Review Article

Feeding the child with congenital heart disease: a narrative review

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Abstract: Children with congenital heart disease (CHD) are prone to nutritional challenges and undernutrition. For children with unrepaired CHD, growth is often compromised due to caloric imbalance stemming from high energy expenditure and poor nutritional intake as a result of feeding intolerance, fluid restriction, and impaired absorption. The resulting undernutrition is associated with frequent infections, poor wound healing, and increased mortality, creating strong incentives for early and aggressive nutrition intervention. Management strategies are therefore aimed at ensuring that dietary provisions meet the child's distinctive needs by prioritising human milk for infants, increasing energy delivery through higher caloric density feeds, use of enteral feeding tubes, parenteral nutrition for energy supplementation, and medical therapy to treat feeding intolerance. The perioperative period also presents unique challenges and opportunities for nutritional support, including early introduction of enteral nutrition to support improved postoperative recovery and ensuring feeding delivery meets the child's energy and protein requirements to avoid a catabolic state. Indirect calorimetry can be utilized to measure energy consumption and avoid under or over nutrition. Specific nutritional approaches affecting the CHD population are also required, such as chylothorax or protein-losing enteropathy, to provide adequate nutritional support without contributing to harm. This narrative review describes the nutritional considerations, obstacles and complications faced by children with CHD across their different phases of care, and the treatment approaches aimed to mitigate a negative impact.

Keywords: Children; congenital heart disease (CHD); enteral nutrition, feed

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Introduction

Congenital heart disease (CHD) is the most common birth defect affecting approximately 0.8% of live births, with many requiring surgical intervention early in infancy (1). Most neonates with CHD are born at term with anthropometric measurements that fall within the normal range but quickly experience nutritional challenges that place them at high risk for growth failure and malnutrition (1). Growth restriction can have numerous detrimental consequences, included delays in cardiac surgery, increased postoperative morbidity and impaired neurocognitive development (2). The present work describes nutrition in children with CHD including determinants of nutritional status and explores perioperative feeding practices including caloric targets and nutrition delivery and discusses the management of special feeding complications within the CHD population.

We present the following article in accordance with the Narrative Review reporting checklist (available at https://pm.amegroups.com/article/view/10.21037/pm-20-77/rc).

Methods

A search of scientific studies published from 1980 to June 2020, related to nutrition in infants and children with CHD was conducted using Medline, PubMed databases. Titles and abstracts of each study were screened for the selection of relevant articles. Reference list of selected papers were also reviewed to identify relevant studies pertaining to this subject domain. Eligible study designs were case reports, case series, cohort studies and prospective randomized controlled trials. We omitted articles that were not written in English. An evaluation of the full text of selected articles was completed by the reviewers.

Nutrition in children with CHD

Children with CHD are challenged with impaired growth, as measured by slower increases in weight, length, and head circumference (3). The initial reduction in growth velocity seen with acute malnutrition disproportionately reduces weight attainment, reflected by lower weight-for-age and weight-for-length z-scores. When sustained, inadequate nutrition leads to impaired length/height attainment, also referred to as stunting, and lower length-for-age z-scores.

Despite medical advances, undernutrition remains common in children with CHD (2). The frequency of acute malnutrition in CHD patients living in a well-resourced health care environment continues between 33–52%, and approximately two-thirds of CHD patients experience stunting (4-7). The prevalence and severity rise dramatically in resource-limited conditions, with nearly universal penetrance (92%) in numerous studies, of which 60% are categorized as severe (8,9). Regardless of health-care system, younger patients are particularly vulnerable and overrepresented. While infants are at the highest risk for acute malnutrition (80%), a similar proportion of toddlers show evidence of stunting. Other important risk factors include symptoms of congestive heart failure, resulting from left-to-right shunting lesions or poor left ventricular function, and chronic cyanosis; growth failure is reported to be nearly double in cyanotic heart disease (80% cyanotic compared to 45% cyanotic CHD). Anemia has also been strongly associated with poor growth in a resource-limited setting, but it is unclear if it is a surrogate for deficiency in micronutrient intake (e.g., iron depletion) or reflects severity of cyanosis rather than an independent cause. Although generally excluded from nutritional studies, coexisting structural anomalies of the gastro-intestinal tract, underlying syndromes and genetic anomalies can further contribute to the poor nutritional status of this group (10).

