume fluid infusion. Neonates and sick children often have low plasma oncotic pressure, primarily dependent on plasma proteins such as albumin[6]. Hypoalbuminemia is common in sick neonates, leading to fluid redistribution and edema formation. Diminished albumin synthesis due to hepatic immaturity further exacerbates oncotic pressure changes and fluid redistribution[7].

The glycocalyx is crucial for regulating blood vessel permeability and is a carbohydrate layer covering the vascular endothelium. Its development and changes over time due to human growth have been detailed. Although studies on the growth of the child's glycocalyx are scarce, it is assumed that its functional maturity enhances liquid transport, especially during stress from surgery or severe illness, evident by increased crystalloid solutions over 40-60 mL/kg[8, 9]. This could hinder isotonic fluid resuscitation in maintaining plasma volume and correcting fluid deficits. In children, lower thresholds may arise due to their unique physiologies, requiring more cautious resuscitation. Guidelines suggest colloid solutions as a second-line therapy after crystalloids, but the evidence is insufficient for definitive guidance[10]. Benefits should be considered alongside risks like allergic reactions, coagulopathy, and renal dysfunction with older hydroxyethyl starch (HES) solutions[11].

Acid-Base Assessment

Acid-base homeostasis is difficult to sustain in children owing to the fact that their metabolic rate is high but compensatory abilities are very low. The neonatal bicarbonate buffering system has a baseline concentration much lower at 20-22 mEq/L while in adults that level is more in the range of 24-26 mEq/L[12]. Thus, the low buffering capacity of neonates for metabolic acids decreases. Another factor that further lowers the low ability to buffer metabolic acids of neonates is the immature renal mechanism for the excretion of acids, which makes neonates much more susceptible to metabolic acidosis beyond stress conditions like surgery and critical illness.

IV fluid administration greatly affects acid-base balance. A major player in such a situation is Normal Saline (0.9% NaCl). As the most typical crystalloid solution, it carries 154 mmol/L chloride where the normal plasma level might average about 100-110 mmol/L[13]. Large normal saline loads may result in

hyperchloremic metabolic acidosis and dramatically worsen pre-existing acidosis in critically ill pediatric patients or patients involved in major surgical management requiring massive fluid input[8].

Some balanced crystalloids (BCS) that do not generate hyperchloremic acidosis and contain electrolyte composition like plasma, plus buffers such as lactate, acetate, or gluconate which are converted to bicarbonate in the body include Ringer's lactate and Plasma-Lyte[9]. These types of solutions are low potential mediators of iatrogenic acid-base disturbances and are gradually becoming the standard practice for intraoperative fluid therapy in the pediatric population to whom large volumes of fluids need to be administered[10]. Conditions that influence the relationship between perioperative fluid choice and acid-base balance are stronger in those with established renal or metabolic conditions. States of chronic kidney disease are associated with an acidosis, hyperkalemia, hypocalcemia, and hyperphosphatemia in a pediatric patient. Thus, during the intraoperative period fluids have to be chosen relative to any baseline electrolyte abnormality or acid-base abnormality to prevent further deviation during the time of surgery.

Glucose Homeostasis

Metabolic differences between children and adults are important in the regulatory control and pertinence of glucose to the regulation of the management of fluids during surgery. Neonates, particularly preterm neonates, have limited stores of glycogen and utilization of glucose accelerated, making them more prone to hypoglycemia in the fasted state[11]. The condition is even more deteriorated in a neonate who is inappropriate for gestational age, or intrauterine exposure to processes of maternal diabetes or beta-blockers[14-16].

Historically, many pediatricians have used glucose solutions as maintenance fluid therapy for pediatric patients due to a general feeling of hypoglycemia risk[17]. Surgical physiological stress leads to hyperglycemia because during any surgery, there is increased catecholamine stress with insulin resistance[18]. Osmotic diuresis can be expected resulting from hyperglycemia, leading to dehydration and adverse neurological outcomes due to electrolyte imbalances, especially in the settings of cerebral ischemia[19].

Modern strategies of glucose management have come to explicitly consider age, fasting duration, and the specific type of surgery. As patients are mostly children, undergoing elective surgeries that require only a short fasting period, routine glucose is usually not necessary at all. The neonates, infants <1 year, and children with a greater inherent risk of hypoglycemia would ideally benefit from treatment with 1–2% glucose in isotonic solutions, diabetic hyperglycemia being prevented very firmly while relatively safely removing the significant hyperglycemia risk[20].

