Current Developments in Nutrition 7 (2023) 102019

American Society for Nutrition
Excellence in Nutrition Research and Practice

Current Developments in Nutrition

journal homepage: https://cdn.nutrition.org/

Original Research

Opportunities for Examining Child Health Impacts of Early-Life Nutrition in the ECHO Program: Maternal and Child Dietary Intake Data from Pregnancy to Adolescence

Megan G. Bragg [1,*], Matt Westlake [2], Akram N. Alshawabkeh [3], Traci A. Bekelman [4], Carlos A. Camargo Jr. [5], Diane J. Catellier [2], Sarah S. Comstock [6], Dana Dabelea [4], Anne L. Dunlop [7], Monique M. Hedderson [8], Christine W. Hockett [9,10], Margaret R. Karagas [11], Kate Keenan [12], Nichole R. Kelly [13], Jean M. Kerver [14], Debra MacKenzie [15], Somdat Mahabir [16], Luis E. Maldonado [17], Lacey A. McCormack [9,10], Melissa M. Melough [18,19], Noel T. Mueller [20], Morgan E. Nelson [2], Thomas G. O'Connor [21], Emily Oken [22], T Michael O'Shea [23], Karen M. Switkowski [22], Katherine A. Sauder [4], Rosalind J. Wright [24], Robert O. Wright [24], Xueying Zhang [24], Yeyi Zhu [8], Kristen Lyall [1], on behalf of program collaborators for Environmental influences on Child Health Outcomes[#]

[1] *AJ Drexel Autism Institute, Drexel University, Philadelphia, PA, United States;* [2] *RTI International, Research Triangle Park, NC, United States;* [3] *College of Engineering, Northeastern University, Boston, MA, United States;* [4] *Lifecourse Epidemiology of Adiposity and Diabetes (LEAD) Center, University of Colorado Anschutz Medical Campus, Aurora, CO, United States;* [5] *Massachusetts General Hospital, Harvard Medical School, Boston, MA, United States;* [6] *Department of Food Science and Human Nutrition, Michigan State University, East Lansing, MI, United States;* [7] *Department of Gynecology & Obstetrics, Emory University School of Medicine, Atlanta, GA, United States;* [8] *Kaiser Permanente Northern California Division of Research, Oakland, CA, United States;* [9] *Avera Research Institute, Sioux Falls, SD, United States;* [10] *Department of Pediatrics, University of South Dakota School of Medicine, Sioux Falls, SD, United States;* [11] *Department of Epidemiology, Geisel School of Medicine at Dartmouth, Hanover, NH, United States;* [12] *Department of Psychiatry & Behavioral Neuroscience, University of Chicago, Chicago, IL, United States;* [13] *Department of Counseling Psychology and Human Services, College of Education, University of Oregon, Eugene, OR, United States;* [14] *Departments of Epidemiology & Biostatistics and Pediatrics & Human Development, College of Human Medicine, Michigan State University, East Lansing, MI, United States;* [15] *Community Environmental Health Program, College of Pharmacy, University of New Mexico Health Sciences Center, Albuquerque, NM, United States;* [16] *National Cancer Institute, National Institutes of Health, Bethesda, MD, United States;* [17] *Department of Population and Public Health Sciences, Keck School of Medicine, University of Southern California, Los Angeles, CA, United States;* [18] *Department of Health Behavior and Nutrition Sciences, University of Delaware, Newark, DE, United States;* [19] *Department of Child Health, Behavior and Development, Seattle Children's Research Institute, Seattle, WA, United States;* [20] *Department of Epidemiology, Bloomberg School of Public Health, Johns Hopkins University, Baltimore, MD, United States;* [21] *Departments of Psychiatry, Neuroscience, Obstetrics and Gynecology, University of Rochester, Rochester, NY, United States;* [22] *Department of Population Medicine, Harvard Medical School and Harvard Pilgrim Health Care Institute, Boston, MA, United States;* [23] *Department of Pediatrics, University of North Carolina at Chapel Hill School of Medicine, Chapel Hill, NC, United States;* [24] *Department of Environmental Medicine and Public Health, Icahn School of Medicine at Mount Sinai, New York, NY, United States*

Abbreviations: ASA24, Automated Self-Administered 24-Hour (ASA24) Dietary Assessment Tool; DAC, Data Analysis Center; DASH, Data and Specimen Hub; DHQ, Diet History Questionnaire; DSQ, Dietary Screener Questionnaire; ECHO, Environmental influences on Child Health Outcomes; FFQ, food frequency questionnaire; HEI, Healthy Eating Index; HHEAR, Human Health and Exposure Analysis Resource; ISPCTN, Institutional Developmental Awards States Pediatric Clinical Trials Network; NICHD, National Institute of Child Health and Human Development.

* Corresponding author. *E-mail address:* Mb4366@drexel.edu (M.G. Bragg).

See Acknowledgments for full listing of collaborators.

https://doi.org/10.1016/j.cdnut.2023.102019
Received 22 August 2023; Received 10 October 2023; Accepted 11 October 2023; Available online 23 October 2023

ABSTRACT

Background: Longitudinal measures of diet spanning pregnancy through adolescence are needed from a large, diverse sample to advance research on the effect of early-life nutrition on child health. The Environmental influences on Child Health Outcomes (ECHO) Program, which includes 69 cohorts, >33,000 pregnancies, and >31,000 children in its first 7-y cycle, provides such data, now publicly available.
Objectives: This study aimed to describe dietary intake data available in the ECHO Program as of 31 August, 2022 (end of year 6 of Cycle 1) from pregnancy through adolescence, including estimated sample sizes, and to highlight the potential for future analyses of nutrition and child health.
Methods: We identified and categorized ECHO Program dietary intake data, by assessment method, participant (pregnant person or child), and life stage of data collection. We calculated the number of maternal-child dyads with dietary data and the number of participants with repeated measures. We identified diet-related variables derived from raw dietary intake data and nutrient biomarkers measured from biospecimens.
Results: Overall, 66 cohorts (26,941 pregnancies, 27,103 children, including 22,712 dyads) across 34 US states/territories provided dietary intake data. Dietary intake assessments included 24-h recalls (1548 pregnancies and 1457 children), food frequency questionnaires (4902 and 4117), dietary screeners (8816 and 23,626), and dietary supplement use questionnaires (24,798 and 26,513). Repeated measures were available for ~70%, ~30%, and ~15% of participants with 24-h recalls, food frequency questionnaires, and dietary screeners, respectively. The available diet-related variables describe nutrient and food intake, diet patterns, and breastfeeding practices. Overall, 17% of participants with dietary intake data had measured nutrient biomarkers.
Conclusions: ECHO cohorts have collected longitudinal dietary intake data spanning pregnancy through adolescence from a geographically, socioeconomically, and ethnically diverse US sample. As data collection continues in Cycle 2, these data present an opportunity to advance the field of nutrition and child health.

