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The varied effects of protein intake during infancy, childhood, and adolescence: Associations with growth metrics, body composition, and pubertal development timelines

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Abstract

Introduction: Protein plays a crucial role in the growth and development of children, impacting various physiological functions and long-term health outcomes. Understanding the optimal protein intake during the dynamic stages of childhood is essential due to its significant implications for metabolic and hormonal pathways, as well as its association with childhood obesity and malnutrition.

Review Methods: The review involved a systematic examination of existing literature, focusing on studies that explored the relationship between protein intake and children's growth, development, and health outcomes. Databases such as PubMed, Scopus, and Web of Science were searched using specific keywords, with the selection criteria emphasizing peer-reviewed articles, clinical trials, and observational studies in English, excluding non-human studies.

Results: The analysis indicates that protein intake has a pivotal influence on children's growth patterns, body composition, and metabolic health. Findings suggest that both excessive and insufficient protein consumption can have adverse effects, highlighting the importance of balanced protein intake. The review also points out the critical impact of maternal dietary quality on infant growth and underscores the significance of protein source and quantity during complementary feeding in determining health outcomes.

Conclusions: Optimal protein intake is vital for supporting children's growth and long-term health, necessitating tailored dietary strategies that accommodate the changing needs of growing children. Healthcare professionals and caregivers must be informed about the nuanced effects of protein to maintain normal growth and development while mitigating risks like obesity. Future dietary guidelines should consider these findings to ensure balanced nutrition for children at various developmental stages.

Keywords: Protein intake; Childhood growth; Body composition; Puberty; Childhood obesity; Malnutrition

1. Introduction

"Understanding the nutritional needs of children at various stages of their development is crucial for optimizing their health and growth. Protein, a vital macronutrient, plays a key role in numerous bodily functions, including tissue repair, enzyme and hormone production, and immune system support. The requirements for protein intake vary substantially

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across the different phases of childhood, affecting not only physical growth but also metabolic and hormonal functions, which are essential for overall health and developmental outcomes (1,2).

The importance of protein in children's diets is well-established, yet the impact of its varying intake levels—whether excessive, insufficient, or balanced—requires thorough exploration. The potential long-term effects of early dietary habits underscore the need to ascertain the optimal protein intake during infancy, childhood, and adolescence. This necessity is amplified by evolving dietary patterns, lifestyle modifications, and the rising prevalence of childhood obesity and malnutrition worldwide (3,4,5).

Accordingly, this paper aims to review existing research on the influence of protein intake during different growth stages, providing a detailed synthesis of the evidence. It aims to elucidate the relationship between protein consumption and its effects on growth metrics, body composition, pubertal development, and long-term health outcomes."

Objectives

This review aims to clarify the complex role of protein in pediatric nutrition, synthesizing research findings to formulate dietary recommendations. It focuses on analyzing collective evidence to highlight the necessity of personalized nutritional strategies that meet the dynamic requirements of children's growth, thereby providing a robust foundation for their healthful development.

2. Methods

The methodology was designed for an exhaustive and methodical review of the existing literature to accurately delineate the role of protein in the growth and development of children.

A systematic search was conducted across PubMed, Scopus, Web of Science, and Google Scholar, utilizing keywords such as “protein intake,” “childhood growth,” and “adolescent development” to retrieve pertinent studies. The inclusion criteria were geared towards studies that correlate protein intake with pediatric growth or developmental outcomes, focusing on peer-reviewed articles, clinical trials, and observational studies in English.

The study selection involved screening titles and abstracts for relevance, followed by a comprehensive review of the full texts to confirm their adherence to the inclusion criteria, specifically excluding non-human studies, reviews, or unrelated topics. This step was critical in refining the selected studies to those expressly examining the impacts of protein intake on the growth of children and adolescents.

Data extraction was meticulous, covering publication details, study designs, participant demographics, specifics of protein intake, and key growth and development outcomes. This information was synthesized to elucidate the connection between dietary protein and pediatric growth metrics, ensuring an in-depth analysis of the compiled literature.