Perioperative blood glucose monitoring remains relatively critical, more so when working with neonates, long surgical procedures, and high-risk patients who, if not carefully managed, may develop problems of glucose imbalance. Early diagnosis of derangements in glucose levels helps in timely intervention and modifications to fluid therapy. Although much debate continues on the optimal upper limit for safe blood glucose levels in children undergoing surgery, it is widely accepted that levels between 70 and 180 mg/dL would be appropriate[21].

The relationship of glucose to electrolyte balance should be appropriately recognized. Until quite recently, glucose used to be the standard maintenance fluid in a pediatric patient conjugated with hypotonic saline solutions i.e. 5% dextrose in either 0.2% NaCI or 0.45% NaCl. The realization that iatrogenic hyponatremia is a major complication of this practice has led to a recommendation that glucose be used only with isotonic solutions when absolutely necessary, and not with hypotonic fluids[22].

Electrolytes

Maintenance of electrolytes in children, inappropriate regulation, and relatively higher metabolic requirements presents some distinct challenges; since the regulatory mechanism is immature and metabolic requirements are high during this period of life.

Sodium is the major determinant of plasma osmolarity and, therefore, the control of the movement of fluid between the different compartments. Increased risk of hyponatremic brain edema in prepubescent children

results from a large brain-to-cranial-vault ratio, low Na-K ATPase activity, and high levels of ADH, especially under stress[23-25]. This relative increase in susceptibility mandates an increased surveillance role for the sodium solutions in IV fluids given in the context of pediatric anesthesia. This rising susceptibility suggests increased vigilance for sodium solutions within IV fluids in pediatric anesthesia management. Current evidence highly recommends isotonic solutions for maintenance therapy during the most common pediatric surgical conditions. Previous studies have additionally pointed to the possible association between hypotonic fluids and hyponatremia among the pediatric population[26]. In 2018, the American Academy of Pediatrics released a Key Action Statement recommending isotonic solutions with appropriate potassium chloride (KCl) and dextrose to be administered to pediatric patients 28 days to 18 years of age who require maintenance intravenous fluids[27].

The management of potassium levels in children is critically important, especially in the immediate postoperative period. Potassium chloride should be added to maintenance fluids unless nutritional fluid is contraindicated for the child because of hyperkalemia or deteriorating renal function[27]. There may be differences in opinions about the amount of potassium to be supplemented. However, in practice, most clinicians give 20 mEq/L of KCl to all patients irrespective of weight. Others suggest 10 mEq/L for patients under 10 kg [27]. Supplementation of potassium would be preferred in long procedures, to avoid hypokalemia, which can cause cardiac arrhythmia and neuromuscular weakness.

Clinical Assessment of Fluid Status

Current clinical and monitoring indicators impose limitations on the accurate assessment of fluid status and responsiveness in pediatric patients.

Traditional clinical markers of dehydration, such as skin turgor, mucous membrane moisture, and capillary refill, provide meaningful but sometimes slightly imprecise approximations to the state of hydration. The dependencies on these parameters are falling even lower in the conditions of anesthesia, that being driven by an influence on peripheral circulation, the effect of anesthetic agents on vascular tone, and external conditions regarding the ambient temperature and use of vasopressors.

Body weight changes remain fairly sensitive to relatively rapid changes in the fluid status of children. A reduction in weight specifically by at least 5% might point towards mild dehydration, 10% to moderate dehydration, and for 15% loss or higher, it would be severe dehydration- at risk of circulatory compromise. In emergent situations, however, practical application is often restricted due to the lack of available pre-illness weight.

Hemodynamic parameters include heart rate and blood pressure, pulse pressure but are of limited value in assessing volume status. Age and temperature, emotion, pain, anxiety, and age physiological variability in heart rate make it a relatively insensitive indicator of early hypovolemia in children[28]. Relatively late blood pressure is often maintained within normal ranges until relatively late in the progression of hypovolemia due to the compensatory increase in peripheral vascular resistance, particularly in healthy children with robust compensatory mechanisms.

Since there is limited information about responsiveness to fluids, Central Venous Pressure (CVP) monitoring is not used. The static values for CVP were also poorly correlated with intravascular volume and preload responsiveness. This complicates its interpretation due to shifts in venous compliance, intrathoracic pressure during mechanical ventilation, and cardiac function. In similar situations, it often creates a misleading perception of its actual presence[29-31].