Poor nutrition can have a profound influence on preoperative morbidity and lead to higher postoperative complications. Caloric deprivation causes endocrine, epithelial and lymphoid dysfunction that can induce a generalized immunodeficient state, with increased risk of severe infections and risk of death (11,12). In addition to the immediate impact on mortality, preoperative infections can create a negative feedback loop that exacerbates nutritional challenges, delays surgical intervention, and ultimately promotes additional infections. When surgery is undertaken in an undernourished state, higher complications are seen, from postoperative infections and poor wound healing that ultimately contribute to prolonged mechanical ventilation support and longer ICU and hospital length of stay (7).

Determinants of nutritional status

Children achieve good nutritional health when caloric delivery matches their basal consumption and growth requirements. Poor somatic growth in children with CHD stems from an imbalance of metabolic supply and demand due to insufficient caloric intake, inefficient utilization and/or absorption, increased energy requirements, genetic growth potential, or a combination thereof.

Poor intake

Poor enteral feeding is a root cause of growth restriction for many children with CHD. Rarely, inadequate intake is a consequence of structural anomalies of the gastro-intestinal tract (10). Esophageal or anal atresia, or tracheoesophageal fistula can be seen with CHD in children with VACTERL and CHARGE syndrome, and patients with trisomy 21 and aneuploidy may have duodenal atresia; a strong association also exists between cardiac heterotaxy/isomerism and intestinal rotational anomalies. Prolonged gaps in enteral feeds during surgical intervention and residual gastrointestinal dysfunction associated with these anomalies can contribute to poor intake.

Feeding difficulties are common even in the absence of gastrointestinal congenital malformations. In a cross-sectional survey study, nearly 50% of parents had significant anxiety emanating from their child's feeding refusal or poor appetite (13). One third of families reported the need for longer feeding times and more frequent feeds. Although these challenges existed across the pediatric age range,

neonates and infants were at particularly high risk due to increased difficulty with the oropharyngeal coordination required for proper oral feeding (14). Also, neonatal hypotonia has been frequently implicated as an important contributor to poor feeding efficiency. Limperopoulos *et al.* found that over one quarter of infants requiring surgery demonstrated a weak suck, and 7% had no suck at all (15). Consistent with other studies, the impaired neurology was strongly associated with cyanosis, pulmonary hypertension, and complex forms of CHD (16,17). Weak oropharyngeal coordination can also be seen in children with pulmonary congestion and significant tachypnea and work of breathing.

Insufficient enteral delivery may also arise from feeding intolerance secondary to gastroesophageal reflux (GERD), gastritis, delayed gastric emptying and poor motility or malabsorption secondary to gut ischemia or oedema. GERD is particularly common in children with CHD (18). Symptoms of abdominal distention or tenderness, arching, retching, recurrent emesis, and hematochezia following feeds can result in a decrease of voluntary feeding volume or withholding of feeds by caregivers. Even when feeding volumes remain stable, significant reduction in intake may arise from volume loss resulting from vomiting. The severity of recurrent emesis with intake was demonstrated in a study in which parents of children with CHD and pulmonary congestion were tasked to keep a structured diary of intake and losses. Their records showed that every child vomited several times during the day, expelling more than 10% of ingested feeds (19). Symptom relief may be achieved through medical management which includes strict fluid restriction and diuretic use that aids in decreasing total volume body water and pulmonary congestion, to alleviate work of breathing (20). Meticulous care is often needed to balance and optimize volume and caloric delivery.

Feeding difficulties may persist, and occasionally be aggravated, following CHD surgery. In one observational study, nearly half postoperative neonates were unable to transition to oral feeds following surgery, and required extended gavage feeds (21). When examined by occupational therapists, the inability to feed orally was attributed to an absent suck or poor coordination of suck and swallowing, recurrent aspiration, or laryngeal penetration (22,23). These feeding difficulties were directly associated with surgical complexity, residual neurologic impairment, prolonged intubation, GERD, and vocal cord paralysis. Vocal cord dysfunction is most commonly seen following surgical repair of the aortic arch which may arise from injury to the left recurrent laryngeal nerve as it courses below the aortic arch; bilateral recurrent laryngeal nerve injury can also occur during thymectomy. Many consider the Norwood procedure to be the highest risk surgery for vocal cord injury, but any surgery that includes aortic arch reconstruction may be similarly affected (24). Postoperative feeding difficulties tend to improve over time for many patients, but studies examining the natural history are scarce. In a small observational study, residual symptoms were reported in 1 in 5 children at 2 year follow-up, more commonly seen in those with single ventricle heart disease, neurologic injury or early feeding difficulties (25).

