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Childhood Obesity and Neurodevelopmental Outcomes Exploring Inflammatory and Metabolic Pathways

Dharmawan Lokanata[1*], Sylvia Wijaya[2]
Mitra Keluarga Kalideres
Corresponding Author: Dharmawan Lokanata lokanatadharmawan@gmail.com

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A B S T R A C T

Childhood obesity is a global health problem related to metabolic disorders and changes in brain developmental function through inflammatory mechanisms and metabolic dysregulation. This study aims to analyze the relationship between childhood obesity and neurodevelopmental outcomes and evaluate the role of inflammatory and metabolic pathways as mediators in these relationships. This study uses an analytical observational design with a structural equation modeling (SEM) approach on 300 children aged 6–12 years. Data were collected through anthropometric measurements (BMI-for-age Z-score, waist circumference, and body fat percentage), examination of inflammatory biomarkers (C-reactive protein, interleukin-6, tumor necrosis factor-α, and interleukin-1β), metabolic biomarkers (glucose, insulin, HOMA-IR, leptin, adiponectine, and lipid profile), and neurodevelopmental assessments covering cognitive, executive, attention, memory, behavioral, and motor functions. The analysis was conducted through the evaluation of measurement models, structural models, and testing of mediating effects using the bootstrapping method. The research model showed that the increase in childhood obesity was related to changes in inflammatory and metabolic pathways which were subsequently related to neurodevelopmental outcomes. These findings provide an understanding of the biological mechanisms that link childhood adiposity to neurocognitive development and support the development of early detection strategies and multidimensional interventions in children at risk of obesity

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INTRODUCTION

Childhood obesity has become one of the global health problems that has increased significantly in recent decades and contributes to the increasing burden of chronic diseases from an early age. Changes in the obesogenic environment, increased consumption of high-energy foods, low physical activity, and lifestyle changes have led to an increase in the prevalence of overweight and obesity in children and adolescents in various countries. The World Health Organization reports that the number of overweight children and adolescents aged 5–19 years continues to increase globally, with obesity being one of the major challenges in modern child health (World Health Organization, 2024). The impact of childhood obesity is not only limited to anthropometric disorders, but also relates to insulin resistance, dyslipidemia, impaired endothelial function, and hormonal regulatory changes that can affect various organ systems, including the central nervous system (Styne et al., 2022). Therefore, childhood obesity is currently seen as a complex condition that involves the interaction between metabolic, inflammatory, environmental, and developmental factors.

Developments in medical science show that adipose tissue in children with obesity acts as an active endocrine organ that produces various biological mediators that can affect systemic function. Excessive expansion of adipose tissue leads to changes in the adipose microenvironment characterized by immune cell infiltration, increased production of proinflammatory cytokines, and activation of low-level chronic inflammatory responses. Increased inflammatory biomarkers such as C-reactive protein (CRP), interleukin-6 (IL-6), tumor necrosis factor-alpha (TNF-α), and interleukin-1β have been associated with impaired metabolic regulation and altered brain function. Chronic systemic inflammation can affect neurodevelopment through neuroinflammatory mechanisms, altered permeability of the brain blood barrier, synaptic plasticity disorders, as well as alterations in neurotransmitter function that play a role in learning and behavioral regulation (Miller et al., 2022; Kullmann et al., 2023). The findings suggest that the inflammatory pathway is one of the potential mechanisms that explains the link between childhood obesity and neurodevelopmental disorders.

In addition to inflammation, the metabolic disorders that accompany childhood obesity also play an important role in influencing the development of brain function. Insulin resistance, increased insulin levels, changes in glucose homeostasis, and adipokine regulatory disorders such as leptin and adiponectin can affect metabolic communication between peripheral tissues and the brain. Insulin and leptin are known to have neurobiological functions in energy regulation, synaptic connection formation, and memory and learning processes. Hyperinsulinemia and leptin resistance conditions in obesity can lead to metabolic signaling disruptions that have the potential to affect children's cognitive and executive functions (Kullmann et al., 2023). In addition, changes in lipid profiles and increased oxidative stress due to metabolic disorders also contribute to changes in brain structure and function. Thus, metabolic pathways are not only a consequence of obesity, but also likely to be biological mediators linking adiposity to neurocognitive development.

