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Substituting ultra-processed food intake with minimally processed foods is associated with lower diastolic blood pressure in children

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ABSTRACT

Background and aims: High blood pressure (BP), a key modifiable risk factor for cardiovascular disease, often begins in childhood. While adult meta-analyses have shown consistent associations between ultra-processed food (UPF) intake and elevated BP, findings in children remain inconsistent. Given that UPFs make up majority of Canadian children's diets, we examined associations between early childhood UPF intake and BP in mid childhood, and assessed the impact of substituting UPFs with minimally processed foods (MPF).

Methods and results: In this study, among 1408 participants from the Canadian CHILD Cohort Study, UPF, defined based on the NOVA classification system, was assessed at three years of age. BP was measured at age eight. We examined associations using multivariable-adjusted mixed-effects linear regression, evaluated substitution models to estimate the effect of replacing UPFs with MPFs, and examined body mass index (BMI) as a potential mediator. At age three, UPFs contributed 44.3% of total daily energy intake. At age eight, mean systolic and diastolic BP were 104 (SD 9) and 59 (SD 6) mmHg, respectively. Each 10% increase in UPF intake was associated with 0.31 mmHg higher diastolic BP (95% CI: 0.01, 0.61), driven by "Breads and cereals" and "Ready-to-eat/heat mixed dishes" categories. Replacing 10% of energy from UPFs with MPFs, in simulated substitution analyses, was associated with 0.45 mmHg lower diastolic BP. The associations between UPF and diastolic BP were partially mediated (~27%) by child BMI.

Conclusions: Lower UPF intake in early childhood was statistically associated with higher diastolic blood pressure at age eight, with simulated substitution models suggesting modest reductions in diastolic blood pressure when substituting energy contributed from UPFs with MPFs. While these effect sizes are small, these findings underscore the importance of early dietary guidance and UPF reduction in pediatric preventive care.

1. Introduction

Cardiovascular diseases (CVD) are a leading cause of mortality in Canada, with an estimated $28.3 billion economic burden [1]. In Canada, hypertension (high blood pressure above the 95th percentile) affects 5.6% of children aged 12 and under [2], with increasing prevalence worldwide [3]. An abundance of observational and clinical evidence suggests that high blood pressure is predictive of short-term (e.g., left ventricular hypertrophy) [4] and long-term (e.g. heart failure, stroke) cardiovascular consequences [1,5]. This is concerning as high blood pressure can track throughout life [6]. Therefore, it is essential to understand early-life modifiable risk factors that can contribute to the development of high blood pressure.

Simultaneously, consumption of ultra-processed foods (UPF) is also rising [7]. These food products, although affordable and convenient, are generally nutritionally imbalanced and energy-dense [8]. Additionally,

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their high added sugars, sodium, and saturated fat content contribute to their hyper-palatable properties [8]. Canada is a top consumer of UPF [7,9], and national data indicate a shift towards consuming more UPF than whole, minimally processed foods (MPF) [10]. Our previous work and data from the Canadian Community Health Survey (CCHS) 2015 showed that young children consumed almost half of their daily energy from UPF [9,11].

While numerous studies have examined UPF consumption and high blood pressure among adults [12], there remains a research gap in the pediatric setting, particularly in Canada. Existing literature from Europe [13–15] or Latin America [16–18] countries is inconsistent, with studies either suggesting that high UPF intake in children is associated with higher blood pressure [13,17], or no significant associations [14–16]. These inconsistencies may be due to a smal study population or low UPF intake levels [7]. Furthermore, the majority of studies in children are cross-sectional, which limits our interpretation of the temporality between exposure and outcome [14,16,18]. In addition, these studies had not examined blood pressure associations with UPF subgroups. It is also important to estimate the potential benefits of substituting UPF with MPF. Such statistical methods can help quantify the expected impact on blood pressure by theoretically replacing a portion of UPF intake with MPF [19]. Lastly, body mass index (BMI) may mediate the relationship between UPF intake and blood pressure. We have previously shown that high UPF intake in early childhood is associated with BMI z-scores and obesity [11]. However, no studies have examined concurrent BMI as a potential mediator in the associations between UPF and blood pressure among children.

Therefore, in the prospective CHILD Cohort Study, we aimed to examine the associations of UPF consumption with systolic and diastolic blood pressure, and determine the change in these associations when statistically substituting UPF with MPF among Canadian children.

2. Methods

2.1. Study population

The CHILD Cohort Study is a longitudinal population-based pregnancy cohort study with four study sites located across Canada: Vancouver, Edmonton, Manitoba (Winnipeg and Morden/Winkler), and Toronto [20]. Pregnant women were recruited between 2009 and 2012 during their second or third trimester (N = 3621) and remained eligible if they delivered a healthy singleton offspring with a gestational age greater than 34 weeks + 4 days (N = 3454) [21]. For the present study, 3232 children were invited to the three-year visit. Of them, 2439 had dietary data. Participants with energy intake outliers, as determined using Tukey's outlier detection test (far-out fence method) by excluding values above the (IQR × 3.0) + third quartile [22], were excluded, resulting in 2409 with valid diet intake data. Participants that did not attend the eight-year visit (N = 871), did not have blood pressure measurements (N = 126), and had blood pressure outliers based on reference charts (N = 4) [5] were also excluded from this study. A total of 1408 participants were included in the final analyses (Fig. S1). The CHILD study was approved by the Human Research Ethics Boards (REBs) at McMaster University and Universities of Manitoba, Alberta, and British Columbia and the Hospital for Sick Children. This study was approved by the REBs at the University of Toronto (RIS# 47810).