Keywords: diet assessment, child nutrition, child health, nutrition research, pregnancy nutrition, nutrient biomarkers

Introduction

Poor nutrition during early life is a significant public health issue in the United States. Many pregnant people and children are consuming inadequate amounts of key vitamins and minerals and excess amounts of sodium, saturated fats, and sugar [1–5]. Significant income- and race-related inequities persist, both in access to nutritious foods and in rates of diet-related chronic disease [6–9]. These factors are known to contribute to poor pregnancy outcomes and suboptimal child growth and development [10], yet the determinants and specific health effects of dietary practices are still being uncovered. Gaps in existing evidence, such as those highlighted by the 2020–2025 Dietary Guidelines for Americans Scientific Advisory Committee report [11], hinder the development of effective, culturally responsive interventions to promote nutrition and health equity. A better understanding of the effect of early-life nutrition on child health outcomes and the complex factors that influence dietary intake is critically needed [12].

Scientific advancement in this area has been constrained, in part, by the limitations of available data sources. Although national birth cohort studies that collect dietary intake data exist in other countries [13–15], no such centralized cohort is available in the United States. Instead, the US NHANES is a major source of dietary intake data used for nutrition monitoring and the development of national nutrition recommendations [16]. However, data from NHANES are cross-sectional and not designed to address maternal-child dyads, which preclude longitudinal investigation of the impact of early dietary exposures on later child health outcomes. Additionally, NHANES does not specifically aim to enroll pregnant people or children; therefore, the number of participants in these life stages is modest, which limits the power to detect associations. Longitudinal measures of dietary exposures and related child health outcomes from time in utero to infancy, through childhood and adolescence, are needed in a large and diverse sample to advance our understanding of the predictors and effects of early-life diet.

The Environmental influences on Child Health Outcomes (ECHO) Program, which in its first 7-y cycle encompassed 69 cohort study sites and more than 42,000 pregnancies and 65,000 children across the United States [17], is poised to provide a unique opportunity for nutrition research. Funded by the NIH, the first 7-y cycle of ECHO began in 2016; the second 7-y cycle of continued follow-up begins in 2023. The overarching scientific goal of the ECHO Program is to examine the effects of early environmental exposures on children's health across 5 main outcome domains: prenatal, perinatal, and postnatal outcomes; neurodevelopment; upper and lower airways; obesity and obesity-related conditions; and positive health [18]. ECHO cohorts collect a range of nutritional and nonnutritional data across a large and varied population, spanning pregnancy to adolescence. Importantly, deidentified ECHO data reflecting >33,000 pregnancies and >31,000 children have recently been made publicly available to researchers through the National Institute of Child Health and Human Development (NICHD) Data and Specimen Hub (DASH; https://dash.nichd.nih.gov/) [19] to encourage broader utilization and boost the potential impact of this federally funded program.

In this article, we summarize the dietary intake data available in the ECHO Program as of August 2022 from pregnancy through adolescence, including cohort and participant numbers. Additionally, we summarize the strengths and weaknesses of these data, including considerations and examples for use in future analyses of child health outcomes, to emphasize the potential for using ECHO dietary intake data to address a range of child health research questions.

Methods

The ECHO Program is a consortium of pregnancy and birth cohorts located throughout the United States and its territories [17,18]. Overall, the ECHO cohort participants are drawn from the general population, with select cohort study sites oversampling for vulnerable population segments at higher risk for certain child health outcomes (i.e., children with autism, children at high risk for asthma or autism, or children born prematurely). Some cohort study sites began data collection many years before joining the ECHO Program, and others began more recently. When cohorts joined ECHO, participants were asked for consent to share previously collected data with ECHO and to participate in new data collection under a common ECHO-wide Cohort Data Collection Protocol [20]. All data are stored in a common ECHO cohort database within a secure, restricted-access data enclave, and biospecimens are sent to a centralized location for storage. A subset of deidentified data from the first 7-y cycle, for those who consented to data sharing, is now available to the public through the NICHD DASH platform.

Dietary intake data

Dietary intake elements included in the Cycle 1 ECHO Protocol Version 2.1 [20] were identified and summarized (Table 1) [20–26]. We defined dietary intake data as any questionnaires or forms that assessed intake of foods, beverages, or supplements. Infant feeding practices were included even though these measures may not provide quantitative measures of food intake (i.e., breastfeeding status, timing of introduction of solid foods), due to the importance of early feeding practices for children's growth and development [27]. In addition to data collected as part of the ECHO Protocol, we also included relevant dietary intake data that cohorts collected prior to joining ECHO. Participants were counted as having dietary intake information if they completed any part of a form that included questions related to dietary intake.

We then categorized these data by type of dietary assessment method: 24-h dietary recalls, food frequency questionnaires (FFQs), dietary screeners, and dietary supplement intake questionnaires. The 24-h dietary recalls included forms assessing intake of foods, beverages, and dietary supplements consumed in a recent 24-h period. FFQs assessed the frequency of consumption of a comprehensive list of foods and beverages over a specified period. Dietary screeners were defined as forms that assessed intake of a limited number of foods and/or beverages consumed over a specific timeframe but did not provide enough information to fully characterize an individual's diet (e.g., a fruit and vegetable screener). Dietary supplements were defined broadly to collect all relevant data; these included vitamins and minerals, fish oils, probiotics, herbs, spices, and other diet-relevant oral supplements.

In addition to being a source of specific food and supplement intake information, these forms can be used to derive macro- and micronutrient intakes, diet patterns, and other variables of interest for nutrition researchers. In this analysis, we identified the number of cohort study sites and participants with derived variables related to dietary intake. For some variables (including macro- and micronutrient intakes), values were calculated by cohorts and shared with ECHO. Then, analysts at the centralized ECHO Data Analysis Center (DAC) [28] harmonized these data across cohorts and assessment methods by identifying similar constructs. Details on harmonization of ECHO data have been described elsewhere [17,28]. For other variables (such as diet patterns), values were calculated by DAC analysts from dietary intake data provided by cohorts.