Although the relationship between childhood obesity and neurocognitive developmental disorders is increasingly researched, there is still a scientific gap regarding the mechanisms that explain how obesity biologically affects brain development. Most previous studies have still focused on the direct relationship between body mass index (BMI) and cognitive, attention, or behavioral functions without simultaneously evaluating the underlying biological pathways. Longitudinal and observational studies have shown a relationship between obesity and changes in executive function, attention, and emotion regulation, but the relative contributions of inflammatory and metabolic pathways are still not fully understood (Miller et al., 2022; Liang et al., 2023). In addition, some studies have used only one type of biomarker so they have not yet described the complexity of the interactions between adiposity, inflammation, metabolism, and neural development. Therefore, an analytical approach capable of evaluating the direct and indirect relationships between variables is needed to understand these mechanisms more comprehensively.

Based on these gaps, this study aims to analyze the relationship between childhood obesity and neurodevelopmental outcomes and evaluate the role of inflammatory and metabolic pathways as mediators that explain these relationships using a structural equation modeling (SEM) approach. This research model examines whether increased obesity indicators, such as BMI-for-age Z-score, waist circumference, and body fat percentage, are associated with changes in inflammatory and metabolic biomarkers, as well as whether these changes contribute to variations in neurodevelopmental function including cognitive ability, executive function, attention, memory, behavior, and motor skills. The use of SEM allows for the testing of complex relationships between latent variables and provides a deeper understanding of the biological mechanisms underlying the relationship between childhood obesity and neurodevelopment.

This research is expected to make a theoretical contribution by strengthening the concept that childhood obesity is an immunometabolic disorder that has implications for brain development, not just weight disorders. Practically, the results of the study can support the development of multidisciplinary clinical approaches in the field of pediatrics through the identification of biological factors related to the risk of neurodevelopmental disorders in children with obesity. Understanding of inflammatory and metabolic pathways can be the basis for prevention and early intervention strategies that integrate weight management, metabolic status improvement, inflammatory control, and optimization of children's cognitive development.

LITERATURE REVIEW

Childhood Obesity as an Immunometabolic Disorder

Childhood obesity is a complex condition that is not only characterized by increased body fat accumulation, but also involves changes in endocrine, metabolic, and immunological functions. Adipose tissue acts as an active organ that produces adipokines and inflammatory mediators that affect energy regulation and function of various organs. In obesity conditions, adipocyte hypertrophy can lead to tissue hypoxia, immune cell infiltration, and increased chronic low levels of inflammation that contribute to systemic metabolic disorders (Blüher, 2023; Ellulu et al., 2022). These biological changes suggest that childhood obesity is an immunometabolic disorder that has the potential to affect the development of other organs, including the central nervous system.

In addition to metabolic complications such as insulin resistance and lipid disorders, childhood obesity is also associated with changes in brain structure and function. Changes in body composition can affect areas of the brain related to behavioral regulation, impulse control, and cognitive function. Neuroimaging studies show that increased adiposity is associated with changes in brain connectivity and the function of nerve networks that support cognitive processes (Morys et al., 2022). These conditions suggest that childhood obesity has the potential to have a direct influence on neurocognitive development through various biological mechanisms.

Based on this evidence, childhood obesity is thought to be related to changes in neurodevelopmental output. Increased adiposity can affect brain function through systemic changes in the metabolic and inflammatory environment.

H1: Childhood obesity is significantly associated with neurodevelopmental outcomes

Inflammatory Pathways Linking Obesity and Neurodevelopment

Inflammation is an important biological mechanism that explains the link between childhood obesity and neurodevelopmental disorders. Increased adipose tissue leads to the activation of immune cells and the release of inflammatory mediators such as C-reactive protein (CRP), interleukin-6 (IL-6), tumor necrosis factor-alpha (TNF-α), and interleukin-1β. These cytokines can affect brain function through the activation of microglia, increased oxidative stress, and synaptic plasticity disorders that play a role in learning and memory (Donohoe et al., 2022).