2.2. Dietary intake assessment

Dietary intake data were collected using a semiquantitative 112-item food frequency questionnaire (FFQ), completed by the caregiver at the three-year clinical visits [11]. UPF was defined using the NOVA classification system [11,23]. Briefly, all items were categorized into one of four groups based on their extent and degree of food processing: (1) *unprocessed and minimally processed foods (MPF)*; (2) *processed culinary ingredients (PCI)*; (3) *processed foods (PF)*; (4) *ultra-processed foods (UPF)*. The percentage of UPF energy contribution was calculated by dividing the energy intake from UPF by the total daily energy intake, then multiplying by 100.

2.3. Blood pressure assessment

Systolic and diastolic blood pressure were measured at age eight years while the child sat comfortably, with their feet on the floor and their back and right arm supported [20]. A validated automatic sphygmomanometer (Carescape Dinamap, GE Healthcare) was used to measure blood pressure at the right brachial artery. Three measurements were taken after a five-minute break between each assessments, and the average of the last two was used in statistical analysis [20].

2.4. Covariates

Maternal sociodemographic characteristics (e.g., post-secondary degree, household income) were self-reported [21]. Maternal UPF intake was calculated from a validated FFQ, adapted from the Nutrition Assessment Shared Resource (NASR) of Fred Hutchinson Cancer Center [24], completed during pregnancy at enrollment [25]. Child biological sex, birth mode and weight, and maternal preeclampsia were obtained from medical records. Child ethnicity (Caucasian White, Multiracial, or Other), breastfeeding exclusivity and duration, and having older siblings, were obtained at follow-up visits [21]. Information on the season of dietary assessment and the study site were also collected. At the eight-year visit, dietary intake was captured using the INTERHEART study food screener [26]. Using this screener, we derived dietary patterns employing principal component analysis [27]. Due to similarities with the UPF diet, in our multivariable-adjusted analyses, we accounted for the "Western-like" dietary pattern. Also at the eight year visit, child height was measured to the nearest millimeter with a stadiometer and weight was measured using a calibrated scale [20]. Body mass index was calculated by dividing the weight in kilograms by the square of height in meters.

2.5. Statistical methods

Descriptive characteristics were reported as mean (SD) for continuous normally distributed variables, median [IQR] for continuous non-normally distributed variables, and counts (percentage) for categorical variables. We performed a non-response analysis to compare the characteristics of the 1408 participants included in this study with the 1001 participants who had dietary assessment done but did not participate at the eight-year follow-up visit and/or had no blood pressure data. We used *t*-test for normally distributed variables, Mann-Whitney test for non-normally distributed variables, and χ^2 test for categorical variables (Table S1).

In our basic linear regression model, we considered child sex, total energy intake at age three, and age and height at the eight-year clinic visit. In our multivariable-adjusted mixed-effect linear regression model, on top of the covariates in the basic model, we accounted for maternal post-secondary degree, UPF intake during pregnancy, preeclampsia, delivery mode, and child birthweight, ethnicity, exclusive breastfeeding at six months, having older siblings, season at dietary assessment, physical activity hours, and adherence to the "Western-like" dietary pattern at outcome assessment as fixed effects, and study sites as a random effect. These covariates were selected based on the confounder rule, model fit (R^2), and variance inflation factor.

To understand the mitigating role of MPF, we fitted a simulation model where we substituted 10% of energy contributed by UPF with MPF. For the statistical substitution analyses, both MPF and UPF were simultaneously introduced into the multivariable-adjusted model, and the differences in the beta estimates, variance, and covariance were used to estimate the beta estimate and 95% confidence intervals [19].

Lastly, we conducted a simple causal mediation analysis to

determine the mediating role of child BMI at outcome assessment in the associations between UPF intake and blood pressure, following Baron & Kenny's criteria [28].

To address limitations of the NOVA classification system, we examined the UPF subgroups defined in the European Prospective Investigation into Cancer and Nutrition (EPIC) Cohort (Breads and cereals; Sweets and desserts; Animal-based products; Ready-to-eat/heat mixed dishes; Artificially and sugar-sweetened beverages; Sauces, spreads, and condiments; Savoury snacks; Plant-based alternatives) [29], used widely in previous research [12]. Further, we performed sensitivity analyses to address NOVA limitations and address the robustness of our findings by: a) further adjusting our model for the three main nutrients of concern related to high UPF intake: saturated fat, sugar, and sodium; b) replicating the analyses using highly-processed foods (HPF) classification based on the University of North Carolina (UNC), which is more reflective of the North American diet [30], and c) additionally adjusting for the change in UPF intake between ages three and five years. Lastly, we also examined our associations using blood pressure z-scores based on the Fourth Report on the Diagnosis, Evaluation, and Treatment of High Blood Pressure in Children and Adolescents [31].