3. Results

The table summarizes the main findings of the studies by the age groups of the subjects.

Table 1 The impact of protein intake on children's growth and development in 20 studies

Study Reference	Age Group Studied	Key Findings
Binder et al., 2023 (6)	Infants (indirectly through mothers)	Maternal diet affects milk protein, impacting infant growth and body composition.
Hemmati & Ghassemzadeh, 2023 (7)	Very low birth weight preterm infants	Protein supplementation shows significant improvements in growth metrics.
Gunnarsdottir & Thorsdottir, 2003 (8)	Infants at 9–12 months, observed until 6 years	High protein intake at 9–12 months is linked to higher BMI at 6 years, suggesting the need to monitor protein intake.

Hoppe et al., 2004 (9)	9-month-old children	Protein intake at 9 months is linked to body size but not body fat at 10 years, emphasizing its impact on growth.
Braun et al., 2016 (10)	1-year-old children	Higher protein intake at 1 year is linked to greater height, weight, and BMI up to 9 years of age.
Koyama et al., 2023 (11)	Children under 3 years	Insufficient weight gain in early life is correlated with short stature later, emphasizing proper early protein intake.
van Vught et al., 2009 (12)	Early childhood	Protein intake is associated with linear growth and changes in body composition, including increases in FMI and FFMI.
van Vught et al., 2009 (13)	Children	Dietary protein affects body composition, with special roles of arginine and lysine in growth.
Hoppe et al., 2004 (14)	Early childhood	Intake of animal protein, especially milk, is positively associated with growth markers like IGF-I concentrations and height.
Kokkou et al., 2023 (15)	Children	Plant-derived protein intake is significantly associated with healthier weight status.
Switkowski et al., 2019 (16)	Mid-childhood and early adolescence	Early protein intake influences body composition, impacting BMI, lean mass, and IGF-I levels, particularly among boys.
Günther et al., 2010 (17)	Children aged 5-6 years	Higher total and animal protein intake is associated with earlier puberty onset, while higher vegetable protein intake was linked to later puberty markers.
Xiong et al., 2023 (18)	Children and adolescents (6-18 yrs)	High protein intake is linked to a reduced linear growth and increased risk of stunting.
Jen et al., 2019 (19)	Infancy up to age 10 years	Higher protein consumption from animal sources was persistently associated with adiposity up to age 10.
Stephens et al., 2009 (20)	Extremely low birth weight infants	Higher first-week protein and energy intakes are linked to better mental development and reduced growth restrictions.
Stokes A et al, 2021. (21)	Infants (from birth to 2 years)	Higher intakes of total and animal protein during infancy are associated with higher BMI in childhood and adolescence. The review highlights a significant positive association between total protein intake and BMI, particularly from animal sources, but not plant protein.
Bell KA et al, 2017 (22)	Infants (from birth to 7 months)	Formula-fed infants show more rapid weight and BMI gain compared to predominantly breastfed infants, with the difference primarily attributed to increased lean mass rather than fat mass. There is no significant difference in linear growth between the groups.
Tang M. 2018 (23)	Infants (from birth to 2 years)	Indicates that infant formulas, which are primarily dairy-based, tend to have higher protein content compared to human breast milk. This higher protein content is associated with greater weight gain in infants and predispose to overweight. Meat protein is suggested to promote linear growth without necessarily increasing the risk of overweight.
Ferré N, et al 2021 (24)	Infants (during the second year of life)- Systemic review	The findings suggest a potential link between higher protein intake during this period and increased fat mass in early childhood. It suggests that while adequate protein is crucial for healthy growth, excessive intake can lead to unintended health consequences, possibly affecting linear growth in a context-dependent manner. The focus is on optimizing protein consumption to support linear growth without contributing to excessive body fat gain, emphasizing the need for nutritional strategies that ensure balanced growth in children.