Chronic inflammation due to obesity can affect communication between peripheral tissues and the central nervous system. Activation of inflammatory mediators has the potential to cause changes in the brain's biological environment associated with impaired executive function, attention, and behavioral regulation. Research on the relationship between adiposity, inflammation, and cognitive function suggests that inflammatory mediators may be a connecting pathway between metabolic disorders and changes in children's brain function (Gouveia et al., 2023).

In the context of this research model, the inflammatory pathway is positioned as a mediator variable that explains how childhood obesity can affect

neurocognitive development. Increased obesity is expected to increase inflammatory activity which is further related to changes in neurodevelopmental outcomes.

H2: Childhood obesity significantly influences inflammatory pathways.

H4: Inflammatory pathways mediate the association between childhood obesity and neurodevelopmental outcomes.

Metabolic Pathways and Brain Development

In addition to inflammation, metabolic disorders are an important pathway that contributes to changes in neurocognitive development in children with obesity. Insulin resistance causes impaired glucose use and changes in metabolic signals that play a role in neuronal function. Insulin has an important function in the regulation of brain energy metabolism, synapse formation, and memory processes, so impaired insulin sensitivity can have an impact on cognitive function (Arnold et al., 2022).

Changes in adipokin also play a role in the relationship between obesity and brain development. Increased leptin in obesity can develop resistance thereby interfering with energy regulation and hypothalamus function, while decreased adiponectin may reduce its protective effects against inflammation and insulin sensitivity. In addition, lipid profile disruption and increased metabolic stress can worsen changes in brain function in children with obesity (Deng et al., 2023).

Therefore, metabolic indicators such as HOMA-IR, insulin, leptin, adiponectin, and lipid profiles are important components in explaining the biological pathway of obesity to neurocognitive development. In the SEM model of this study, the metabolic pathway is seen as a mediator that explains the indirect relationship between childhood obesity and neurodevelopmental outcomes.

H3: Childhood obesity significantly influences metabolic pathways.

H5: Metabolic pathways mediate the association between childhood obesity and neurodevelopmental outcomes.

Childhood Obesity and Neurodevelopmental Outcomes

Children's neurocognitive development is influenced by complex interactions between biological, environmental, nutritional, and metabolic health factors. Childhood obesity has been associated with impairments in various neurodevelopmental domains, including executive function, attention, memory, cognitive abilities, and behavior. Children with obesity tend to exhibit alterations in the function of the prefrontal cortex that plays a role in behavioral control, decision-making, and emotion regulation (Liang et al., 2023).

The link between obesity and neurodevelopment is not only direct, but likely occurs through biological mechanisms involving inflammation and metabolism. Metabolic disorders can affect neuronal function, while chronic inflammation can alter the biological environment of the brain during development. Studies on the relationship between physical activity, obesity, and cognitive development also show that metabolic and lifestyle conditions play a

role in determining the development of children's brain functions (Martin et al., 2022).

The findings support the concept that childhood obesity is a biological factor that can affect neural development through the interaction of several physiological pathways, not just the result of weight changes.

Structural Equation Modeling Approach in Understanding Biological Pathways

The relationship between childhood obesity, inflammation, metabolic disorders, and neurodevelopmental outcomes is a complex relationship that involves several biological pathways simultaneously. Conventional analyses often only evaluate the direct relationships between variables and thus are less able to explain the mediation mechanism. The structural equation modeling (SEM) approach allows testing direct and indirect relationships through latent constructs and provides a more comprehensive picture of biological mechanisms (Kline, 2023).