We evaluated the potential modifying role of sex by including the product term with UPF in the basic model and found no significant interaction terms (p-value >0.20). Therefore, we did not further explore sex-stratified analyses. To limit potential bias associated with missing data (ranging from 0.3 to 9.1%), missing values of covariates were imputed (n = 5) according to the fully conditional specification method, assuming no monotone missing pattern [32]. We reported the pooled effect estimates after multiple imputations [33].

All statistical analyses were performed on RStudio, version 2024.12.1 (Posit PBC). All statistical analyses were two-sided with a significance level of $\alpha = 0.05$.

3. Results

3.1. Participant characteristics

Table 1 shows the study participant characteristics. The median age at dietary assessment was 3.0 [IQR 3.0, 3.1] years and at outcome assessment was 8.3 years [8.1, 8.7]. Males comprised half of the participants (51.5%), and majority identified as Caucasian White (67.2%). 80.3% of the mothers in the study had completed post-secondary education, and 54.8% of the families had an annual household income of greater than $100,000.

We observed similar participant characteristics (e.g. maternal education, annual family income) among children included in this study and those lost to follow-up. Those who continued in the study had slightly lower energy intake and were majority of Caucasian White ethnicity (Table S2).

3.2. MPF, UPF and UPF subgroups and blood pressure

At three years of age, median energy intake was 1477.0 kcal/day [1200.4, 1815.9]. On average, 38.5% (10.9) of energy contributions came from MPF and 44.3% (11.3) of total daily energy intake from UPF (Fig. 1). The main UPF subgroups contributing the most of dietary energy are 'Breads and cereals' (12.3%), 'Sweets and desserts' (10.7%), 'Animal-based products' (8.2%), and 'Ready-to-eat/heat mixed dishes' (6.2%) (Fig. 1). At eight years of age, the mean systolic blood pressure was 104 mmHg (9) and the mean diastolic blood pressure was 59 mmHg (6) (Table 1). Mean BMI was 16.7 kg/m^2 (2.6) (Table 1).

3.3. Associations between UPF intake at three years and blood pressure at eight years

In the basic model (adjusted for child age, sex, height and energy intake at dietary assessment), every 10% energy contribution from UPF was significantly associated with 0.35 mmHg higher diastolic blood pressure (95%CI: 0.08, 0.61) (Fig. 2a). This association remained significant in the multivariable-adjusted model, where every 10% energy contribution from UPF was significantly associated with 0.32 mmHg higher diastolic blood pressure (95%CI: 0.02, 0.62) (Fig. 2a). We did not observe a statistically significant association between UPF intake and systolic blood pressure (0.03 mmHg (95%CI: −0.42, 0.49)) (Fig. 2a). Our simulation analyses showed that substituting 10% of energy contributed by UPF with MPF was associated with 0.46 mmHg (95%CI: −0.78, −0.13) lower diastolic blood pressure (Fig. 2b). There was a

Table 1
Characteristics of participants included in the analysis (N = 1408).

Family Characteristics[a]	(N = 1408)
Maternal Education (Post-Secondary vs. None)	1130 (80.3)
Maternal Energy Intake Contributed from Ultra-processed Food (%)	46.8 (10.5)
Annual Family Income	
< $100,000	543 (38.6)
≥ $100,000	772 (54.8)
Prefer Not to Say	93 (6.6)
Older Siblings (Yes vs. No)	683 (48.5)
Study Site	
Edmonton	347 (24.7)
Manitoba	456 (32.4)
Toronto	206 (14.6)
Vancouver	399 (28.3)
Birth Characteristics[a]	
Child Sex (Males vs. Females)	725 (51.5)
Birth Weight (kg)	3.5 (0.5)
Birth Mode (C-section vs. Vaginal)	331 (23.5)
Child Ethnicity[b]	
Caucasian White	946 (67.2)
Multiracial	324 (22.9)
Other	138 (9.8)
Exclusive Breastfeeding at 6 Months (Yes vs. No)	281 (20.0)
Childhood Characteristics[a]	
Exact Age at Dietary Assessment (years)	3.0 [3.0, 3.1]
Season of Dietary Assessment	
Spring	373 (26.5)
Summer	364 (25.9)
Autumn	345 (24.5)
Winter	326 (23.1)
Daily Caloric Intake (kcal/day)	1477.0 [1200.1, 1816.4]
Daily Sodium Intake (mg/day)	2108.6 [1663.7, 2678.3]
Daily Sugar Intake (g/day)	84.2 [66.2, 104.1]
Daily Saturated Fat Intake (g/day)	20.1 [16.0, 25.6]
Energy Intake Contributed from NOVA Groups (%)	
Minimally Processed Food	38.5 (10.9)
Processed Culinary Ingredients	2.5 (3.3)
Processed Foods	14.7 (5.5)
Ultra-Processed Foods	44.3 (11.3)
Exact Age at Outcome Assessment (years)	8.3 [8.1, 8.7]
Physical Activity (hours/week)	7.2 [5.0, 11.6]
Adherence to the "Western-like" Dietary Pattern[c]	0.0 (1.0)
Body Mass Index (kg/m^2)	16.7 (2.6)
Systolic Blood Pressure (mmHg)	104 (9)
Diastolic Blood Pressure (mmHg)	59 (6)

[a] Values are mean (SD) for continuous normally distributed variables, median [IQR] for continuous non-normally distributed variables, n (%) for categorical variables. Family, birth, and childhood characteristics are the pooled values after multiple imputations (n = 5 imputation).