Kittisakmontri K et al 2022. (25)	A multicenter, prospective, cohort study Infants first year	The study focuses on the quantity and source of protein intake during complementary feeding and its effects on infant growth. It particularly examines how different protein sources, such as dairy, may influence weight-related growth outcomes. The findings suggest that while protein intake is crucial for growth, the source of protein plays a significant role in how it affects weight gain and possibly linear growth, with a notable impact observed from dairy proteins.

Twenty research papers were meticulously selected, screened, and analyzed. The results unveiled significant insights:

- **Maternal Diet Influence:** The nutritional quality of a mother's diet significantly impacts the protein content of her milk, influencing her infant's growth patterns and body composition. This underscores the critical importance of maternal nutrition during breastfeeding.
- **Protein Supplementation in Preterm Infants**: In very low birth weight preterm infants, targeted protein supplementation has been demonstrated to significantly enhance growth metrics, highlighting the importance of customized nutritional interventions for this sensitive group.
- **Impact of Protein Source on Infant Growth**: The protein source, notably dairy during complementary feeding, plays an essential role in affecting weight-related growth outcomes, indicating that both the quantity and the source of protein are crucial in shaping growth and development.
- **Second-Year Protein Intake and Childhood Fat Mass:** Increased protein intake during the second year of life may contribute to a higher fat mass in childhood, though the implications for BMI and adiposity are less conclusive.
- **Protein Intake During Infancy and Later Obesity Risk**: Higher protein intake during infancy, particularly from dairy sources, is correlated with an elevated risk of higher BMI and obesity in subsequent childhood, signaling the possible risks of high-protein diets in early years. High protein consumption between 9–12 months of age is associated with an increased BMI by age 6, indicating that excessive protein intake during this pivotal growth period may predispose children to later overweight or obesity.
- **Long-term Adiposity and Protein Intake**: Early-life protein intake, especially from animal sources, is linked to a sustained increase in adiposity until the age of 10, emphasizing the potential enduring effects of early dietary protein on body fat composition.

These findings collectively emphasize the critical role of protein intake and its sources during early life in influencing growth patterns, body composition, and the potential risk of obesity in children.

4. Discussion

Protein intake in children is closely linked to IGF-1 secretion and weight gain, primarily through its role in enhancing the liver's IGF-1 production, essential for growth, cell division, muscle development, and tissue repair. Adequate protein consumption also influences growth hormone activity, which collaboratively boosts IGF-1 levels, facilitating bone and muscle growth and metabolic regulation. However, excessive protein, particularly from animal sources, may contribute to unwanted weight gain and body fat accumulation, driven by high caloric content and the potential for increased IGF-1 and insulin levels, which can promote fat cell formation and raise the risk of obesity. (figure 1) These data emphasize the need for balanced protein intake in line with overall dietary needs and physical activity levels. (26-30)

It appears that the nutritional quality of a mother's diet significantly impacts the protein content in her milk, which in turn influences her infant's growth patterns and body composition. Binder et al. (2023) found significant positive associations between maternal protein, fat, carbohydrate, and energy intake and the corresponding macronutrient levels in human milk, particularly protein concentrations. (6,25) Increased protein intake was correlated with higher levels of adiponectin and leptin in human milk. Mexitalia et al. (2022) suggested that even if a mother's protein intake is less than the recommended levels, her breast milk can still support the sufficient growth of exclusively breastfed infants aged 0-6 months. (31)

Protein supplementation can significantly influence the growth outcomes of preterm infants. A randomized clinical trial by Hemmati and Ghassemzadeh (2023) found that extra protein supplementation, resulting in a higher average protein intake, significantly increased postnatal weight gain, linear growth, and head circumference growth. The intervention group, receiving higher protein, showed improved growth parameters without any short-term adverse effects. (7,32) A

systematic review by Amissah, et al, suggested that protein supplementation of human milk might increase in-hospital growth rates in weight, length, and head circumference for preterm infants. (33)