Most parameters reflecting preload dependence are inspired by the functional interaction between the heart and lungs in mechanically ventilated patients—pulse pressure variation, stroke volume variation, and inferior vena caval respiratory variations. In adults, they have been studied extensively as predictors of fluid responsiveness[32, 33]. Evidence of their applicability in pediatric patients is poor and sometimes contradictory. This reduces the possibility of applying these dynamic indices clinically. Increased chest wall compliance and higher basal heart rate with smaller tidal volumes in children may further contribute to limited reliability of these dynamic parameters.

Technological advances, including esophageal Doppler monitoring, transpulmonary thermodilution, and non-invasive cardiac output monitoring, offer potential advantages in assessing fluid status and responsiveness in pediatrics. Table 2 summarizes various monitoring methods that can be used to assess fluid status in pediatric patients during the perioperative period. However, it tends to face challenges in terms of technological complexity as implementation factors, requiring expertise and, in general, insufficient validation in diverse cohorts of pediatrics studies.

The limitations of single assessment methods call for the need to undertake a multimodal approach to assess fluid status. Integrating clinical signs, basic hemodynamic data, laboratory parameters (lactate, base deficit, and urine output), and, if available, advanced monitoring tools enable one to achieve the most complete assessment of fluid status in a child and therefore guide proper management.

Table 2. Monitoring methods for body fluid status in pediatric perioperative care.

Monitoring Method	Key Characteristics	Advantages	Limitations
CLINICAL ASSESSMENT METHODS			
Clinical Signs	Heart rate, blood pressure, capillary refill time, mucous membrane moisture, skin turgor, mental status	Readily available Non-invasive First-line assessment tool	Late indicators Poor correlation with mild/moderate dehydration Subjective assessment
Body Weight	1 kg weight change approximates 1L fluid loss/gain	Gold standard for acute fluid changes Objective measurement	Baseline weights often unavailable in acute settings Affected by factors other than fluid (e.g., food intake)
Standardized Dehydration Assessment	Structured tools based on % weight loss and clinical symptoms	Categorizes dehydration severity Systematic approach	Relies on symptoms that may not always be present Variable interpretation between clinicians
INVASIVE HEMODYNAMIC MONITORING			
Central Venous Pressure	Direct measurement of right atrial pressure	Continuous monitoring Direct pressure measurement	Poor correlation with actual volume status Invasive with risks of central line Limited value in children
Arterial Pressure Monitoring	Continuous arterial pressure waveform analysis	Continuous hemodynamic data Enables dynamic parameter assessment	Limited predictive value in children Pulse pressure variation utility is variable Age/ventilation dependent
Esophageal Doppler Monitoring	EDM calculates SV, CO, FTc, and peak velocity. FTc serves as a preload indicator.	Minimally invasive Clinically accurate across all pediatric ages Continuous monitoring	Technical limitations such as age and size restrictions, probe positioning difficulties, and operator dependency Esophageal stricture, recent esophageal surgery, severe coagulopathy, and esophageal varices are absolute contraindications for EDM.
Transpulmonary Thermodilution (PiCCO)	Combines thermodilution with pulse contour analysis; measures CO, GEDV, EVLWI	Comprehensive hemodynamic data Useful in complex surgeries Validated in pediatric liver transplantation	Requires arterial and central venous access Not suitable for routine cases Invasive
NON-INVASIVE MONITORING TECHNOLOGIES			