[b] If both parents' ethnicities are "Caucasian White", then the child's ethnicity is "Caucasian White". If both parents' ethnicity is different from one another (and not "Other") or both ethnicities are "Multiracial", the child is defined as "Multiracial". If either parent's ethnicity is "Other" (e.g. the provided options did not apply: Black, Caucasian White, East Asian, First Nations, Hispanic, Middle Eastern, Multiracial, South Asian, South-East Asian), then the child is defined as "Other" as well.

[c] Dietary pattern is derived from principal component analysis.

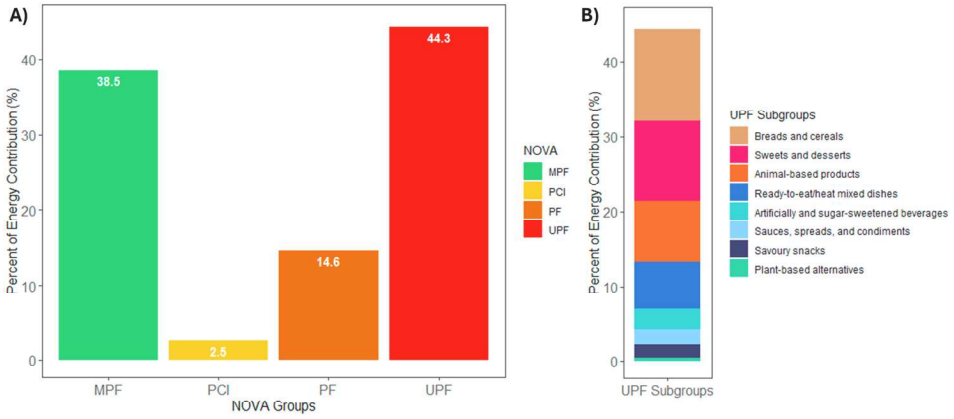

Fig. 1. Distribution of energy intake across NOVA Classification Groups and ultra-processed food subgroups at three years (N = 1408).
A) Bar graph of energy intake contributed by each NOVA Classification System groups: Group 1 – Minimally Processed Foods (MPF), Group 2 – Processed Culinary Ingredients (PCI), Group 3 – Processed Foods (PF), Group 4 – Ultra-Processed Foods (UPF). B) Stacked bar graph of UPF subgroups that make up the total energy contributed by UPF items.

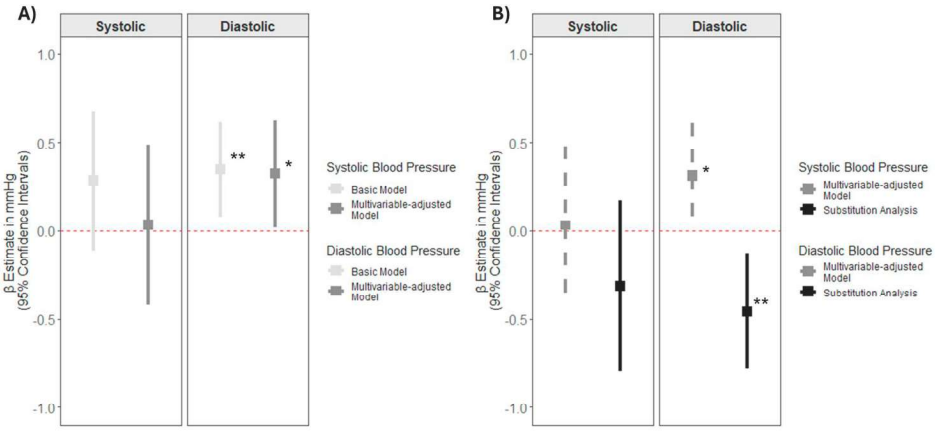

Fig. 2. Ultra-processed foods (UPF) intake and substitution with minimally processed food (MFP) at three years and blood pressure at eight years in the CHILD Cohort Study (N = 1408).
A) Values are beta estimates with 95% confidence intervals from linear mixed-effect regression analyses of every 10% increase in energy intake from UPF at age three years and their associations with blood pressure at age eight years, in the CHILD Cohort Study. The basic model accounted for biological sex, total energy intake at three years, and age and height at eight years. The multivariable-adjusted model accounted for the basic model + maternal post-secondary degree, maternal UPF intake during pregnancy, preeclampsia, child ethnicity, birthweight, delivery mode, exclusive breastfeeding at six months, older siblings, hours of physical activity, adherence to the "Western-like" dietary pattern, and season of dietary assessment, with study site as random effect. B) Values are beta estimates with 95% confidence intervals from substitution analysis using linear mixed-effect regression of every 10% energy intake from ultra-processed foods substituted with minimally processed foods at age three years and their associations with blood pressure at age eight years, in the CHILD Cohort Study (N = 1408). The substitution analyses accounted for the same potential confounders as the multivariable-adjusted model. * p-value <0.05; ** p-value <0.01.

tendency for lower systolic blood pressure, although not statistically significant (−0.31 mmHg, 95%CI: −0.80, 0.17) (Fig. 2b).