The relationship between protein intake in infancy early childhood and subsequent body mass index (BMI) ,child growth and obesity risk Infancy and Early Childhood has been studied. Zheng et al., 2021 found that high intakes of total protein and nondairy animal protein during infancy are associated with higher BMI z scores in early childhood. Although protein is essential for growth, excessive intake might contribute to an increased risk of elevated BMI. (34) Ferré et al., 2021 showed moderate-quality evidence suggesting an association between increased protein intake during the second year of life and increased fat mass in early childhood.(24) In rats, Shahkhalili et al., 2020 studied the effect of whey versus casein protein sources during the weaning period on intrauterine growth restricted rats and highlighted that the type of protein can have distinct impacts on growth, glucose homeostasis, and potentially long-term adiposity. (35)

In addition, it appears that the source of protein (especially dairy versus meat) during complementary feeding plays a crucial role in influencing weight-related growth outcomes. Kittisakmontri et al., 2022**:** investigated the impact of the amount and source of protein on infant growth during complementary feeding in a context where under- and overnutrition co-exist. It was found that animal source foods, particularly dairy protein, had a greater impact on weight-for-age, weight-for-length, and BMI z-scores compared to non-dairy animal source foods or plant-based proteins. They suggested that dairy proteins, mainly from infant formula, significantly influence weight gain and growth-related hormones, although they were not associated with linear growth. (25) While T**ang et al., 2023**, and **Nova E et al., 2021**, compared meat- versus dairy-based complementary diets and found that infants consuming meat-based diets had an increase in length-for-age Z scores, whereas dairy-based diets did not show this effect. The microbiota composition also varied significantly between the groups, suggesting that the type of protein source in the diet might influence both physical growth and gut microbiota development. (23, 36)

A study by Kouwenhoven et al. (2021) examined the impact of different protein intakes in infants on blood metabolic and hormonal markers and their association with growth and body composition until two years of age. The study found that formula-fed infants had a lower insulin sensitivity compared to breast-fed infants, and associations were found between early-life metabolic and hormonal markers and growth and body composition up to two years of age. (37)

Moreover, the relationship between protein intake and growth patterns in early childhood is nuanced, with studies indicating that both excessive and inadequate protein consumption can have adverse effects on growth. Xiong et al., reported that high protein intake may negatively affect growth Patterns. A cross-sectional study involving children and adolescents aged 6 to 18 years found that high protein intake was associated with reduced linear growth and an increased risk of stunting. (17,38) On the other hand Duane et al, 2020 reported that intake of dairy products lead to higher height Z score and decreased risk of stunting . (39) A systematic review by Ferré et al., 2021 suggested that high protein intake during the second year can be moderately linked with increased fat mass in early childhood. (23)

Protein consumption has been linked to adolescent physical growth and the timing of puberty. Tryggestad, J., & Chernausek, S., (2020), highlighted the association between childhood obesity, which can be influenced by high protein intake, and the early onset of puberty. They emphasized the significant role of body mass index (BMI) in advancing pubertal development, potentially mediated through increased fat mass and related hormonal changes, affecting both linear growth and the timing of puberty onset. (40) Oyewole, O., Adediran, A., & Oduwole, A. (2023) proposed that protein intake, and socioeconomic factors can influence the timing of puberty. They pointed out that better nutritional status, indicative of adequate protein consumption, is associated with earlier puberty onset, suggesting that nutrition plays a crucial role in the maturation process and subsequent growth patterns. (41)