Increased energy expenditure

Increased energy expenditure plays an important role in the ability for children with CHD to meet their caloric requirements. Recent studies have demonstrated a 28–35% increase in total daily energy expenditure in this population (19). Although often attributed to increased tachycardia and work of breathing seen in those with pulmonary congestion, the cause of increased metabolic demand is unclear as studies have failed to show a consistent association with CHF symptoms (26). Alternate explanations for increased consumption include higher myocardial muscle mass and a heightened catecholaminergic state (27). Regardless of the underlying aetiology, poor growth results from the diversion of calories to support the basal metabolic rate (19,28).

Human milk, formula alternatives and caloric density

Human milk is preferred for all neonates including those with CHD. Despite limited supporting data in this population, it is generally believed that human milk is better tolerated, promotes intake and growth, and may be associated with fewer postoperative complications (29). If breast feeding is not possible, delivery of human milk by bottle or feeding tube is considered the best alternative. In an effort to promote human milk ingestion, milk banks have also been established in many jurisdictions that facilitate the provision of donor breast milk in the event that maternal milk is not possible or insufficient. Standard infant formulas are also available and are generally well tolerated. Partially or extensively hydrolyzed formulas may be needed in the setting of feeding intolerance that is commonly experienced by infants with more complex CHD.

Fortification of feeds is an early response to caloric deprivation and growth impairment, particularly if fluids are restricted. When human milk is available, the caloric

density of expressed milk/donor milk can be increased by adding a standard infant formula. When manipulating feed fortification and/or concentration, it is important to monitor both macronutrient and micronutrient intake; the consideration of additional modules of fat or carbohydrate may also be indicated to achieve optimal nutrition support. Concentration of infant formula (above 0.67 kcal/mL) is possible by adding less water to powder or liquid concentrate, through using standard mixing ratios. Feed intolerance may be influenced by the caloric density of feeds. Transitioning to hydrolyzed or elemental formula may improve feed tolerance. Similar results can be achieved by offering toddlers and older children energy rich foods, such as purees prepared with added fat (butter or table cream). Care must always be taken to ensure adequate macro and micronutrient intake.

Enteral feeding tubes

Many infants struggle to meet their nutrition requirements with oral feeds alone and require use of nasogastric tubes (NG) (30). NG tubes can be used to supplement or substitute oral feeds when oral feeding is contraindicated, and higher caloric feeds can be achieved through this route. When replacing oral feeds, this established route can allow for either bolus or continuous feeding delivery, either method is effective in providing supplemental nutrition. Moreover, increased delivery is coupled with a reduction in energy expenditure associated with feeding in children with symptomatic CHF and can result in dramatic improvement in weight velocity. Extended support can be safely and reliably provided with insertion of a gastrostomy tube (31).

Perioperative nutrition

Feeding children early following cardiac surgery has been widely accepted but poses a number of unique challenges. *Table 1* summarizes strategies for perioperative nutrition support as recommended by the American Society of Parenteral and Enteral Nutrition (ASPEN), and the European Society of Pediatric and Neonatal Intensive Care (ESPNIC) (32,33). Initiation of enteral nutrition (EN) within 48 hours of admission has consistently been associated with improved critical care outcomes (34-36). Early initiation of EN helps reduce muscle wasting, promote wound healing, and stimulate splanchnic circulation to avoid gastro-intestinal dysfunction that can occur even after short periods of starvation. In the absence of feeds, increase in GI permeability can lead to bacterial translocation, localized and systemic infection, and in turn, can intensify the postoperative systemic inflammatory response (37). Although the evidence for critically ill children is limited to observational studies, provision of earlier EN delivery translated to less respiratory ventilation and neuromuscular relaxation, lower vasoactive support, and improved survival (38-41). Survival benefit has been seen even with the delivery of a portion (25%) of prescribed calories, with better outcomes in a dose-related response (41). Younger patients with a lower severity of illness scores were most likely to benefit from early EN (41,42). In light of this limited evidence, early EN has been recommended by ASPEN, ESPEN, and ESPNIC (32,33).