3.4. UPF subgroups at three years and blood pressure at eight years

We found that higher intake of 'Ready-to-eat/heat mixed dishes' was associated with higher systolic blood pressure (1.01 mmHg (95%CI: 0.06, 1.95)) and diastolic blood pressure (0.77 mmHg (95%CI: 0.13, 1.40)) (Fig. 3). Furthermore, higher intake of 'Breads and cereal' was also associated with higher diastolic blood pressure (0.62 mmHg (95% CI: 0.10, 1.13)) (Fig. 3). Tendencies for higher blood pressure were observed for 'Animal-based products' and 'Artificially and sugar-sweetened beverages', however they were not statistically significant. 'Plant-based alternatives' showed tendencies for lower blood pressure, although not statistically significant (SBP: −1.94 mmHg (95%CI: −4.23, 0.35); DBP: −1.34 mmHg (95%CI: −2.89, 0.20)) (Fig. 3).

3.5. BMI mediation analyses

In a mediation analysis, following the conditions of Baron and Kenny's mediation criteria (e.g., UPF was significantly associated with the mediator BMI; and child BMI was significantly associated with diastolic blood pressure, adjusting for UPF), we found that child BMI at age eight partially mediated 26.7% (p-value = 0.02) of the association between UPF intake and diastolic blood pressure (Fig. 4).

3.6. Sensitivity analyses

We run several sensitivity analyses to determine the robustness of our results. First, the association between UPF intake and diastolic blood pressure remained consistent after further adjustments for the nutrients of concern (sodium, sugar and saturated fat) (β = 0.41; 95%CI: 0.04, 0.79) (Fig. S2). Second, examining HPF using the UNC classification system also showed similar results for diastolic blood pressure with slightly stronger effect estimates (β = 0.47; 95% CI: 0.16, 0.78) (Fig. S2).

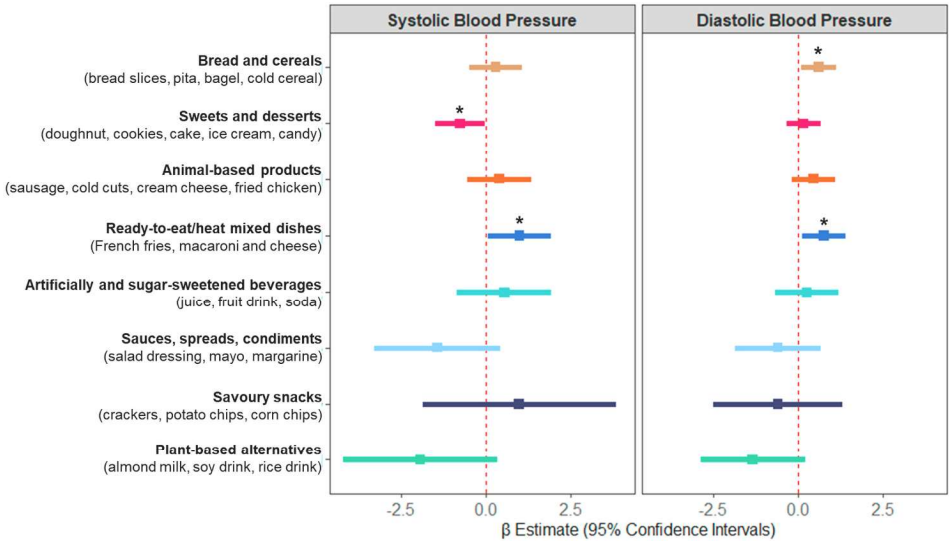

Fig. 3. Ultra-processed foods (UPF) subgroups at three years and blood pressure at eight years in the CHILD Cohort Study (N = 1408).
Values are beta estimates with 95% confidence intervals from linear mixed-effect regression analyses of every 10% increase in energy intake from UPF subgroups at age three years and their associations with blood pressure at age eight years, in the CHILD Cohort Study. The multivariable-adjusted model accounted for biological sex, total energy intake at three years, and age and height at eight years, maternal post-secondary degree, maternal UPF intake during pregnancy, preeclampsia, child ethnicity, birthweight, delivery mode, exclusive breastfeeding at six months, older siblings, hours of physical activity, adherence to the "Western-like" dietary pattern, and season of dietary assessment, with study site as random effect. * p-value <0.05.