In this study, SEM was used to test whether childhood obesity affects neurodevelopmental outcomes through two main pathways, namely the inflammatory pathway and the metabolic pathway. This model allows the evaluation of the direct effects of obesity on neurocognitive development as well as indirect effects through biological mediators. This approach is in accordance with the concept of brain-body interaction, namely peripheral biological changes can affect brain development through certain molecular mechanisms.

Based on previous theoretical and empirical evidence studies, this study develops five main hypotheses:

1. H1: Childhood obesity is significantly related to neurodevelopmental outcomes.
2. H2: Childhood obesity has a significant effect on inflammatory pathways.
3. H3: Childhood obesity has a significant effect on metabolic pathways.
4. H4: Inflammatory pathways mediate the relationship between childhood obesity and neurodevelopmental outcomes.
5. H5: Metabolic pathways mediate the relationship between childhood obesity and neurodevelopmental outcomes.

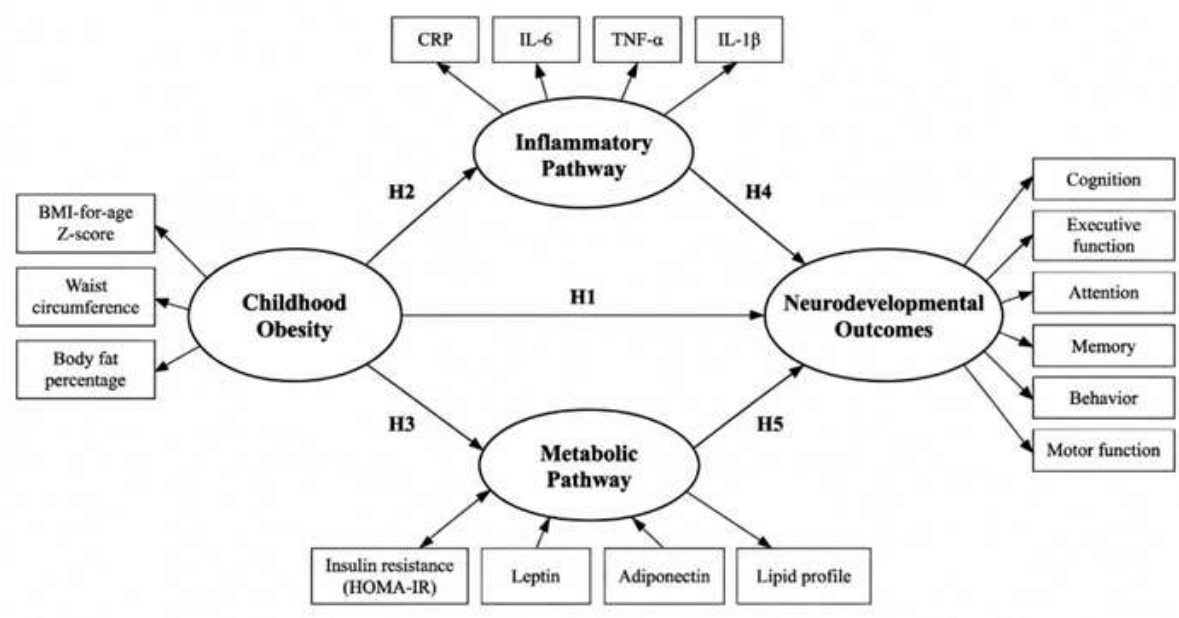


Figure 1. Hypothetical Model

METHODOLOGY

Types of Research

This study uses a quantitative approach with an analytical observational design to analyze the relationship between childhood obesity, inflammatory pathways, metabolic pathways, and neurodevelopmental outcomes. The analysis was conducted using Structural Equation Modeling (SEM) to test the direct and indirect relationships between variables. The research model consists of childhood obesity as an exogenous variable, inflammatory pathway and metabolic pathway as mediators, and neurodevelopmental outcomes as endogenous variables (Hair et al., 2022).