To highlight the potential for analyses involving both subjective and objective measures of diet, we identified participants with dietary intake data who also had nutrient biomarkers, which we defined as objective measures of nutritional status from biospecimens such as blood, urine, and stool [29]. We included biomarkers that were analyzed in the ECHO-affiliated Human Health and Exposure Analysis Resource (HHEAR) [30] from biospecimens collected by cohorts prior to joining ECHO. Assays from biospecimens collected under ECHO's common protocol are forthcoming. We also included nutrient biomarkers that were measured by cohort study sites prior to joining ECHO. This may not represent all nutrient biomarkers measured by the individual cohorts. Instead, these are data that were specifically requested by the ECHO DAC for a prior analysis, and thus, are now publicly available for further use.

Statistical analysis

Descriptive statistics of pregnant persons and children included in this analysis were calculated from self-reported sociodemographic data or medical record abstraction, including maternal age at delivery, prepregnancy BMI, education, and race and ethnicity; child sex, age at enrollment, race and ethnicity, preterm status, birthweight category for gestational age (large for gestational age, small for gestational age, or neither), and year of birth; and household income.

The total number of cohort study sites and unique pregnancies or children with dietary intake data was calculated for each assessment method and categorized by life stage (for pregnant individuals: prenatal or postnatal; for children: infancy [0–1 y], early childhood [1–5 y], middle childhood [6–11 y], adolescence [12–18 y]). To illustrate opportunities for longitudinal analyses of dietary intake, the number of pregnancy-child dyads with dietary data and the number of participants with repeated measures (defined as >1 measure) was calculated for each assessment method.

To correspond with the publicly available data on the NICHD DASH, this report includes participants who have consented to the ECHO Protocol and who provided dietary data through 31 August, 2022, or biomarker data through 14 June, 2023. In supplemental tables, we also included participants who have not yet consented to data collection via the ECHO Protocol (and therefore whose data are not included in the publicly available dataset) but have consented to share previously collected data, representing sample sizes that ECHO-affiliated researchers could expect to access. While more data are being continuously added, the current analysis represents sample sizes up through year 6 of the first 7-y phase of ECHO. As data collection for the first cycle of ECHO is completed, researchers can expect increased sample sizes for the assessment methods listed in the ECHO Protocol Version 2.1 (summarized in Table 1). While potential future updates to the protocol in the second cycle of ECHO may alter the types and timing of dietary intake data collection, similar methods for collection of dietary data collection are expected to be employed.

TABLE 1
Dietary intake forms required or recommended for collection by ECHO cohort study sites according to the ECHO-wide Cohort Data Collection Protocol Version 2.1 [20]

Description		Timing for collection in ECHO protocol[1]					
24-hour dietary recalls		Prenatal	Postnatal	Infancy (0–1 y)	Early childhood (1–5 y)	Middle childhood (6–11 y)	Adolescence (12–18 y)
Automated Self-Administered 24-Hour (ASA24) Dietary Assessment Tool [21, 22]	The ASA24 is a validated online, self-administered recall tool that guides respondents through multiple passes to enter all food and beverages eaten on the previous day or in the past 24 h. Supplement use may also be collected in ASA24-2016 and later versions.	X			X	X	X
FFQs							
NCI Diet History Questionnaire 3rd ed (DHQ III)[23]	In this freely available FFQ developed by the National Cancer Institute, adults report their usual intake of a list of >100 foods, beverages, and supplements in the past 12 mo.	X[2]					
ECHO Eating Habits questionnaires (ages 2–7 and 8–17)	These proprietary questionnaires are based on validated Block FFQs for children ages 2–7 y and 8–17 y [24]. In the version for 2–7 y-olds, caregivers are asked to report the child's usual intake of a list of ~90 foods in the past 6 mo. In the version for 8–17 y-olds, the child reports their intake of ~80 foods over the past week.				X[2]	R[2]	R[2]
Screeners							
Dietary Screener Questionnaire (DSQ) [25]	Adapted from the 26-item NHANES Dietary Screener Questionnaire 2009–2010, the DSQ measures intake of fruits, vegetables, dairy, added sugars, whole grains, and red and processed meat in the past 30 d. Parent-reported DSQs are collected for children younger than 12 y, and self-reports are completed by adolescents and adults.	X[3]			X[3]	R[3]	R[3]
ECHO Maternal and Child Food Source Preparation questionnaires	These questionnaires were designed to describe food-based exposure to environmental chemicals. Participants (or for children, their caregivers) are asked to categorize their intake of a limited set of foods (including rice, fish, organic products, canned foods, and fast-food/take-out) in the past 30 d.	X			X	R	
ECHO Infant Feeding Practices questionnaire	Adapted from the Infant Feeding Practices Study II postnatal questionnaire [26], this questionnaire includes detailed questions about breastfeeding (initiation, length and frequency of feeds, use of pumped or donated milk, etc.), formula feeding (type of formula, bottle feeding practices, addition of cereals or other items to bottles), and complementary feeding (timing of introduction of solid foods).			X			
ECHO Complementary Feeding History questionnaire	In this form, caregivers are asked to report which months during the first year of life infants were given breast milk, formula, supplements, and foods and food groups. It should be completed as early as possible during the "early childhood" life stage.				X		
Supplement use							
Maternal medical record abstraction	Among the many data collected via maternal medical record abstraction, maternal supplement use from 4 wk prior to the last menstrual period to 8 wk postpartum is noted. Supplements included in this form are folic acid, prenatal vitamins, vitamin B6, vitamin D, and "other, specify."	X[4]	X[4]				
Maternal Supplements or Maternal Supplements Short Form	Adapted from the Early-Life Exposures Assessment Tool (ELEAT) (The Regents of the University of California, Davis campus), this form asks pregnant people to report their use of supplements during the 3 mo before pregnancy, through the prenatal period, and during the first year of breastfeeding (if applicable). Supplements queried on the shortened form include folic acid, prenatal vitamins, multivitamins, iron, and vitamin C. The full version asks about 22 additional vitamins, minerals, and dietary supplements, including vitamins A, B6, B12, D, and E.	X[4]	X[4]				

ECHO, Environmental influences on Child Health Outcomes; FFQ, food frequency questionnaire.
[1] X = required during this life stage, R = recommended during this life stage.
[2] Requirement can be met using the DSQ.
[3] Requirement can be met using the DHQ III (prenatal) or ECHO Eating Habits questionnaires (childhood).
[4] Timing of collection of prenatal supplement use data is not mandated. This requirement can be met with either maternal medical record abstraction or the Maternal Supplements (or Maternal Supplements Short Form) questionnaire.