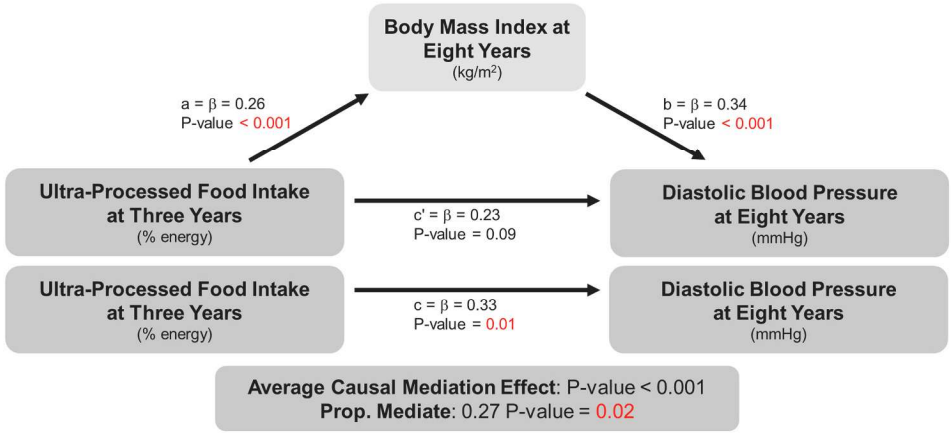

Fig. 4. Mediation analysis of ultra-processed food (UPF) intake at three years, body mass index at eight years, and blood pressure at eight years in the CHILD Cohort Study.
Mediation analysis between UPF intake and diastolic blood pressure, with child BMI as a potential mediator (N = 1381). All four conditions of Baron and Kenny's mediation criteria were satisfied. Firstly, there was a statistically significant direct association between the independent variable (UPF intake) and the dependent variable (diastolic blood pressure). Secondly, there is a statistically significant association between the independent variable (UPF intake) and the hypothesized mediating variable (child BMI). Thirdly, there is a statistically significant association between the hypothesized mediating variable (child BMI) and the dependent variable (diastolic blood pressure) when both the independent (UPF intake) and mediating (child BMI) variables are in the model. Lastly, the beta estimate of the direct association is larger in absolute value than the beta estimates in the indirect association between the independent (UPF intake) and dependent (diastolic blood pressure) variables, when both the independent and mediator are predictors of the dependent variable.

Third, further adjusting our main analyses for the change in UPF intake between ages three and five showed consistent results (β = 0.38; 95%CI: 0.02, 0.74) (Fig. S2). Lastly, when looking at blood pressure z-scores, higher UPF intake was associated with 0.06 higher diastolic blood pressure z-score (95%CI: 0.01, 0.11). No significant associations were observed for systolic blood pressure z-score (Fig. S3).

4. Discussion

In this large longitudinal, population-based cohort, we found that almost half of the daily energy intake in young children came from UPF, with the greatest contributing subgroups being 'Breads and cereals', 'Sweets and desserts', 'Animal-based products', and 'Ready-to-eat/heat mixed dishes'. Additionally, we found that overall higher UPF intake at age three years was associated with higher diastolic blood pressure in eight-year-old children, and that child BMI partially explained this association. Looking closer into subgroups, we found that 'Ready-to-eat/heat mixed dishes' and 'breads and cereals' drove the association with blood pressure. Furthermore, we showed that in a simulation model, statistically substituting UPF with MPF was associated with lower diastolic blood pressure.

Previous studies in children have also examined the associations between UPF intake and blood pressure. Similar to our findings, the Spanish INfancia y Medio Ambiente Cohort (N = 1248), found that

children in the lowest UPF intake tertile, compared to the highest, at four years of age, had 0.15 lower diastolic blood pressure z-scores at age seven [13]. Similar to our findings, they also did not find a significant association between UPF intake and systolic blood pressure [13]. Additionally, in a longitudinal Brazilian study (N = 305), UPF intake at age three was significantly associated with 0.13 mmHg higher diastolic, and not systolic, blood pressure at age six [17]. However, the Generation XXI cohort in Portugal (N = 3034) did not find a significant association between UPF intake at age seven years and blood pressure at ten years [15], nor did the cross-sectional Spanish CORALS study (N = 1426) [14] and the Brazilian Grow up with Health in Vitória de Santo Antão study (N = 164) [16]. These inconsistent findings could be due to the cross-sectional designs, the age at which dietary exposure and clinical outcomes were assessed, and the varying level of UPF intake across countries (e.g., the participants of Generation XXI had lower average UPF intake (31%) than our study (44%)) [15].