The relationship between protein intake and body composition in children has been investigated. Thams et al., 2022, investigated the combined and separate effects of high dairy protein intake on body composition and cardiometabolic markers in children aged 6-8 years. The results indicated that a higher dairy protein intake compared to normal protein intake inhibited an increase in the fat mass index and influenced fat distribution in children. (42) Mbabazi et al., 2023, assessed the effects of milk protein and whey permeate in a lipid-based nutrient supplement on linear growth and body composition among stunted children. The study found that adding dairy to the supplement had no additional effects on linear growth or body composition. However, supplementation with the lipid-based nutrient supplement supported linear catch-up growth and accretion of fat-free mass, but not fat mass, indicating that the quality and source of protein are crucial in influencing body composition. These studies highlighted the importance of considering the type (quality) and amount (quantity) of protein intake in influencing the body composition of children. They suggest that while protein is essential for growth and development, the source of protein (dairy vs. non-dairy) and the context of its intake (e.g., in combination with other nutrients like vitamin D or as part of a nutrient supplement) can have significant implications in terms of body composition and growth patterns. (43)

In a study on a large cohort of adults (n = 6504), Hajihashemi et al. (2021) followed adults who had no MetS for a median follow-up of 11.25 years and found an inverse association between total, animal, and plant protein intake and the risk of MetS, suggesting that dietary protein can influence long-term metabolic health and may help in reducing the risk of MetS. (44)

A systematic review by Alexandra Stokes et al., 2021, highlighted that higher intakes of total and animal protein during infancy were associated with higher BMI in childhood and adolescence. They suggested a potential link between early-life protein intake and later-life cardiovascular risks, given the established relationship between obesity and cardiovascular disease. (45)

5. Conclusion

These studies highlight the critical impact of maternal diet quality on the protein content of breast milk, influencing infant growth and body composition. Studies underline the significant correlation between maternal intake of macronutrients and the nutrient profile of breast milk, which in turn affects infant development. Additionally, studies emphasize the importance of protein supplementation in preterm infants for enhancing growth metrics. Moreover, the broader implications of protein intake in infancy and early childhood on BMI, growth patterns, and metabolic health are evident, suggesting a nuanced balance is crucial to optimize health outcomes without contributing to obesity risks. The findings underscore the necessity of tailored nutritional strategies during early life stages to foster optimal growth trajectories and long-term health.

Recommendations

To optimize infant growth and long-term health outcomes, it's crucial to adopt a multifaceted nutritional approach. First, mothers should maintain a nutrient-rich diet, ensuring their breast milk is high in quality protein to support their infant's developmental needs. Second, for preterm infants, targeted protein supplementation is essential to foster proper growth metrics without overstepping the bounds into potential adverse effects. Third, ongoing monitoring and adjustment of protein intake during the critical periods of infancy and early childhood are necessary to balance growth with the risk of elevated BMI and related health concerns. Lastly, comprehensive education for caregivers about the significance of nutritional quality, particularly protein intake during lactation and early childhood, is vital. This holistic strategy not only supports optimal growth patterns but also contributes to the metabolic health of the child, laying a foundation for a healthier future.

The ethical approach in this review was meticulously maintained, adhering strictly to scientific research's ethical standards. Despite being a literature review without primary human data, the authors ensured a thorough, unbiased evaluation of the literature, respected intellectual property rights, and upheld transparency and honesty in presenting their findings.

- Potentially strong points:

The review's comprehensive methodology ensures a thorough and systematic evaluation of the existing literature, providing a robust synthesis of findings on protein intake's impact on children's growth and health. By integrating data from diverse studies, the review offers a nuanced understanding of the role of protein in pediatric nutrition, highlighting critical insights into optimal intake levels and potential health outcomes.

- Potentially weak Points:

Given the scope of literature reviews, there may be an inherent selection bias in the articles chosen for analysis, which could influence the review’s conclusions and generalizability.