Despite evidence demonstrating that feeding critically ill children is generally well tolerated, delays in EN delivery are common (43). A European survey of 59 pediatric intensive care units reported that only 30% of the units routinely initiated feeds within 12–24 hours after surgery (44). Feeding initiation rose to 60% when a threshold of 48-hours from intensive care admission was used (42). Perceived medical instability, use of vasoactive agents or neuromuscular agents were often evoked as an explanation (36,42). Children undergoing additional surgical procedures, on extra-corporal membrane oxygenation (ECMO), requiring delayed sternal closure, or deemed medically unstable are most commonly affected. While withholding feeds stems from a concern that EN could induce splanchnic ischemia in a vulnerable patient, practice variability exists due to a lack of universal criteria or consensus for who is safe to feed. This variability is highlighted in the absence of clear thresholds for vasoactive support under which EN initiation is considered safe. As a result, a large retrospective study found that EN was often held in patients for fears of poor mesenteric perfusion at similar vasoactive support levels as others who received EN; no difference in GI complications were seen between patients who were fed and those who were not (45). Safety for early EN was also recently demonstrated in a range of vasoactive support levels in adult critical care trials (46). The frequency of early EN initiation can be improved through a reduction in practice variability with the implementation of institutional-specific protocols or feeding guidelines (47). Nevertheless, in a recent survey, only one third of pediatric intensive care units had an established feeding algorithm (42).

Caloric targets

Somatic growth during critical illness is arrested, as metabolic

Table 1 Summary of perioperative nutrition support goals and clinical management critically ill children

Nutrition feature	Goals of care	Management
Nutrition support modality		
Enteral nutrition (EN)	Initiate EN as soon as patient status deemed safe	• No clear consensus for minimal hemodynamic support threshold
		• Consideration to post-operative biochemical profile and dosage of vasopressor/inotropic support
	Aim to initiate EN within 24–48 hours post ICU admission (ASPEN, ESPNIC)	• Infants: Human milk or donor milk (whenever possible)
		• Consider EN with higher caloric content
		• When fluid restricted (dependent on preoperative EN tolerance)
	Delivery of full prescription	Fortify human/donor milk, concentrate formula feeds stepwise
		• Increase 0.1 kcal/mL per day as tolerated
	Limit feeding interruptions	Optimize through use of a nutrition protocol/algorithm to minimize NPO times for ICU/non-ICU based procedures
	Standardized response to intolerance	• Fortify feeds with partially hydrolyzed, extensively hydrolyzed, or elemental formulas
		• Consider change from bolus to continuous feeds for severe aspiration risk, frequent NPO
		• Change to post-pyloric feeding tube
		• Use of a nutrition protocol/algorithm to guide detection and management of feeding intolerance
Parenteral nutrition (PN)	ASPEN	To determine supplemental PN initiation, conduct daily monitoring of EN prescribed versus delivered, combined with evaluation of preoperative malnutrition
	• Do not initiate within 24-hour post-surgery	Requires institutional pharmacy to provide micronutrients for infusing
	• Delay PN one week for patients with normal baseline nutrition state and low risk of not	Perform nutritional assessment to determine malnutrition risk
	• Meeting nutrition targets	Low volumes not described; aim to achieve two thirds of prescribed energy requirements per day by end of first week in ICU
	• PN supplementation for patients who are severely malnourished and receiving inadequate EN volumes, or patients unable to receive any EN during first week of ICU admission	
	ESPNIC	
	• For critically ill term neonates and children: consider withholding PN for up to 1 week, independent of nutritional status; provide micronutrients	

Table 1 (*continued*)

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Nutrition feature	Goals of care	Management
	• Supplement for children unable toreceive any EN during first week of admission; or children severely malnourished or at risk for nutritional depletion • Supplement if unable to advance EN past low volumes	
Energy and protein requirements		
Energy expenditure	ASPEN, ESPNIC (use indirect calorimetry to determine REE to guide energy delivery) • Avoid over and underfeeding Predicted equations ASPEN Use WHO equation, without additional factors ESPNIC Use Schofield equation or WHO equation, without additional factors	Measure REE frequently throughout the course of illness to customize energy delivery prescription Aim to provide 35–55 kcals/kg/d in the immediate post–operative period (0–3 days)
Protein	ASPEN • 0–2 years: 2–3 g/kg/d • RCT 4.0 g/kg/d in infants post CPB ESPNIC • Minimum EN intake 1.5 g/kg/d	• Provide a minimum 1.5 g/kg/d protein • For infants and young children advance to goals as per ASPEN recommendations insufficient evidence to recommend increased protein delivery in acute phase