Results

Number of ECHO cohorts and participants with dietary intake data

Recommended and required dietary intake assessment methods included in the ECHO Protocol Version 2.1 are summarized in Table 1. It is important to note that ECHO data are continually updated, and with a new 7-y cycle of ECHO beginning in 2023, the exact numbers presented here represent minimums and are intended to be used as benchmarks to guide future work.

Overall, 66 of the 69 ECHO cohort study sites have thus far collected publicly available dietary intake data. Cohorts' recruitment sites spanned across 34 US states and territories (Figure 1) and included a variety of participant populations and study aims. Although the majority of cohorts (n = 38) enrolled from the general population of healthy pregnant people and children, others exclusively enrolled or oversampled specific population segments, including very preterm or very low birth weight infants (n = 7), children with autism or pregnant people/children with immediate family members with autism (n = 6), children at risk for asthma and allergy (n = 3), children who had been adopted (n = 3), pregnant people who smoke (n = 2) or have psychosocial stress (n = 2), and pregnant people or children of specific race, ethnicity, or socioeconomic status (n = 6). Brief cohort study site descriptions, sample sizes, and types of dietary data collection as of this writing are presented in Supplemental Table 1. Further description of the ECHO cohort study sites in Cycle 1 is available elsewhere [17].

As of August 2022, publicly available dietary data has been collected for a total of 26,941 pregnancies (representing 24,988 pregnant individuals) and 27,103 children (Table 2 [publicly available data only] and Supplemental Table 2 [all data]). Nearly 50% of participants were non-Hispanic White; ~25% were Hispanic; ~15% were non-Hispanic black; and smaller percentages were Asian, Native Hawaiian/Pacific Islander, American Indian/Alaska Native, multiple races, or another racial/ethnic group. Approximately 46% of pregnant individuals had a bachelor's degree or higher, and 44.3% were overweight or obese prior to pregnancy. Among children, 14.8% were born preterm (<37 wk gestational age); 5.3% were small for gestational age; and 13.7% were large for gestational age. The year of child's birth ranged from 1999 to 2022, with the majority after 2014.

Number of cohorts and participants by dietary intake assessment method

Thus far in Cycle 1 of ECHO, 10 cohort study sites have collected 24-h dietary recalls, encompassing >3000 participants (1550 pregnancies, 1457 children) from the prenatal period to adolescence (Table 3, Supplemental Table 3). Most of these

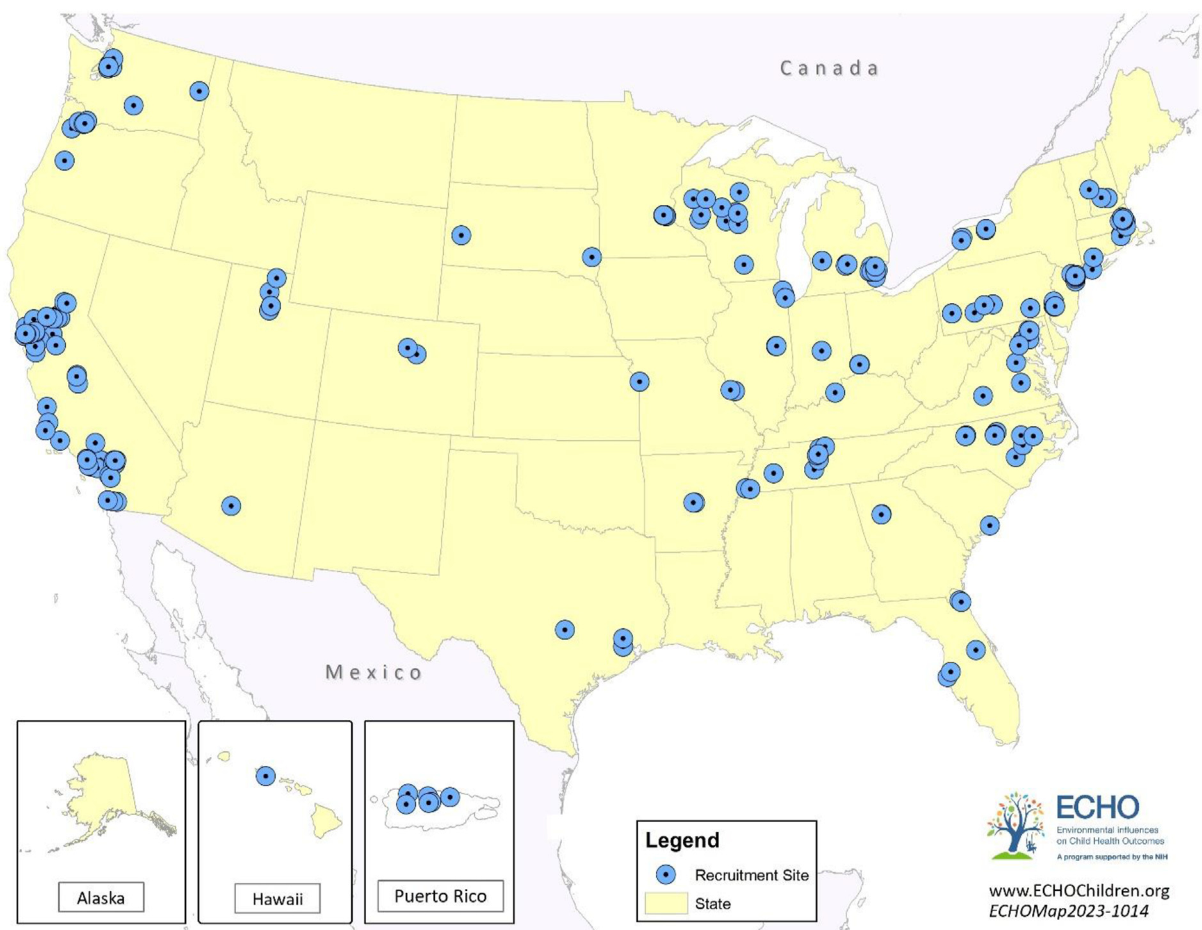

FIGURE 1. United States map of recruitment sites for the 66 Environmental influences on Child Health Outcomes (ECHO) cohorts with publicly available dietary intake data as of 31 August, 2022.