In our study, we found that the top UPF subgroups contributing the most dietary energy were 'Breads and cereals' (including sliced bread, waffles, cold cereal), 'Sweets and desserts' (including cookies, ice cream, chocolate or candy bar), and 'Ready-to-eat/heat mixed dishes' (including macaroni and cheese, French fries, and egg McMuffin); which aligns with CCHS 2015, where among children aged two to five years, the highest dietary energy intake came from 'Commercial bread', 'Fruit juices and fruit drinks', and 'Chocolate, candies, etc' [9]. Our findings align with a Brazilian study that further divided their UPF items into subgroups [17]. They found that the top three energy contributors were 'Chips, crackers, and cookies', 'Sweets and candies', and 'Soft drinks and sweetened fruit juices' [17]. Similar to our study, the Hellenic Nutrition and Health Survey from Greece has reported similar UPF subgroups contributing the most dietary energy for children and adolescents aged two to eighteen ('Ready-to-eat/heat dishes', 'Sweet grain products', 'Savoury snacks', and 'Sweets') [34]. These items may be made with emulsifiers and other additives and come in attractive packaging, and previous animal models and human studies have demonstrated that molecules from additives and packaging are associated with adverse cardiovascular health outcomes [35]. Yet, no previous studies have examined the associations between UPF subgroups and blood pressure in children.

To determine the mitigation effects of whole minimally processed diet, we fitted a substitution simulation analysis, a commonly used approach in nutrition epidemiology [19], where we replaced 10% of the energy contributed from UPF with MPF. To the best of our knowledge, only one study has done a statistical substitution simulation analysis between UPF with MPF intake and blood pressure among children, and they concluded no significant associations [14]. While this study adjusted for many of the same confounders as our study, comparison with our results is limited, as their study was cross-sectional, participants ranged from three to six years old, and Spain generally has lower UPF intake levels than Canada [7].

The underlying mechanisms between UPF intake and blood pressure are largely unknown, but several potential pathways have been hypothesized. Diastolic blood pressure is directly influenced by peripheral vascular resistance [36] and may be more sensitive to dietary exposures in children, such as high saturated fat and added sugar intake [37,38]. UPF is characteristically defined as being high in saturated fats, sugars and sodium [8], where overconsumption may lead to stiffer arteries, fluid retention in the bloodstream, and atherosclerosis, ultimately developing high blood pressure [39]. However, in our study, we adjusted for these nutrients and observed consistent results. Diastolic blood pressure is also more predictive than systolic blood pressure for adverse cardiovascular events in young adults, such as isolated diastolic hypertension [40,41] and coronary heart disease [42]. Meanwhile, systolic blood pressure increases more steadily with age, and isolated systolic hypertension is more common among older adults above age 60 years [43].

Additionally, UPF may increase blood pressure through obesity development and the associated low-grade chronic inflammation. Previous studies [14], including our own [11], have demonstrated that high UPF intake in early childhood is associated with higher BMI [11,14], and greater risk of living with overweight/obesity [11]. Two studies among children living with overweight/obesity, one in Iran (N = 203) and the other in Brazil (N = 96), have shown a significant association between higher UPF intake and higher diastolic blood pressure [44,45]. In our study, we found that BMI partially mediates the association between UPF and diastolic blood pressure, suggesting that BMI represents a more proximal factor in this pathway, while other potential mechanisms may also contribute to the observed relationship. Obesity is a multifactorial condition, meaning some children may have a high BMI due to factors unrelated to UPF intake. Additionally, diastolic blood pressure may also be influenced by multiple factors and may be elevated due to mechanisms independent of UPF intake and BMI. Nevertheless, isolated diastolic hypertension is found to be more common among individuals living with obesity [46]. Further, it has been hypothesized that the higher cardiac output and increased systemic vascular resistance associated with obesity might be responsible for the abnormal mean arterial pressure, a hemodynamic determinant of isolated diastolic hypertension [41,46].

Lastly, studies have also found that high intake of common emulsifiers used in food products is associated with gut microbiota dysbiosis, which may lead to inflammation and the development of metabolic syndrome [47]. An umbrella review of meta-analysis found that gut microbiome can impact only the diastolic blood pressure among individuals with type 2 diabetes mellitus, indicating that gut microbiota modulation can specifically affect the diastolic blood pressure based on the existing health conditions of the individual [48]. Majority of UPF are characteristically low in dietary fiber [8], and mice models have demonstrated that a diet high in dietary fiber can modify gut microbiota composition, subsequently improving cardiovascular health [49]. Future work is needed, particularly among healthy children, to examine the role of gut microbiota in systolic and diastolic blood pressure development.

Given that high blood pressure in early childhood can track throughout life [6] and is predictive of CVD in adulthood [40], our results may hold public health and clinical implications. Our statistical simulation substitution analysis showed that substituting energy obtained from UPF with MPF is associated with a reduction in diastolic blood pressure. These results, along with previous work in this field, offer insights for informing evidence-based dietary recommendations that could help lower the burden of childhood CVD. Additionally, we found that BMI partially mediates the association between UPF and blood pressure, thereby offering another opportunity to indirectly reduce high blood pressure development through obesity prevention strategies. Our observed effect size of 0.32–0.46 mmHg for diastolic blood pressure may appear modest and represents a small shift when compared with the variability of diastolic blood pressure in our cohort (SD 6 mmHg), therefore, it should be interpreted with caution at the individual level regarding immediate clinical implications. However, this modest difference can have meaningful consequences at the population level. Previous literature demonstrated that population-wide shifts as small as 1 mmHg in diastolic blood pressure can translate into measureable reductions in later-life cardiovascular morbidity [50,51]. Additionally, these modest effect sizes may have greater implication among children than adult populations. Numerous studies, including meta-analyses, have shown that blood pressure in early childhood tracks into adulthood [6,52,53]. Blood pressure trajectory studies also demonstrated that children with higher diastolic blood pressure in early life follow a trajectory with increasing diastolic blood pressure in later childhood and are at a greater risk of arterial stiffness in adulthood [54]. Given that our observed effect size is independent of many potential confounders that influence blood pressure development, this modest difference contributes to the cumulative change in blood pressure from childhood risk factors. Further, our observed effect size