ASPEN, American Society of Parenteral and Enteral Nutrition; CPB, cardiopulmonary bypass; ESPNIC, European Society of Pediatric and Neonatal Intensive Care; RCT, randomized control trial; REE, resting energy expenditure.

substrates are diverted to support systemic inflammation and tissue repair (48). Optimal nutrition support has therefore been aimed to avoid a catabolic state by meeting total energy expenditure and protein demands (49). Nevertheless, pediatric critical care nutritional practices have been based on limited data, largely observational in nature (50). Providing adequate nutrition during acute illness is essential as overnutrition may increase the risk of infections and lead to prolonged ventilation due to increased carbon dioxide production (42). Alternatively, underfeeding, worsens whole body catabolism, induces a negative nitrogen balance, attenuates tissue repair, and delays recovery. Clinically, cumulative nutrient deficits have also been associated with increased infections, multi-organ failure, increased length of stay and mortality (42).

Critical illness has historically been considered a hypermetabolic state due to physiologic stress and high systemic inflammation. Energy expenditure was calculated from predictive equations based on anthropometric measurements and derived from healthy pediatric populations, with added corrective factors to account for physiologic stress, temperature, and activity. Several equations have been repurposed to determine the caloric requirements for critically ill children, including the Altman-Dittmer, Harris-Benedict, Schofield, Talbot tables, White, World Health Organization (WHO), and allometric scaling (51,52). Nevertheless, the role of predictive equations has been challenged with emergence of indirect calorimetry for nutritional sciences research and clinical care. Unlike the child with chronic CHD, REE in the immediate postoperative period is considerably reduced. Resting energy expenditure, caloric consumption

during rest that does not account for somatic growth, in the immediate postoperative period have consistently shown lower than expected metabolic demands, ranging between 35 to 65 kcals/kg/d (40–60% predicted) (53-56). Energy expenditure did not vary significantly by age, underlying cardiac diagnosis, or surgical intervention, but was associated with the height of systemic inflammatory response (42,55,57). Although these studies involved small sample sizes, diverse measurement equipment and different sampling schedule, these findings are consistent with similar adult and pediatric critical care studies (56).

In view of the balance of evidence, ASPEN, and ESPNIC, guidelines for pediatric critically ill patients recommended indirect calorimetry as the gold standard for determination of energy expenditure to avoid over or underfeeding, whenever possible (32,33). Unfortunately, availability of indirect calorimetry is limited and generally not feasible due to its high costs, dedicated equipment, and specialized training required. In fact, an international survey revealed that fewer than 20% of all pediatric intensive care units had access to this technology (58). The use of predictive equations without application of correction factors was therefore endorsed as then next best alternative. There is no agreement to the best performing predictive equation for critically ill children with CHD; use of the Schofield equation or Talbot tables were recommended in a systematic review, while others have shown the WHO equation to perform best (51,58).

Meeting caloric targets

Achieving adequate EN delivery in critically ill children is often challenging with a significant discrepancy existing between the nutrition treatment prescribed and delivered. In a large cohort study, only one third of prescribed calories and approximately 40% of prescribed protein were provided to the patient (42). Fluid restriction, GI dysmotility, and feeding interruptions and subjective gastric aspirate volumes are often blamed for this discrepancy (52). Total fluid intake is regularly limited to avoid postoperative oedema and pulmonary congestion associated with systemic inflammation and to facilitate early extubation. Feeds are frequently interrupted for airway procedures (intubation, extubation), transports, and interventions. Of concern, children under 6 months of age are the most vulnerable and also most likely to be affected (59). The implementation of nutrition guidelines by a multidisciplinary team (including dietitians, nurses, and physicians) remains the best strategy to enhance caloric delivery and optimize clinical outcomes (60). Notably, ongoing vigilance to prescribed guidelines is required as an observational study found that the majority (~60%) of all interruptions were considered avoidable—feeds were held for prolonged periods during intubation and extubation, and bedside providers had an exceedingly low threshold to diagnose feeding intolerance (34).