Echocardiography & Ultrasound	Transthoracic echo, IVC ultrasound, lung ultrasound	Non-invasive Bedside evaluation Comprehensive cardiac assessment IVC collapsibility predicts fluid responsiveness	Operator-dependent Requires specialized training Intermittent measurement Equipment availability
Electrical Bioimpedance	Measures total body water, extracellular and intracellular fluid volumes	Non-invasive Validated in children Pre/post-op utility Good correlation with reference methods	Electromagnetic interference in OR Limited intraoperative monitoring Requires specific equipment
Electrical Cardiometry / USCOM	Non-invasive cardiac output monitoring based on changes in thoracic electrical conductivity / ultrasonic Doppler technology	Non-invasive Continuous monitoring Predicts fluid responsiveness Validated in children	Evidence still emerging Device-dependent results Variable accuracy in specific populations
Pleth Variability Index	Calculates respiratory variations in pulse oximetry waveforms	Non-invasive Can be automated Uses existing monitoring equipment	Limited value in spontaneously breathing children Variable evidence in children <2 years Requires mechanical ventilation for optimal use
EMERGING TECHNOLOGIES			
Near-Infrared Spectroscopy	Continuous monitoring of regional tissue oxygenation	Non-invasive Continuous monitoring Valued in cardiac surgery Reflects tissue perfusion	Limited to specialized settings Primarily research application Requires interpretation expertise
Advanced Ultrasound Techniques	Multi-organ protocols, left brachiocephalic vein assessment	Comprehensive assessment Non-invasive Point-of-care evaluation	Not standardized Requires operator skill Developing evidence base
Machine Learning Applications	Integrates multiple physiological variables for fluid responsiveness prediction	Multi-parameter integration Potential for improved accuracy Automated interpretation	Experimental Not in routine clinical use Requires validation

Abbreviations: CO, Cardiac Output; EDM, Esophageal Doppler Monitoring; EVLWI, Extravascular Lung Water Index; FTc, Corrected Flow Time; GEDV, Global End-Diastolic Volume; IVC, Inferior Vena Cava; SV, Stroke Volume; USCOM, Ultrasonic Cardiac Output Monitor.

Types of Fluids Used in Pediatric Intraoperative Management

Optimal intraoperative fluid treatments in pediatrics are performed using an IV route. Many IV fluids are available with major differences in properties, indications, and contraindications (see, Table 1). A detailed choice of fluid will assure patient-tailored administration that fits the needs of the patient, complies with the intricacies of the surgery performed on the patient, and complies with various physiological factors. The management of fluids in pediatrics has undergone considerable changes over the last decade. There is a

growing body of evidence to support these changes because it decreases iatrogenic complication risks as an evidence-based practice.

Table 1. Comparison of perioperative fluids in pediatric patients.

Fluid Type	Composition (per 100 mL)	Tonicity	Key Indications	Potential Adverse Effects & Considerations
CRYSTALLOIDS				
0.9% Sodium Chloride	Na^+ 15.4 mEq, Cl^- 15.4 mEq	Isotonic (308 mOsm/L)	Initial resuscitation for hypovolemia, replace gastric losses, correct hyponatremia and hypochloremia.	Large volumes may cause transient hyperchloremic metabolic acidosis and decreased glomerular filtration rate.
Lactated Ringer's Solution	Na^+ 13 mEq, K^+ 0.4 mEq, Ca^{2+} 0.3 mEq, Cl^- 10.9 mEq, Lactate 2.8 mEq	Isotonic (273 mOsm/L)	Maintenance fluid. Replacement of fluid deficits and ongoing losses. Balanced composition mimics plasma.	Lactate converts to bicarbonate; use cautiously in liver failure. Avoid with blood products due to calcium (clotting risk).
Plasma-Lyte A	Na^+ 14 mEq, K^+ 0.5 mEq, Mg^{2+} 0.3 mEq, Cl^- 9.8 mEq, Acetate 2.7 mEq, Gluconate 2.3 mEq	Isotonic (294 mOsm/L)	Maintenance fluid. Replacement of fluid deficits and ongoing losses. A balanced, buffered solution.	Contains magnesium, important for patients with renal failure. Acetate, metabolized by muscle, is suitable for liver dysfunction.
D5W	Dextrose 5g	Isotonic in the bag (252 mOsm/L), but physiologically hypotonic	Correction of free water deficit. Vehicle for medication administration.	Not suitable for resuscitation or maintenance as it spreads throughout body water compartments, providing minimal blood volume increase. Rapid dextrose metabolism leaves free water, raising the risk of hyponatremia and cerebral edema.
D5 ½ NS	Dextrose 5g, Na^+ 7.7 mEq, Cl^- 7.7 mEq	Hypertonic in the bag (406 mOsm/L), but physiologically hypotonic	Historically used for maintenance, but now less favored due to hypotonicity.	Poses a high risk of hyponatremia post-surgery due to elevated ADH levels; not advised for routine maintenance by current guidelines.
D5 ¼ NS	Dextrose 5g, Na^+ 3.4 mEq, Cl^- 3.4 mEq	Isotonic in the bag (280 mOsm/L), but physiologically hypotonic	Previously used for maintenance in neonates and young infants.	High risk of iatrogenic hyponatremia; isotonic solutions are preferred.
COLLOIDS				
5% Albumin	Albumin 5g	Isotonic	Volume expansion in severe hypovolemia or hypoalbuminemia. Cases with significant capillary leak.	Expensive. Risk of allergic reactions. No proven mortality benefit over crystalloids in most situations.