Population and Sample

The study population was children aged 6–12 years who were in an important period of cognitive and metabolic development. The study involved 300 children who were selected using purposive sampling techniques based on inclusion and exclusion criteria. The inclusion criteria included children aged 6–12 years, obtaining parental consent, and being able to participate in all research examinations. Children with severe chronic diseases or neurological disorders that could affect the results of the study were not included. The number of samples was determined based on the needs of SEM analysis to obtain a stable parameter estimate (Kline, 2023).

Research Instruments

Childhood obesity measurements were carried out using anthropometric indicators in the form of BMI-for-age Z-score, waist circumference, and body fat percentage. The inflammatory pathway was measured through the biomarkers CRP, IL-6, TNF-α, and IL-1β, while the metabolic pathway was assessed through fasting glucose, insulin, HOMA-IR, leptin, adiponectine, and lipid profiles.

Neurodevelopmental outcomes included cognitive domains, executive function, attention, memory, behavior, and motor using standardized neurocognitive developmental instruments. All instruments were evaluated to ensure validity and reliability before the analysis was performed.

Data Collection Procedure

Data collection began with ethical approval, instrument preparation, and research team training. Respondents who met the criteria then underwent anthropometric measurements, inflammatory and metabolic biomarker examinations, and neurodevelopmental evaluations after obtaining parent/guardian consent.

The collected data was checked for completeness, variable coding was carried out, and compiled according to the research construct for SEM analysis.

Data Analysis Techniques

Data analysis was carried out using Structural Equation Modeling (SEM) through the evaluation of measurement models and structural models. Confirmatory Factor Analysis (CFA) was used to assess the validity of constructs based on factor loading, Composite Reliability (CR), and Average Variance Extracted (AVE).

The structural model was used to test five research hypotheses, namely the relationship between childhood obesity and neurodevelopmental outcomes (H1), the effect of obesity on the inflammatory pathway (H2), the effect of obesity on the metabolic pathway (H3), and the mediating effects of inflammatory (H4) and metabolic (H5) pathways. The mediation test was conducted using bootstrapping 5,000 resamples, while the model fit was evaluated through the χ^2/df, CFI, TLI, RMSEA, and SRMR indices (Hair et al., 2022; Kline, 2023).

RESULTS

Characteristics of Respondents and Distribution of Research Variables

This study involved 300 children aged 6–12 years who were analyzed in a structural equation modeling (SEM) model. The characteristics of the respondents showed a relatively balanced gender distribution, with 162 boys (54.0%) and 138 girls (46.0%). The average age of the respondents was 9.11 ± 1.93 years. Anthropometric measurements showed variations in adiposity status based on indicators of BMI Z-score, percentile BMI, waist circumference, and body fat percentage. All respondents had complete data related to inflammatory biomarkers (CRP, IL-6, TNF-α, and IL-1β), metabolic parameters (glucose, insulin, HOMA-IR, leptin, adiponectine, and lipid profiles), as well as assessment of neurodevelopmental outcomes that included cognitive function, executive function, attention, memory, behavior, and motor skills.

Evaluation of Research Constructs (*Measurement Model*)

The evaluation of the measurement model was carried out to ensure that the research indicators were able to represent the latent constructs used in the SEM model. The *construct of childhood obesity* was formed by anthropometric indicators, namely BMI Z-score, percentile BMI, waist circumference, and body fat percentage.

The construct *of the inflammatory pathway* is represented by the biomarkers CRP, IL-6, TNF-α, and IL-1β, while the construct *metabolic pathway* is represented by the indicators of fasting glucose, insulin, HOMA-IR, leptin, adiponectin, and lipid profiles. The construct *of neurodevelopmental outcomes* is represented through the domains of cognitive, executive function, attention, memory, behavior, and motor.

The results of the analysis show that the research indicators form a latent construct in accordance with the conceptual model of the research.

The relationship between childhood obesity, inflammatory pathways, metabolic pathways, and neurodevelopmental outcomes

Inter-construct correlation analysis showed a positive relationship between *childhood obesity* and *the inflammatory pathway* and *metabolic pathway*. On the other hand, obesity showed a negative relationship with *neurodevelopmental outcomes*.