Re-evaluating caloric targets

As previously discussed, the association between underfeeding and poor clinical outcomes has been extensively reported in the pediatric critical care literature. Recently, there is a growing appreciation of the potential role systemic bias may play in overestimating its impact. The selection bias inherent to all pediatric observational studies may erroneously link feeding practice to outcome, when in reality it merely behaves as a confounder. Patients who are well are more likely to be fed early, EN is advanced more quickly, and they have fewer complications; these patients have better clinical outcomes because they are fundamentally healthier not because they receive more EN. The influence of bias on overestimating benefits has also been recognized in adult randomized studies (61).

Although untested in the pediatric population, this paradigm has been challenged by a number of important randomized studies. In the earlier PERMIT study, critically ill adults with restricted EN to 40–60% of required daily calories were compared to standard of care (70–100% of requirements) (62). Permissive underfeeding was associated with similar 90-day mortality, infection rates, and intervals of care. A separate study (INTACT) of critically ill adults with acute lung injury was stopped prematurely because improved survival was observed in patients who received fewer calories (standard of care) compared to those provided at least 75% of requirements (63). Arguably, the combination of these studies suggest that underfeeding may not be beneficial for all patients but does not portend harm in this group. These differences are reflected with divergent recommendations for underfeeding by the European society guidelines but not the North American (37,64). In contrast, the benefits of increased caloric delivery were questioned in a series of randomized studies by Peake and colleagues. This study group first showed that hypercaloric feeds (1.5 kcal/mL) could safely deliver nearly 50% more calories to critically ill adults without an increased incidence of intolerance (65). In a larger follow-up study, hypercaloric

feeds were not associated with a reduction in 90-day survival, or any other the predetermined secondary (66). Although no benefit was found with higher caloric delivery, with usual protein dosing, the potential impact in pediatrics remains unknown.

The consensus from the recent ESPNIC guidelines did not provide a lower boundary for nutrition support but concluded that it should not exceed resting energy expenditure (32).

Protein delivery

The acute phase response to critical illness is a complex series of metabolic alterations that result in protein catabolism (67). The intensity of the inflammatory response directly influences lean body mass breakdown, which may disproportionately affect children with limited nutrient reserves. Targeting protein supplementation that matches the metabolic demand is considered essential during this acute inflammation, and a current focus of critical care nutrition research.

Little is known about protein needs for children recovering from cardiovascular surgery. In one study, higher protein delivery was associated with increased likelihood of achieving a positive protein balance when protein delivery matched catabolism (68). Anabolism was achieved over a wide range of protein intakes (median 1.1 g/kg/day) with a caloric delivery of 55–60 kcal/kg/day. However when protein requirements were evaluated using the nitrogen balance technique in a separate study of infants following cardiopulmonary, a positive nitrogen balance was only achieved on postoperative day 3 with delivery of approximately 4 g/kg/day (69). In the absence of robust cardiac specific data, direction is taken from the pediatric intensive care literature that shows that a positive protein balance was possible with a provision of 1.5 g/kg/d of protein, but varies from 1.1–2.2 g/kg/d in observations trials to 2.8–4.7 g/kg/d in randomized control studies (56,70). It is important to note that higher protein delivery has been independently associated with lower mortality (71).

Given the scarcity of data, bedside practice is often guided by the age specific protein requirements delineated in the recent ASPEN recommendations. Suggestions for protein delivery are 2–3, 1.5–2, and 1.5 g/kg/d for the 0–2, 2–13, and 13–18 years, respectively (33). This is significantly greater than the dietary reference intakes (DRI) for age, which range from 1.5 g/kg/d in infants, to 0.8 g/kg/d in teens 14–18. In contrast, during critical illness for neonates more recent ESPNIC recommendations indicate that there is insufficient evidence to providing protein intakes at 1.5 g/kg/d or higher, as clinical benefits have not been shown (32).

The current debate surrounding protein supplementation has been best portrayed in a growing body of conflicting adult studies. Whereas several studies have shown an association between higher protein delivery and reduced mortality, fewer infections, and faster recovery (72-74), others have found no clinical advantage (75,76). Of concern, a recent publication of non-septic critically ill patients, showed that increased protein intake early in the critical care course was associated with higher 6-month mortality (77). These studies may not translate directly to pediatrics but provide an important framework from which to base future investigations in critically ill children.