HES	Varies by product	Isotonic to hypertonic	Previously used for volume resuscitation.	Avoided in critically ill adults due to risks of kidney injury, coagulopathy, and increased mortality. Restricted and not recommended for children. Considered for surgeries with major bleeding risk, but evidence is lacking.
Gelatins	Varies by product	Isotonic	Volume expansion.	More anaphylactoid reactions than other colloids; shorter intravascular half-life than HES.

Abbreviations: ADH, Antidiuretic hormone; D5W, 5% Dextrose in Water; D5 ½ NS, 5% Dextrose+0.45% Sodium Chloride; D5 ¼ NS, 5% Dextrose+ 0.2% Sodium Chloride; HES, Hydroxyethyl Starches.

Crystalloid Solutions

Crystalloids play a rudimentary role in pediatric intraoperative fluid management, with major strides in their preparation and application over the years. Solutions consist primarily of a solvent with some electrolytes, which is notable for the lack of larger macromolecules of protein or starch. Tonicity classification describes isotonic and hypotonic solutions, whereas electrolyte composition may be categorized as balanced or unbalanced. Each type has its advantages and aspects to be taken into consideration, which are applied to pediatric patients based on the proper clinical setting.

Isotonic versus Hypotonic Solutions

Given the vulnerability of pediatric patients to electrolyte imbalances, isotonic solutions are preferred because they closely mimic the osmolarity of the child's plasma, reducing the risk of exacerbating imbalances. A major shift has occurred in pediatric fluid management, specifically in the fluid's tonicity for maintenance purposes. Traditionally, besides 5% glucose, hypotonic solutions were widely used, such as 0.2% NaCl (30 mmol/L sodium) and 0.45% NaCl (77 mmol/L sodium)[34]. Based on the historical framework established by Holliday and Segar, the metabolic needs of children are prescribed[35]. This methodology has been around since the 1950s and was really based on a wrong assumption, that relatively immature renal function of children would limit their ability to excrete sodium effectively. Moreover, contemporary research has proved that using hypotonic solutions radically increases potential risks for iatrogenic hyponatremia, especially in a perioperative setting[36].

The risks of hypotonic solutions have been extensively reported by several randomized controlled trials about the risks associated with the administration of hypotonic fluids to surgical patients. An interesting Cochrane review proved that there was a decrease in the incidence of hyponatremia by 52% when isotonic fluids were used as compared to hypotonic fluids[37]. The finding is of substantive relevance since in the prepubertal child, a very high degree of vulnerability to the cerebral edema phenomenon associated with hyponatremia is expressed, which includes increased brain-to-cranial-volume ratio, Na-K ATPase pump activity, and levels of ADH responsive to surgical stress. Hyponatremia can be a very significant clinical entity with restlessness, headache, seizures, and even sudden death in its severe form in this population[38, 39].

In its revised guidelines, the American Academy of Pediatrics now defines that isotonic solutions with proper concentrations of potassium chloride and dextrose be used for children aged from twenty-eight days to eighteen years for maintenance intravenous fluid therapy[22]. This dramatic reversal of advice marks a major deviation from customary practice, supported by newly available strong evidence towards the same end, which is the improvement of patient safety.

Balanced versus Unbalanced Solutions

In the field of isotonic solutions, one major comparison that can be formed is BCS against their unbalanced siblings, with the main characteristic being the widely used `normal saline' or 0.9% sodium chloride. Although it is very common in clinical practice, that solution does not meet the physiological standard

because the chloride level (154 mmol/L) is way over the level found in plasma, which is around at about 100-110 mmol/L.

The infusion of large amounts of 0.9% NaCl is associated with a diversity of adverse physiological effects. Such include hyperchloremic metabolic acidosis, fluid retention, renal vasoconstriction, and a fall in the GFR that have been seen both in adults and in pediatrics[40].

These formulations, indeed like BCS, have an electrolyte composition closer to that of human plasma and have buffering agents like lactate, acetate, or gluconate that are metabolized to bicarbonate. Such buffers decrease the appearance of hyperchloremic as well as dilutional metabolic acidosis, which can develop after infusion with normal saline. Some of the frequently used balanced solutions are Ringer's lactate (also known as Hartmann's solution) and Plasma-Lyte as well as other acetate buffered isotonic preparations.