represented every 10% energy contributed from UPF intake. As shown, Canadian children obtain nearly 50% of their daily energy intake from ultra-processed foods, and our linear mixed-effects regression model estimates that, for the average child, switching to a predominantly minimally processed food diet could result in up to a fivefold improvement in the blood pressure. Furthermore, larger effect sizes (0.62 and 0.77 mmHg) were observed for specific UPF subgroups, such as 'Bread and cereals' and 'Ready-to-eat/heat mixed dishes'. Our work can also inform public health and government policies (e.g., school food programs on designing school lunch menus that limit UPF intake). Lastly, this work can inform future studies and encourage further research on understanding components of UPF, such as emulsifiers and other additives, to determine the underlying pathways that lead to adverse cardiovascular outcomes.

To the best of our knowledge, this is one of the first prospective cohort studies examining UPF intake and blood pressure in Canadian children. The extensive data collected in the large, multiethnic, population-based CHILD study allowed this work to adjust for various potential confounders. We measured blood pressure in triplicate and examined the average of the last two readings, following the American Academy of Pediatrics 2017 guidelines. We examined blood pressure in mmHg and z-scores based on the Fourth Report on the Diagnosis, Evaluation, and Treatment of High Blood Pressure in Children and Adolescents, yielding consistent results. We further examined the potential impact of statistically substituting UPF with MPF on blood pressure in a simulation model. Our study also assessed UPF subgroups, mutually adjusted for each other, as we acknowledge that not all UPF items have the same impact on health, to identify drivers in the observed associations.

However, our study does have some limitations. Our assessment of UPF exposure was based on dietary intakes at age three, which may not fully represent intake patterns until age eight, the time of our outcome assessment. Although prior studies suggest that dietary intake shows stability in early childhood [55,56], other evidence indicates that dietary patterns can evolve as children age, particularly with increasing autonomy over food choices as they enter school. In our study, we accounted for the change in UPF intake between ages three and five, and the "Western-like" dietary pattern at age eight, which reflects similarities to a UPF diet. However, the lack of UPF-specific measures at the time of outcome assessment restricted our ability to evaluate whether current UPF intake would be more strongly associated with blood pressure.

We also acknowledge inherent limitations of the NOVA classification. This classification system is solely based on the degree and extent of food processing, and therefore unintentionally treats all UPF as equally harmful. Some nutritionally beneficial foods, such as fortified whole-grain breads or plant-based beverages, are being grouped together as UPFs despite their differing nutritional profiles. To mitigate this limitation, we conducted UPF subgroup analyses and adjusted for key nutrients of concern (sugar, sodium and saturated fat intake). We also replicated our findings using the UNC system, which is adapted for North America that accounts for convenience. Additionally, FFQs are not ideal for assessing the degree of food processing. While the NOVA system is the most used classification system in epidemiology studies, the criteria interpretability can be subjective and vary based on the interpreter [57]. In our study, two researchers independently mapped the FFQ items into the NOVA groups and ambiguous items were discussed with a third researcher to reach a consensus. Future studies would benefit from repeated dietary measures across childhood and from ingredient-level characterization of UPFs to disentangle the processing effect from nutritional composition. Lastly, despite adjustment for a wide range of maternal and childhood confounders, the possibility of residual confounding remains.

5. Conclusion

In this large population-based prospective cohort, ultra-processed food intake at age three was statistically associated with higher diastolic blood pressure at age eight, and simulated substitution models replacing energy contribution of UPF with minimally processed foods was associated with modest reduction in blood pressure. Although the individual-level clinical implications of the observed <0.5 mmHg difference are modest relative to natural variability in childhood blood pressure, early-life UPF intake shows a measurable statistical association with diastolic blood pressure at the age of eight years old. Given that UPFs contribute towards nearly half of the children's dietary energy intake, even small shifts could have meaningful long-term implications towards cardiovascular disease prevention.

Authors contributions

KM designed, managed and supervised this project. The CHILD Study Founding team (PS, TJM, ES, PJM, and SET) conceived the CHILD cohort design, managed study recruitment and oversaw clinical assessments of study participants. ZHC and SM mapped all food items into the NOVA groups. ZHC conducted all the statistical analyses. ZHC and KM interpreted the data and drafted the manuscript. All authors provided feedback and approved the final version.

Disclosures

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.numecd.2026.104570.

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