Parenteral nutrition

Provision of PN for critically ill children has been a topic of immense focus and debate. Proponents believe that PN delivery will help improve outcomes in those with pre-existing malnutrition. Nevertheless, in the only randomized study on this subject, PEPaNIC investigators reported worse outcomes in critically ill children for whom PN was initiated within 24 hours of admission compared to those receiving PN only after 7 days (78). Earlier PN was associated with higher rates of nosocomial infections and intervals of care (mechanical ventilation, and duration of intensive care and hospital admission). A secondary analysis of undernourished children showed a similar reduction only in nosocomial infections and duration of intensive care admission (79). Similarly, a subgroup analysis of neonates, 35% of these studied were post cardiac surgery, found reduced nosocomial infections, shortened mechanical duration, and ICU stay (80). Long-term follow-up has shown possible improved behaviour and cognition in the late PN group (81). Despite several limitations and wide variability in PN use across institutions, the results from this study have informed recent ASPEN, ESPEN, and ESPNIC guidelines on this subject (32,33,82).

Postoperative catch-up growth

Improvement in weight attainment and growth velocity commences nearly immediately following cardiac surgery and reaches near normal values by 1 year as a better balance of energy supply and demand is achieved (83-85). Normalization of cardiac physiology results in better

nutritional intake and near immediate decline in energy requirements (83,86). Unfortunately, some patients continue to struggle after surgery with undernourishment. Risk factors of persistent undernourishment include important residual cardiac lesions, severe preoperative malnutrition, low genetic growth potential (genetic anomalies/syndromes, low birth weight, and lower parental height) (83,84). Nevertheless, as demonstrated by longitudinal data from the Single Ventricle Reconstruction trial, improved weight gain does not always translate to better linear growth (87). Weight-for-age z-scores improved dramatically following the bidirectional cavopulmonary shunt (Glenn operation), but poor height attainment led to a persistently high weight-to-height ratio. Although some data suggests that earlier cardiac repair would result in earlier weight correction, this is refuted by others (88).

Special considerations

Chylothorax

Chylothorax is the accumulation of chyle in the pleural cavities and is a common complication of cardiovascular surgery, occurring in 2.8–5% of infants (89). Chylous fluid leaks from the lymphatic system (usually an injured thoracic duct) and is rich in proteins, fats (including fat soluble vitamins), and immunoglobulins (90). In light of its constituents, high output can lead to fluid imbalance, electrolyte dysregulation, and complications from hypoproteinemia (coagulopathy, protein-energy malnutrition, poor wound healing and impaired immune function) (91). Treatment with a minimal/low fat diet, which continues for approximately 6 weeks post chest tube removal, is used as first-line therapy to promote recovery by minimizing lipid absorption by mesenteric lymphatics and reducing flow through the thoracic duct. Reduction of thoracic duct flow can also be attempted with octreotide, steroids, or extended periods of withholding feeds. Refractory cases may require catheter occlusion or surgical ligation.

Infant treatment of chylothorax requires substitution of cow-milk based infant formulas that are rich in long chain triglycerides with a high medium chain triglyceride formula that is absorbed directly into portal venous system. Fat reduced human milk (by centrifuge) has been shown to be equally effective as medium chain triglyceride formula at reducing chylous drainage but was associated with poor growth in a prospective randomized study formula (89,92). Growth parameters improved when fat-depleted breast milk was fortified with additional protein (93). Studies evaluating the nutrient composition of defatted milk have found lower concentrations of some constituents, while no difference was found in other investigations (94,95). Further studies examining nutrient composition (including immunoglobulins) should be conducted prior to widespread adoption. Attention to product composition for children with a cow's milk protein allergy is necessary when determining an appropriate formula substitute for feeding or fortification of human milk. Older children who adhere to a low or minimal fat restricted diet require a larger quantity of non-fat dietary food sources, and more frequent meals to achieve adequate energy intake required for growth, with understanding that weight gain during this period can be challenging. Monitoring and possible supplementation of essential fatty acid and fat-soluble vitamins is required for all patients following a high medium-chain and low long-chain triglyceride diet.