Table 1. Correlation Between Research Construct

Construct	Childhood Obesity	Inflammatory Pathway	Metabolic Pathway	Neurodevelopmental Outcomes
Childhood Obesity	1.00	0.945	0.802	-0.531
Inflammatory Pathway	0.945	1.00	0.793	-0.537
Metabolic Pathway	0.802	0.793	1.00	-0.497
Neurodevelopmental Outcomes	-0.531	-0.537	-0.497	1.00

SEM Structural Model Results

Structural models were used to test the direct relationship between research variables according to the five hypotheses that have been formulated. The results of the analysis showed that childhood obesity has a direct relationship with neurodevelopmental outcomes.

In addition, an increase in obesity is associated with increased inflammatory pathway activity and changes in the metabolic pathway. The obesity pathway to inflammation shows a strong positive relationship, while the obesity pathway to metabolism shows a positive relationship.

Table 2. Results of the Structural Pathway of the Research Model

Jalur Hypothesis	Line Coefficient (β)	p-value	Remarks
Childhood obesity → Neurodevelopmental outcomes	-0.252	<0.001	Supported
Childhood obesity → Inflammatory pathway	0.914	<0.001	Supported
Childhood obesity → Metabolic pathway	0.384	<0.001	Supported
Inflammatory pathway → Neurodevelopmental outcomes	-0.134	0.071	Insignificant
Metabolic pathway → Neurodevelopmental outcomes	-0.170	0.038	Signifikan

Analysis of Inflammatory and Metabolic Mediating Effects

Mediation analysis was conducted to evaluate whether inflammatory and metabolic pathways explain the indirect relationship between childhood obesity and neurodevelopmental outcomes. As per the study design, mediation testing was conducted using a bootstrapping approach to evaluate indirect effects through biological mediators.

The results of the analysis showed that metabolic pathways contributed to the relationship between childhood obesity and neurodevelopmental outcomes. Meanwhile, inflammatory pathways showed a direction of negative association with neurodevelopmental outcomes, but the direct effects of mediators have not reached statistical significance in structural models.

Table 3. Summary of Mediation Effects

Mediation Pathway	Direction of Effect	Results
Childhood obesity → Inflammatory pathway → Neurodevelopmental outcomes	Indirect negatives	Insignificant
Childhood obesity → Metabolic pathway → Neurodevelopmental outcomes	Indirect negatives	Signifikan

Summary of Key Findings of the Research Model

Overall, the results of the analysis showed that the increase in the indicator of childhood obesity was related to the increase in inflammatory biomarkers and changes in metabolic parameters. The structural model showed that obesity had a direct relationship with changes in neurodevelopmental outputs. The metabolic pathway showed a stronger contribution than the inflammatory pathway in explaining the variation in *neurodevelopmental outcomes* in the study model.

These findings are in line with the objectives of the study to evaluate the relationship between childhood obesity and neurocognitive development and test the role of inflammatory and metabolic pathways as a linking mechanism.

DISCUSSION

This study shows that childhood obesity has a significant direct relationship with neurodevelopmental outcomes in the direction of negative relationships (β = -0.252; $p < 0.001$). These findings suggest that increased adiposity in childhood is related to a decrease in neurodevelopmental abilities that include cognitive function, executive function, attention, memory, behavior, and motor function. These results reinforce the concept that childhood obesity is not only a disorder of weight gain, but is a complex biological condition involving metabolic, hormonal, inflammatory, and neurological changes that can affect brain development during critical periods of growth. The period of school-age children is an important phase because the development of brain structure and function is still actively ongoing, so changes in the biological environment due to obesity have the potential to impact the maturation process of the nervous system.