TABLE 2
Characteristics of pregnancies ($N = 26,941$) and children ($N = 27,103$) with any publicly available ECHO dietary intake data as of 31 August, 2022

Characteristics	*n* (%)
Maternal age at delivery, y	
<18–28	9092 (33.8)
29–34	9732 (36.1)
35–40	5286 (19.6)
41+	756 (2.8)
Missing	2075 (7.7)
Maternal race and ethnicity	
Non-Hispanic White	13230 (49.1)
Non-Hispanic Black	3556 (13.2)
Hispanic	6670 (24.8)
Asian	1301 (4.8)
Native Hawaiian or Pacific Islander	35 (0.1)
American Indian or Alaska Native	366 (1.4)
Multiple race	813 (3.0)
Other groups	116 (0.4)
Missing	854 (3.2)
Annual household income	
<$30,000	4424 (16.4)
$30,000–49,999	1723 (6.4)
$50,000–74,999	1311 (4.9)
$75,000–99,999	1095 (4.1)
$100,000 or more	3781 (14.0)
Missing	14607 (54.2)
Maternal education	
<High school	1913 (7.1)
High school degree or equivalent	4051 (15.0)
Some college	6138 (22.8)
Bachelor's degree	6869 (25.5)
Master's, professional, or doctoral degree	5666 (21.0)
Missing	2304 (8.6)
Maternal prepregnancy BMI, kg/m^2	
<18.5	631 (2.3)
18.5–24.9	9629 (35.7)
25–29.9	5728 (21.3)
30 or more	5920 (22.0)
Missing	5033 (18.7)
Child's sex assigned at birth	
Male	14020 (51.7)
Female	13070 (48.2)
Missing	13 (0.1)
Child's race and ethnicity	
Non-Hispanic White	12958 (47.8)
Non-Hispanic Black	3808 (14.1)
Hispanic	6699 (24.7)
Asian	796 (2.9)
Native Hawaiian or Pacific Islander	29 (0.1)
American Indian or Alaska Native	255 (0.9)
Multiple race	1986 (7.3)
Other groups	174 (0.6)
Missing	398 (1.5)
Preterm birth	
<37 wk gestational age	4020 (14.8)
Term birth	21749 (80.3)
Missing	1334 (4.9)
Size for gestational age	
Small for gestational age	1431 (5.3)
Large for gestational age	3709 (13.7)
Neither	17171 (63.4)
Missing	4792 (17.7)
Child year of birth	
1999–2004	3366 (12.4)
2005–2009	2539 (9.4)
2010–2014	8897 (32.8)
2015+	11769 (43.4)
Missing	532 (2.0)

BMI, body mass index; ECHO, Environmental influences on Child Health Outcomes.

recalls were collected during pregnancy. Two cohorts (encompassing 185 pregnancies) collected interviewer-administered 24-h recalls via the Nutrition Data System for Research developed by the Nutrition Coordinating Center, University of Minnesota, Minneapolis, MN. The rest used the Automated Self-Administered 24-Hour (ASA24) Dietary Assessment Tool [21, 22]. The ASA24 has been updated several times to reflect commonly consumed foods. In ECHO, nearly half of the recalls (46%) were collected using the ASA24-2011 version. Less than 1% were the 2014 version, and 36%, 6%, and 11% were the 2016, 2018, and 2020 versions, respectively.

FFQs were collected by 24 cohort study sites encompassing 4902 pregnancies and 4117 children. The most commonly used instrument was the Block FFQ [31]. Life stage-specific versions of this FFQ were implemented during pregnancy and childhood. These include the "ECHO Eating Habits" child diet questionnaires, which are proprietary measures based on validated Block FFQs for children [24]. Other FFQs included the Diet History Questionnaire (DHQ) II, developed by the National Cancer Institute [23], and the Willett FFQ, developed by researchers at Harvard [32]. Both of these FFQs were completed in 2 cohorts.

Over 60 cohort study sites (including 8816 pregnancies and 23,626 children) collected dietary screeners, which were further categorized as pertaining to the general diet, environmental toxins, or complementary feeding. Screeners pertaining to the general diet captured intake of food groups but were shorter and less detailed than FFQs (e.g., they captured fewer food items). The most common was the Dietary Screener Questionnaire (DSQ; 84% of all data in this category), which was adapted from the 26-item NHANES Dietary Screener Questionnaire 2009–2010 and measures intake of fruits and vegetables, dairy, added sugars, whole grains, and red and processed meat [25]. Other forms in this category included cohort-specific questionnaires collected prior to joining ECHO, such as fruit and vegetable screeners.

The second category of screeners included those focused on dietary sources of environmental and chemical toxins. Screeners in this category asked about intake of foods, such as fish (which may be high in mercury) and fruits and vegetables (which may contain pesticides), specifically for research examining environmental and chemical exposures. Although the intent of these forms was not to calculate nutritional intake, these data may be useful for certain nutrition analyses. The ECHO Maternal and Child Food Source and Preparation forms were the main source of data in this category (93% of data).

The third category of screeners included infant feeding and complementary feeding history questionnaires, which were completed for 18,741 children. These screeners describe breast feeding, formula feeding, and introduction of solid foods. Almost all (99%) of these data were collected via the ECHO Infant Feeding Practices and Complementary Feeding History questionnaires.

TABLE 3
Number of ECHO cohort study sites (and individual participants) with publicly available dietary intake data as of 31 August, 2022, by participant and life stage