A recent meta-analysis of three randomized controlled trials on 162 critically ill pediatric patients showed that hydration with balanced crystalloids improved metabolic acidosis and bicarbonate levels as compared with 0.9% NaCl at 4-12 hours[41]. In its recommendation, the Society of Pediatric and Neonatal Intensive Care also strongly prefers balanced crystalloid solutions as maintenance fluids in acutely and critically ill children[42]. In fact, in the European Consensus Statement from 2011 and the guidelines of the Association of the Scientific Medical Societies in Germany from 2016, preferential use of balanced crystalloid solutions for pediatric intraoperative maintenance fluid therapy is strongly advised[20, 43].

Solutions Containing Glucose

The shift from conventional fluid regimens to the use of glucose marks a radical change in the field of medicine. Pediatric patients, especially neonates and young infants, maintain pronounced biochemical differences in glucose metabolism compared with adults. With lower glycogen storage and higher basal glucose consumption rates, these individuals are prone to hypoglycemia in fasting states. Generally, 5% dextrose solutions previously served as maintenance infusions in pediatric care.

The surgical stimulation of the stress response also generally increases blood glucose levels by eliciting an increase in catecholamine secretion and developing insulin resistance[44-46]. Either condition can further worsen hyperglycemia admitted with high-concentration glucose solutions. This then makes the healthcare provider face a somewhat intense task in which they must mitigate the neurological hazards posed by both hyper- and hypoglycemia, the latter whose adverse effects might impend onto pediatric patients.

The current evidence suggests that in most pediatric patients, it is preferable to use isotonic balanced solutions with 1%-2.5% glucose than the previously used 5% glucose concentration[47, 48].

A 2-4% glucose solution administered at 10 ml/kg/h was found to be more effective in the prevention of intraoperative catabolism, insulin resistance, rebound hyperglycemia, and acidosis when compared with a 1% solution in low-birth-weight neonates[49]. This underlines the need for the right person and situation regarding the concentration of glucose. In the absence of other concerns, healthy children undergoing brief procedures for which they have been minimally fasted probably do not require provision of glucose[50]. Routine blood glucose measurements are, however, imperative for neonates, individuals undergoing prolonged procedures, and those with imbalances risk factors.

Colloid Solutions

Colloids comprise relatively large molecules, mostly proteins and starches. Logically, these substances should be kept inside the intravascular compartment for a longer time than crystalloids. Therefore, theoretically, colloids should be more effective in expanding volume. However, the debate concerning the use of colloids in pediatrics still continues because relatively low-quality evidence does not yet provide an answer that would be sufficiently satisfactory for guiding patient management[51]. Colloids can be primarily structured as natural proteins and synthetic colloids.

Natural Protein Colloids

Albumin has usually been taken as the gold standard colloid for pediatric patients. However, new evidence has complicated that old perspective. In the year 2023, a quality improvement initiative implemented a systematic change program intervention to reduce the use of 5% human albumin solution in the Pediatric Intensive Care Unit[52]. Human albumin comes in concentrations from 5% to 20%, with 5%, the osmotic equivalent to plasma[53]. More than 50% of total plasma protein, and in fact, 80% of intravascular oncotic pressure, is due to this protein[54].

Although the empirical promise of albumin may appear optimistic, the evidence that is currently available does not support its clinical superiority over crystalloids. The use of albumin has been extensively researched among critically ill adult populations, and no study has shown a significant reduction in mortality[55, 56]. Furthermore, high-quality studies involving pediatric populations are few. Although it is known to be the least allergenic colloidal solution, the disadvantage of albumin is that it is the most expensive treatment with the potential to leave the blood vessels for the extra-vascular space, especially with high vascular permeability due to inflammation and critical illness conditions. Other natural protein colloids include stable human serum and lyophilized plasma; however, their use is uncommon, and evidence to support their use in pediatric perioperative settings is lacking.

Synthetic Colloids

Synthetic colloids have emerged because of their high cost and limited availability of albumin. The major classes are HES, gelatin, and dextran, which differ in their properties and safety considerations. Development in the third-generation HES solutions such as tetrastarch (HES 130/0.4) is the definitive response to the prolonged evolution observed. This is inspired mainly by the goal to rectify security issues attached to the former mixture Contemporary starches with a low molecular mass of 130,000 Da makes them safer. Hence, the risk of associated adverse events, such as renal failure, itching, and changes in hemostasis, is lower, while their volumetric effects are about the same[57].