The relationship between childhood obesity and neurodevelopmental changes can be explained through the concept of brain–body interaction, which is a two-way interaction between the peripheral metabolic system and the central nervous system. The accumulation of excess adipose tissue leads to changes in the function of adipose tissue as an endocrine organ that produces various biological mediators, including adioxins, metabolic hormones, and inflammatory cytokines. These mediators can affect neuronal function, synaptic plasticity, as well as the regulation of brain areas related to executive function and behavioral control. Neuroimaging research by Morys et al. (2022) shows that obesity is associated with changes in the structure and connectivity of brain tissues that play a role in cognitive processes. Similar findings were reported by Brooks et al. (2023) through an analysis of Adolescent Brain Cognitive Development (ABCD) data showing that increased BMI in children and adolescents is related to developmental changes in brain circuits that support high levels of cognitive function. The results of this study expand on the findings by showing that the relationship between obesity and neurodevelopment is not only seen as a statistical relationship, but can also be explained through biological mechanisms involving inflammatory and metabolic pathways.

In addition to demonstrating a direct relationship between obesity and neurocognitive development, this study found that childhood obesity had a very strong influence on the inflammatory pathway (β = 0.914; $p < 0.001$). These results suggest that increased adiposity is consistently associated with increased systemic inflammatory activity represented through the biomarkers CRP, IL-6, TNF-α, and IL-1β. These findings support the theory that obesity is a chronic low-grade inflammation condition, which is a low-intensity chronic inflammatory state that occurs due to changes in adipose tissue function. In obesity, adipocyte hypertrophy causes tissue hypoxia, increased oxidative stress, and activation of

immune cells, especially adipose tissue macrophages, which in turn increase the production of proinflammatory cytokines.

These inflammatory mechanisms have relevance to brain development because inflammatory mediators can affect the biological environment of the central nervous system. Increases in IL-6, TNF-α, and IL-1β are known to increase the activation of microglia, alter the function of the brain's blood barrier barrier, and affect synaptic plasticity processes that are important in learning and memory. Donohoe et al. (2022) explain that obesity-induced inflammation plays a role in impaired communication between peripheral tissues and the immune system, while Gouveia et al. (2023) showed that increased inflammation in children with obesity is related to changes in cognitive and executive function. Thus, the increase in inflammatory pathways in this study is consistent with previously reported biological mechanisms.

Nevertheless, this study showed that the inflammatory pathway did not have a significant direct influence on neurodevelopmental outcomes ($\beta = -0.134$; $p = 0.071$). These findings suggest that although obesity strongly increases inflammatory activity, inflammation has not independently been able to explain variations in neurocognitive development in this study model. These results differ from several previous studies that reported a direct relationship between inflammatory biomarkers and children's cognitive function. These differences are likely due to several factors, including differences in population characteristics, respondent age ranges, variations in obesity rates, the type of biomarkers used, as well as the analytical approaches applied. In addition, inflammation is likely not a final pathway that directly affects brain function, but interacts with other mechanisms such as insulin resistance, adipokine changes, and impaired energy metabolism. Therefore, in the context of this study, inflammation likely plays a role as a biological process that amplifies metabolic disorders, but is not a primary mediator of neurodevelopmental changes.

In contrast to inflammatory pathways, the results showed that the metabolic pathway had a more dominant role in explaining the relationship between childhood obesity and neurodevelopmental outcomes. The analysis showed that obesity was significantly associated with changes in metabolic pathways ($\beta = 0.384$; $p < 0.001$), and metabolic pathways were significantly associated with neurocognitive development ($\beta = -0.170$; $p = 0.038$). In addition, the results of the mediation analysis showed that metabolic pathways play a significant role as mediators between obesity and neurodevelopmental outcomes. These findings suggest that obesity-induced metabolic changes, including insulin resistance, changes in leptin and adiponectin levels, and lipid profile disorders, may be an important mechanism linking adiposity overload to the development of brain function.

Biologically, insulin not only functions in the regulation of peripheral glucose metabolism, but also has an important role in the nervous system through the regulation of neuronal energy, synapse formation, and the learning process. Insulin resistance conditions can cause disruption of insulin signals in the brain that impact the function of the hippocampus and prefrontal cortex, which are areas that play a role in memory and executive function. Arnold et al.