	Total[1]	Pregnancies		Children			
		Prenatal	Any postnatal	Infancy (0–1 y)	Early childhood (1–5 y)	Middle childhood (6–11 y)	Adolescence (12–18 y)
	Number of cohort study sites (number of individuals)						
24-h dietary recall	10 (3045)	6 (1548)	2 (817)		3 (585)	2 (223)	2 (663)
Food frequency questionnaires	24 (9019)	10 (4902)	0		11 (2901)	9 (1240)	4 (246)
Block	22 (6891)	6 (2774)	0		11 (2901)	9 (1240)	4 (246)
Diet History Questionnaire	2 (232)	2 (232)	0		0	0	0
Willett	2 (1896)	2 (1896)	0		0	0	0
Screeners	61 (32,442)	20 (8811)	1 (479)	51 (18,741)	45 (14,391)	41 (6278)	13 (2002)
General dietary screeners	40 (12,924)	15 (6094)	1 (479)	2 (62)	19 (2359)	22 (2829)	11 (1854)
Environmental toxin focused	52 (17,348)	16 (6347)	0	0	34 (6116)	37 (5200)	5 (155)
Infant/complementary feeding	51 (18,741)			51 (18,741)			
Supplement usage (any)	66 (51,311)	56 (25,793)	32 (8549)	58 (20,746)	48 (16,917)	49 (9974)	28 (3754)
Multivitamins/prenatal vitamins	66 (46,997)	56 (25,793)	32 (8549)	38 (10,719)	41 (11,705)	49 (9883)	27 (3659)
Iron	66 (46,878)	56 (24,674)	32 (8549)	38 (10,719)	41 (11,705)	49 (9883)	27 (3659)
Folic acid	55 (24,218)	55 (24,218)	31 (8070)	0	0	0	0
Vitamin D	66 (46,875)	56 (24,671)	32 (8549)	38 (10,719)	41 (11,705)	49 (9883)	27 (3659)

ECHO, Environmental influences on Child Health Outcomes.
[1] For the "Total" column, participants are counted once per assessment method. For the remaining columns, participants are only counted once per life stage but may be included in several life stages. Cells in gray reflect data elements that cannot be collected in a given life stage.

Overall, 66 cohort study sites collected supplement use data for 24,798 pregnancies and 26,513 children, whether on dedicated supplement intake questionnaires, as modules on dietary recalls, or via medical record abstraction. Of note, data on preconception supplement use was also available among 12 cohorts and 12,892 pregnancies. Across life stages, the most commonly queried supplements were multivitamins/prenatal vitamins (collected in 92% of participants with any supplement data), iron (91% of participants), vitamin D (91%), and folic acid (pregnancy and postnatal only; collected in 97% of pregnant individuals who provided any supplement data). Other common supplements included vitamins E, A, C, B6, B12, calcium, zinc, fluoride, fish oil/ω-3 fatty acids, and probiotics (data not shown).

Repeated measures of dietary intake data

The number of pregnant individuals and children who provided more than one measure of a given dietary assessment are shown in Table 4. A total of 1246 pregnancies and 824 children provided more than one 24-h recall, representing 80% and 56% of participants who completed any 24-h recalls, respectively. Of these, 62% had 2 d of recall; 16% had 3 d of recall; and 22% had 4 or more days of recall. Time between recalls was not examined in this analysis; therefore, these values may include both repeated recalls within a short time frame and longitudinal measures of diet over time. However, dates of completion are available for all forms. Multiple FFQs were completed among 1907 pregnancies and 870 children (39% of pregnancies, 21% of children who completed any FFQs). As data collection continues under the ECHO Protocol, increases in the number of participants (particularly children) with repeated measures are expected.

TABLE 4
Number of ECHO cohort study sites (and individual participants) with repeated measures (>1 measure) of a given dietary intake assessment, as of 31 August, 2022

	Pregnancies	Children[1]
	Number of cohort study sites (number of individuals) with >1 measure of a given dietary intake assessment	
24-h dietary recall	6 (1246)	5 (824)
Food frequency questionnaires	5 (1907)	13 (870)
Screeners[2]		
General dietary screeners	5 (515)	13 (841)
Environmental toxin focused	7 (841)	14 (950)

ECHO, Environmental influences on Child Health Outcomes.
[1] Children were counted as having >1 measure regardless of whether repeated measures were within or across life stages.
[2] Screeners were limited to the dietary assessments that provided the bulk of the data for that category to represent repeated measures data that may be used in longitudinal analyses. For the "general dietary screeners" category, this was the Dietary Screener Questionnaire. For the "environmental toxin focused" category, this was the ECHO Maternal and Child Food Source and Preparation questionnaires. The "infant/complementary feeding" category was not included, as there were no true repeated measures of the Infant Feeding Practices or Complementary Feeding History questionnaires.

Within the "Screeners" categories, many participants completed multiple *different* measures in Cycle 1 of ECHO. For example, within the "general dietary screeners" category, a person may have completed a DSQ and a cohort-specific screener. To capture true "repeated measures," these categories were limited to the single assessment method which provided the bulk of the data. Within "general dietary screeners," multiple DSQs were completed for 515 pregnancies and 841 children (12% of pregnancies, 13% of children who completed any DSQs). Within "environmental toxin focused screeners," repeated measures of the Maternal and Child Food Source and Preparation questionnaires were available for 841 pregnancies and 950 children (19% of pregnancies, 9% of children with any of these questionnaires). Because all infant/complementary feeding questionnaires reflect a single, defined time span, no true repeated measures of these data were available.

For supplement intake data, no main assessment method was used. Additionally, some participants had multiple measures representing the same time period. For example, medical record abstraction of prenatal supplement use overlapped with supplement use as reported on a prenatal FFQ. For this reason, we were unable to estimate the number of individuals with true repeated measures for supplement intake. However, it should be noted that the ECHO Maternal Supplements forms ask participants to report supplement use during 3 time periods: the 3 mo before pregnancy, through the prenatal period, and during the first year of breastfeeding. By nature of the questionnaire, all of the 12,061 individuals who completed the ECHO Maternal Supplements forms have repeated measures of supplement intake data.

Maternal-child dyads with dietary intake data

A total of 22,712 pregnancy-child dyads from 58 cohort study sites provided dietary intake data (cross-tabs of maternal and child data from different diet assessment methods are shown in Table 5). Only 2 cohorts (18 dyads) provided both maternal and child 24-h recall data; however, more provided dyadic data from FFQs (7 cohorts, 1786 dyads), dietary screeners (7 cohorts, 962 dyads), and environmental toxin focused screeners (15 cohorts, 1476 dyads). Over 20,000 dyads from 57 cohorts provided maternal and child supplement intake information.

Derived variables pertinent to nutrition analyses

Several diet- and nutrition-related variables have been derived using ECHO dietary data (Table 6). When possible, data were harmonized across dietary intake assessment methods. Given that a range of dietary components and pattern scores can be calculated from the dietary data available in ECHO, these numbers represent the lower bounds of what researchers may have access to and serve as an example of readily available derived data.