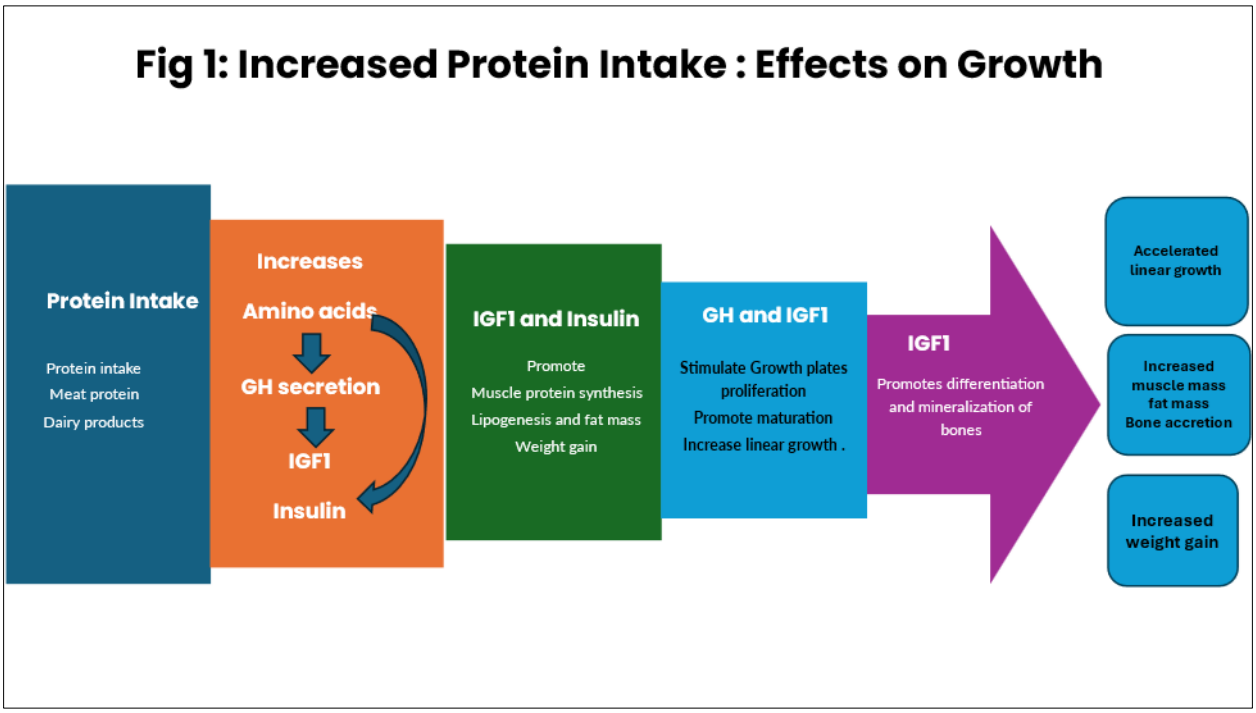

Figure 1 Increased Protein Intake: Effect on Growth

Protein Intake (e.g. meat, and dairy). Increased amino acids lead to the secretion of Growth Hormone (GH), which elevates Insulin-like Growth Factor 1 (IGF1) and impacts on insulin levels. IGF1 and Insulin promote muscle protein synthesis, lipogenesis, increasing fat mass, and weight gain. GH and IGF1 stimulate growth plate proliferation, promote maturation, and contribute to linear growth. IGF1 stimulates the differentiation and mineralization of bones. The outcomes of Increased Protein Intake include enhanced linear growth, greater muscle and fat mass, bone accretion, and overall weight gain.

Compliance with ethical standards

Disclosure of conflict of interest

There is a conflict between the authors regarding certain aspects of the study. However, all authors have participated in the resolution of these conflicts to maintain the integrity and quality of the research.

Authors' Contributions

NS was responsible for the conceptualization of the review study, setting the stage for the research with a clear outline of the scope and objectives. All authors actively participated in the data collection, screening, and analysis process, ensuring a comprehensive and meticulous evaluation of the research findings. The original draft preparation was undertaken by NS, who integrated the collected data and articulated the study's key insights. ATS significantly contributed to refining the manuscript, providing expert review, and editing to enhance the intellectual content and clarity. All authors have given their final approval of the version to be published, collectively ensuring the manuscript's accuracy and integrity, and have agreed to the published version, thus upholding rigorous scholarly standards, and ensuring the work's credibility and reliability.

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