Necrotising enterocolitis

Feeding practices of critically ill neonates is strongly influenced by fears of developing necrotizing enterocolitis (NEC), a condition characterized by intestinal inflammation, disruption of mucosal integrity, epithelial necrosis, and bacterial translocation. Although similar in frequency (3.3–6.8%) and symptomatology, unlike premature neonates, NEC in term infants with CHD has not been associated with EN but is believed to be a consequence of intestinal hypoperfusion and splanchnic ischemia (96-98). Infants with single ventricle physiology (99) (particularly HLHS), systemic outflow tract obstruction, and diastolic run-off lesions are at highest risk (100-102). Nevertheless, while studies have repeatedly shown no association between EN and NEC in neonates with CHD (99,103), significant variability in feeding practices exist across institutions, particularly during the perioperative period. Analysis of the Pediatric Cardiac Critical Care Consortium, a quality improvement registry, demonstrated that only half of the neonates (range 29-79%) from participating institutions were fed prior to cardiac surgery (104). Preoperative feeding was not associated with a higher incidence of NEC, and may even improve postoperative recovery by lowering the severity of the systemic inflammatory response (93,105). Initiating and advancing postoperative feeds in the vulnerable population is often met with similar hesitancy. Although there is no consensus to guide which neonates are

safe from intestinal ischemia and are ready to accept feeds, use of standardized feeding protocols have been shown to safely advance feeds without increasing the frequency of NEC even in the highest risk groups (94,95). Use of human milk or donor human milk has been encouraged due to its favourable impact on the intestinal microbiome, promotion of gastric motility, and reduction in intestinal inflammation. There is limited data available to support reduction in NEC in this population (106).

Treatment of neonates diagnosed with NEC is informed primarily by the premature population and includes cessation of EN, initiation of parenteral nutrition (PN) support, antibiotic coverage of enteric pathogen, and surgical consultation (107). Fluid resuscitation, administration of blood products, and inotropic or vasopressor support may be necessary depending on the clinical severity. Bowel perforation may prompt surgical intervention. Although EN is usually held between 7–14 days, the impact on patient enteral nutrition is significantly longer as feeds are escalated slowly after re-introduction.

Protein losing enteropathy (PLE)

PLE is a rare condition of hypoproteinemia caused by gastrointestinal mucosal protein loss (108). PLE is most commonly a complication of a failing Fontan circulation or right sided CHD, with a prevalence between 3.7% and 24% (109). It is believed that mesenteric congestion and elevated vascular resistance damages the mucosal epithelium, increases gut permeability, and enlarges intestinal lymphatics. Affected children present with gastrointestinal symptoms of chronic diarrhea and feeding intolerance, and systemic manifestations of hypoalbuminemia, including edema, ascites, and/or pericardial effusions (108,110). PLE is confirmed by detecting alpha-1-antitrypsin in the stool and an increased in alpha-1-antitrypsin clearance (110).

PLE-associated protein malnutrition is common but dietary interventions vary widely. A high energy, protein enriched diet has been recommended with a protein intake of 2.0–3.0 g/kg/d to support a positive nitrogen balance for anabolism and growth (111). Nutrition support through a NG tube may be required if oral intake of nutrients is inadequate and a therapeutic formula (elemental or semi-elemental) with an altered fat profile should be considered in the presence of fat malabsorption. Diets low in long-chain triglycerides and high medium-chain triglycerides have also been indicated in children with an associated primary or secondary intestinal lymphangiectasia (112); the direct absorption of medium chain triglycerides into the portal system is thought to decrease lymphatic pressure and reduce protein leakage. If nutritional rehabilitation cannot be met orally or through a tube feed, the use of parenteral nutrition therapy is necessary.

Conclusions

In children with CHD the provision of adequate enteral nutrition during their course of illness is met with significant challenges. Caloric insufficiency is common and results from poor intake, poor absorption, feeding intolerance, excessive energy consumption and interruptions in delivery. Supplemental calories can be provided by increasing caloric density, introducing tube feedings, and adjuvant therapies. Despite its importance, practice is guided predominantly by retrospective cohort studies as well-designed prospective trials are lacking. Perioperative nutrition management focuses on early initiation and optimizing enteral feeds. Based on adult and preliminary pediatric studies, protein delivery is emerging as the principal nutritional element to supplement but additional pediatric-specific studies are required. A continual assessment of nutritional status (risk of malnutrition), is necessary to determine suitable therapies that will aid in a child's optimal nourishment. As research investigating nutrition therapies continues to advance, it is evident that large scale prospective studies are needed to improve clinical outcomes.

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