Intake of micro- and macronutrients (including total energy) has been calculated for more than 5000 pregnancies and 4000 children. Intake of food groups may also be calculated using ECHO diet data. Thus far, a categorical prenatal fish consumption variable has been calculated for nearly 9000 pregnancies. ECHO data have also been used to determine index-based dietary patterns. To date, the Healthy Eating Index (HEI)-2015 score, a measure of adherence to the Dietary Guidelines for Americans [33], has been derived for 4133 pregnancies and >3,000 children, and the Empirical Dietary Inflammatory Index score, a measure of the inflammatory potential of the diet [34], has been calculated for 2746 pregnancies. Publicly available food intake data could likely be used to calculate other index-based dietary indexes (e.g., Dietary Approaches to Stop Hypertension Index [35]) in the future. Finally, variables related to breastfeeding practices at 3 and 6 mo have been harmonized across 55 cohorts to date in Cycle 1, reflecting nearly 20,000 maternal/child dyads.

Number of cohorts and participants with dietary intake data and nutrient biomarkers

Overall, 17% of participants (20% of pregnancies, 15% of children) with any type of dietary intake data also had at least one measured nutrient biomarker in Cycle 1 as of 14 June, 2023 (Table 7; Supplemental Table 4). The most commonly measured biomarkers were vitamin D, trace metals (including arsenic,

TABLE 5
Number of ECHO cohort study sites (and number of pregnancy/child dyads) with prenatal and childhood measures of a given dietary intake assessment, as of 31 August, 2022

		Child diet, any life stage					
		24-h recall	Food frequency questionnaires	Screeners			Supplement usage (any)
				General dietary screeners	Environmental toxin focused	Infant/ complementary feeding	
Pregnancy diet	24-h recall	2 (18)	1 (303)	5 (261)	7 (720)	7 (1411)	7 (1444)
	Food frequency questionnaires	2 (728)	7 (1786)	3 (93)	9 (2179)	9 (3383)	10 (4867)
	Screeners						
	General dietary screeners	3 (184)	3 (297)	7 (962)	13 (1942)	15 (3578)	16 (4246)
	Environmental toxin focused	3 (49)	5 (402)	9 (803)	15 (1476)	18 (3966)	18 (4268)
	Infant/ complementary feeding	4 (826)	18 (3352)	26 (4027)	45 (8035)	51 (18,741)	52 (19,139)
	Supplement usage (any)	5 (1448)	20 (3901)	29 (5370)	47 (9451)	45 (15,899)	57 (21,324)

ECHO, Environmental influences on Child Health Outcomes.

TABLE 6
Number of ECHO cohort study sites (and individual participants) with nutrition-related variables derived from dietary intake data as of 31 August, 2022

Derived variable(s)	Variable(s) description	Diet assessment tools included in derivation	Life stages included	Number of cohort study sites (participants)
Nutrient and energy intake	Estimated intake of total kilocalories, macronutrients (fat, carbohydrates, proteins), and micronutrients (folate, calcium, iron, etc.).	24-h recalls, FFQs, DSQ	Pregnancy	13 (5071)[1]
			Early childhood	15 (4055)[1]
			Middle childhood	13 (1890)[1]
			Adolescence	8 (1079)[1]
Fish intake	Fish consumption, 4 categories from "never/ <1x per month" to "more than twice per week"	FFQs, screeners	Pregnancy	23 (8927)
Healthy Eating Index	Total and component scores for the Healthy Eating Index-2015, a measure of adherence to the Dietary Guidelines for Americans [33]	ASA24, Block FFQ	Pregnancy	10 (4133)
			Early childhood	13 (3270)
			Middle childhood	11 (1463)
			Adolescence	6 (909)
Empirical Dietary Inflammatory Index	A measure of the inflammatory potential of the diet [34]	Block FFQ	Pregnancy	6 (2746)
Breastfeeding practices	Duration of exclusive and nonexclusive breastfeeding and child age at introduction of formula, supplements, and complementary foods	Infant Feeding Practices questionnaire, Complementary Feeding History questionnaire, child medical record abstraction	Infancy	55 (19,986)

ASA24, Automated Self-Administered 24-Hour Dietary Assessment Tool; DSQ, Dietary Screener Questionnaire; ECHO, Environmental influences on Child Health Outcomes; FFQ, food frequency questionnaire.
[1] Participant counts for nutrient and energy intake are based on "total energy intake." Small differences in the number of individuals with a given macro- or micronutrient may occur due to type and availability of nutrients provided by the dietary intake assessment method.

cadmium, and lead), and zinc. Biomarkers were measured in a range of biological matrices, including blood, urine, hair, and teeth. Of note, a subset of vitamin D, zinc, and trace metal concentrations were provided by cohorts who collected these data prior to joining ECHO and may have used varying sample collection, storage, and analytic processes. All other biomarkers were measured in the centralized HHEAR laboratory using standardized protocols [30].

As more ECHO bioassays are completed, the quantity and breadth of measured nutrient biomarkers is likely to increase. In

TABLE 7
Number of ECHO cohort study sites (and individual participants) with publicly available dietary intake data as of August 31, 2022 who also have nutrient biomarkers measured

Nutrient	Matrix	Total[1]	Pregnancies (prenatal only)	Children			
				Delivery/infancy	Early childhood	Middle childhood	Adolescence
		Number of cohort study sites (number of individuals)					
Carotenoid	Blood	8 (948)	2 (428)	0 (0)	7 (512)	1 (8)	0 (0)
Fatty acid	Blood	8 (948)	2 (428)	0 (0)	7 (512)	1 (8)	0 (0)
Folate	Blood	9 (593)	4 (461)	0 (0)	0 (0)	5 (92)	3 (40)
Iodine	Urine	10 (682)	10 (682)	0 (0)	0 (0)	0 (0)	0 (0)
Iron	Blood	9 (594)	4 (461)	0 (0)	0 (0)	5 (93)	3 (40)
Trace metals	Blood	5 (1669)	5 (1669)	0 (0)	0 (0)	0 (0)	0 (0)
	Cord blood	1 (23)	0 (0)	1 (23)	0 (0)	0 (0)	0 (0)
	Cord tissue	1 (198)	0 (0)	1 (198)	0 (0)	0 (0)	0 (0)
	Hair	1 (120)	1 (120)	0 (0)	0 (0)	0 (0)	0 (0)
	Tooth	4 (255)	0 (0)	0 (0)	0 (0)	4 (255)	0 (0)
	Urine	12 (2940)	8 (2036)	1 (<5)	2 (729)	0 (0)	1 (171)
Vitamin D	Blood	20 (4464)	10 (2793)	1 (149)	11 (1443)	8 (477)	3 (40)
	Cord blood	5 (2253)	0 (0)	5 (2253)	0 (0)	0 (0)	0 (0)
Zinc	Blood	5 (1642)	5 (1642)	0 (0)	0 (0)	0 (0)	0 (0)
	Cord tissue	1 (198)	0 (0)	1 (198)	0 (0)	0 (0)	0 (0)
	Hair	1 (120)	1 (120)	0 (0)	0 (0)	0 (0)	0 (0)
	Urine	8 (2058)	4 (1154)	1 (<5)	2 (729)	0 (0)	1 (171)

ECHO, Environmental influences on Child Health Outcomes.
[1] For the "Total" column, participants are counted once per nutrient biomarker. For the columns describing stages of childhood, participants are only counted once per life stage but may be included in several life stages.

addition, a subset of cohorts ($n = 18$) has contributed data for untargeted metabolomics (with numbers expected to increase in Cycle 2), presenting opportunities for nutrient biomarker identification and examination of metabolites.