(2022) explain that brain insulin resistance is related to impaired cognitive function through changes in neuronal energy metabolism and synaptic communication disorders. In addition, adipokine changes also play an important role in this mechanism. In obesity, an increase in leptin is often accompanied by leptin resistance, which interferes with energy regulation and neuronal function, while a decrease in adiponectin can reduce its protective effects against insulin inflammation and sensitivity (Deng et al., 2023).

The predominance of metabolic pathways in this study makes an important contribution to understanding the mechanisms of childhood obesity and brain development. Most previous studies have assessed the direct relationship between BMI and cognitive ability, while this study suggests that the effects of obesity on neurodevelopment may occur through certain biological changes, especially metabolic disorders. The SEM approach allows for simultaneous identification of these pathways, providing a more comprehensive picture than a simple relationship analysis. These findings support the concept that childhood obesity is an immunometabolic disorder, which is a condition that involves interactions between adipose tissue, the immune system, energy metabolism, and brain function.

From a clinical perspective, the results of this study suggest that the management of childhood obesity needs to be carried out in a multidimensional manner. Interventions should not only focus on weight loss, but also need to consider improving metabolic status and monitoring neurocognitive development. Strategies such as increasing physical activity, improving dietary quality, controlling insulin resistance, and optimizing children's sleep patterns and developmental environment can be an important part of preventing the long-term impact of obesity on brain function. Early identification of metabolic changes in children with obesity has the potential to help determine which groups are at higher risk of developing neurodevelopmental disorders.

Although it provides important findings, this study has some limitations. The observational design causes the causal relationship between obesity, metabolic changes, inflammation, and neurocognitive development to be not yet fully ascertained. In addition, the research model has not included environmental factors that can also affect child development, such as diet, physical activity, sleep quality, socioeconomic status, family stimulation, and psychosocial factors. Longitudinal research with repeated biomarker measurements is needed to understand changes in biological mechanisms over time. Further research can also integrate neuroimaging approaches, gut microbiota analysis, and genetic factors to gain a deeper understanding of the interactions between obesity, metabolism, inflammation, and child brain development.

Overall, this study shows that childhood obesity is associated with changes in neurodevelopmental outcomes through biological mechanisms involving inflammatory and metabolic pathways. Although obesity strongly increases inflammatory activation, metabolic pathways show a more dominant contribution as mediators of the relationship between obesity and neurocognitive development. These findings strengthen the understanding that childhood obesity is a systemic condition with consequences for brain development and

provide a scientific basis for the development of prevention strategies and interventions based on biological mechanisms.

CONCLUSIONS AND RECOMMENDATIONS

This study shows that childhood obesity is significantly related to changes in neurodevelopmental outcomes through biological mechanisms involving inflammatory and metabolic pathways. Increased adiposity in children is associated with increased inflammatory activity as well as changes in metabolic regulation, while metabolic pathways show a more dominant role in explaining the relationship between obesity and neurocognitive development. These findings reinforce the concept that childhood obesity is an immunometabolic disorder condition that not only impacts physical health, but also has the potential to affect the development of brain function through disruption of energy metabolism and biological regulation of the nervous system.

Based on these findings, approaches to prevent and intervene in childhood obesity need to be carried out in a multidimensional manner by considering anthropometric, metabolic health, inflammation, and neurocognitive development. Further research is recommended to use a longitudinal design to evaluate the cause-and-effect relationship and include additional factors such as diet, physical activity, sleep quality, psychosocial factors, gut microbiota, and genetic factors to gain a more comprehensive understanding of the mechanisms of the relationship between obesity and child brain development.

FURTHER STUDY

Further research can be developed through a multimodal longitudinal research approach by integrating serial inflammatory and metabolic biomarker data, neuroimaging examinations, gut microbiota analysis, and environmental factors of child development. These approaches can help identify biological changes from the early stages of obesity and determine the specific pathways that contribute most to neurodevelopmental disorders. In addition, the development of SEM-based prediction models combined with machine learning has the potential to produce an early detection system to identify children at risk of neurocognitive impairment due to obesity.

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