A meta-analysis of nine randomized controlled trials showed that third-generation HES administration did not affect renal output or blood loss in pediatric consented patients to surgery[58]. There is reason to believe that HES in balanced electrolyte solutions may have less effect on acid-base and electrolyte balance compared to HES in saline[59].

With reference to their influence on coagulation and renal function, the questions about the synthetic colloids remain to be debated[60, 61]. Different studies have proposed increased blood loss potential after pediatric cardiopulmonary bypass procedures when HES solutions are used, though this is not constantly associated with higher transfusion needs[62, 63]. Some data is available on the "tipping of the balance" of thromboelastographic alterations in pediatric samples towards HES[64].

Gelatin solutions have high potential for eliciting anaphylactoid reactions and little positive volume effects, almost no hemostasis impact[65, 66]. Dextrans, being less used today, impede coagulation and pose imminent risks of anaphylaxis[67, 68].

Regulatory issues have played a major role in the availability of synthetic colloids, with HES products having been placed under regulatory suspension for patients of all ages in both Europe and the United States. This situation is further constraining the selection available to pediatric anesthesiologists.

Clinical Application and Limitations

The function of colloids in pediatric patient fluid balance management continues to evolve. However, current recommendations support the preference for crystalloids as the initial therapy[69]. However, there are situations where colloids may be quite appropriate, when, first of all, crystalloids are not effective. Some guidelines suggest starting colloids after 30-50 ml/kg of crystalloids have been given without achieving successful volume restoration. Most institutions have limited the routine use of colloids because they are more expensive than crystalloids and have scarce supporting evidence of improved outcomes.

A pragmatic approach, therefore, is that balanced crystalloid solutions should be used first, and colloids should be reserved for specific indications. Blood products should only be used when Hb levels or coagulation parameters indicate need. In scenarios where colloids are thought necessary, third-generation HES solutions might provide such a compromise amongst efficacy and safety in children with normal renal function and coagulation, although this remains controversial. There remains even more specific caution about synthetic colloids in neonates (due to immature coagulation systems) and post-cardiopulmonary bypass procedures.

Conclusion

Fluid management in pediatric surgery requires attention to total body fluid physiology, individual circumstances, and current evidence. The use of isotonic balanced crystalloid solutions with glucose (1% to 2.5%) is strongly advocated, moving away from previous hypotonic solutions with higher glucose levels. Evidence is limited in more controversial areas such as the use of colloids or advanced monitoring techniques. Colloids have limited roles, and crystalloids are preferred as first-line therapy. Colloid therapy may be beneficial in high blood loss surgeries (e.g., cardiac surgery, major tumor surgeries, major trauma) where crystalloid administration exceeds 30-50 mL/kg without hemodynamic stability. Caution is advised in neonates and preterm infants due to risks of adverse effects. Colloids should be avoided in patients with renal dysfunction or coagulopathy. While HES solution has mixed safety profiles, natural colloids like albumin may be considered in specific cases, despite limited evidence for improved outcomes.

Pediatric fluid management must be age-appropriate. Neonates require tailored approaches, whereas school-age children typically tolerate standard isotonic protocols, with adolescents needing more adult-like strategies. Crucial gaps in pediatric fluid therapy include validating dynamic fluid responsiveness monitors in children and developing pediatric-specific assessment protocols for point-of-care ultrasound. The application of artificial intelligence in fluid management, including predictive algorithms for fluid responsiveness, is an emerging area of interest. Comparative effectiveness research is needed for optimal fluid strategies in subpopulations with conditions such as congenital heart disease and chronic kidney disease. Advancements in pediatric fluid monitoring should prioritize non-invasive, continuous tools tailored for children. Wearable devices for real-time fluid status assessment and automated decision support systems could enhance fluid management. Additionally, integrating telemedicine for remote monitoring in varied healthcare settings may improve pediatric outcomes.

In summary, while crystalloid solutions are central to pediatric intraoperative fluid therapy, individual treatment strategies based on age and surgical complexity are crucial. Future research should focus on pediatric-specific technologies, validating fluid parameters, and refining evidence-based protocols.

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