Discussion

In its first 7-y cycle, ECHO cohort study sites have collected a wide array of longitudinal dietary intake data spanning pregnancy through adolescence from a geographically, socioeconomically, racially, and ethnically diverse sample. The main dietary assessment methods collected thus far, based on Protocol Version 2.1 and data collected by cohorts prior to joining ECHO, were FFQs and screeners, although 24-h dietary recalls were also available for >1500 pregnant individuals and >1400 children. Data on maternal and child supplement use were collected in almost every cohort. As ECHO data collection continues in its second 7-y cycle, sample sizes will increase for diet-related elements included in the ECHO Protocol (see echochildren.org for more information). Combined with other data from ECHO, including measurement of nutrient biomarkers, these dietary data represent a prime opportunity for nutrition researchers.

Strengths and limitations of dietary assessment methods in ECHO

ECHO cohort study sites employed several dietary assessment methods, each with strengths and limitations. In-depth information on uses, biases, and participant requirements for each dietary assessment method is available elsewhere [36]. Generally, the strengths and limitations of ECHO dietary data reflect those in the broader nutrition literature. Here, we briefly summarize the most relevant features.

Because 24-h recalls ask about intake on the preceding day, their accuracy is less reliant on participants' long-term memory, allowing for more accurate estimation of true short-term intake compared to other assessment methods [37]. However, single 24-h recalls do not capture daily variation in an individual's diet; generally, they are used to estimate mean intakes at the population level [38]. When multiple recalls are collected over several days (i.e., weekends and weekdays), estimates of usual intake are improved, especially when measurement error modeling is utilized [39]; however, even multiple recalls may not capture intake of seasonal or episodically consumed foods and nutrients. FFQs, and to a lesser extent screeners, can overcome this limitation by asking participants to recall how often they consumed foods over the entire year or a shorter time period [38]. However, FFQs and screeners rely on the respondent's long-term memory, and these assessment methods are generally less accurate than 24-h recalls [40,41]. All of these dietary assessment methods are subject to random and systematic error, and both 24-h recalls and FFQs are known to substantially underestimate energy intake in comparison to doubly labeled water [42–44]. ECHO-affiliated researchers are actively involved in the testing and validation of novel, less subjective dietary assessment methods, including remote food photography [45,46]. Researchers should consider the unique strengths, limitations, and intended uses of each assessment method when planning analyses using dietary intake data and seek to optimize and align methods to their specific research question.

Considerations for use of consortium data in ECHO

In addition to the strengths and challenges unique to each assessment method, combining dietary intake data across cohort study sites and assessment methods poses other challenges to consider. The ability to combine data across cohorts for analysis is a major strength of ECHO; however, harmonization of dietary data is not without its obstacles [47]. Across cohort study sites, variation in the timing of data collection may occur, including the time frame of recall, the life stage captured, and the year of collection; these differences are most pronounced among data collected by cohorts prior to the implementation of the ECHO Protocol. For example, although many Cycle 1 cohort study sites collected prenatal dietary data during midgestation, others collected these data in early and/or late pregnancy, and harmonization of timing of prenatal diet data across cohorts is ongoing as of the time of this writing. Analytic methods for assessing potential differences by cohort, such as "leave one out" sensitivity analyses, are available to ensure robustness in the pooled consortium strategy [48,49]. There are also considerations when combining dietary data across multiple assessment methods. For example, ECHO data include 3 different FFQs (Block, DHQ, and Harvard Willett). Differences in the measurement of energy and nutrient intake across these FFQs have been documented [40], although these questionnaires have since been updated. Even more complicated is the combination of data from FFQs with data from 24-h recalls or other assessment methods. In an ECHO study of micronutrient intake during pregnancy, the percentage of participants meeting micronutrient intake recommendations varied based on whether intake was measured by FFQ or 24-h recall [3]. Researchers interested in maximizing sample sizes for consortium-wide analysis must carefully consider the implications of combining dietary intake data across multiple sources and may choose to prioritize the measure best suited for the research question. Cohort- and individual-level missingness for dietary variables or relevant covariates also represents a potential concern. Of note, we were unable to investigate item-level missingness in this analysis; it is possible that individuals may have only partially completed a given dietary assessment form. Several methods are available for dealing with such missingness [50], including one developed using ECHO data [51]. Each of these challenges will become less relevant as the ECHO Program continues collecting data under a common protocol, increasing consistency of the timing and methodology for dietary data collection across cohorts.

Leveraging the strengths of ECHO for nutrition research

Despite these considerations, ECHO data represent a prime opportunity to advance our understanding of early-life diet and child health outcomes. The strengths and promise of ECHO more broadly have been outlined elsewhere, including the size and diversity of the sample, the richness of the data, the life-course approach to data collection, and a focus on solution-oriented research [17,52,53]. Here, we expand upon these strengths and connect them to promising areas of nutrition research.

First, the large and diverse sample of ECHO participants can be leveraged to examine the magnitude and nature of nutrition-related health disparities. Differences in children's BMI by geographic region have been documented using ECHO data [54]; however, variations in children's dietary intake by region and whether these variations are influenced by family- or neighborhood-level factors have yet to be explored. Differences in maternal prenatal micronutrient intake [3], fish intake, and ω-3 fatty acid supplement use by maternal age, race, ethnicity, education, and prepregnancy BMI have also been reported in ECHO. Other factors that merit investigation include demographic or regional differences in adherence to Dietary Guidelines for Americans (as measured by the HEI) and breastfeeding practices. Of note, ECHO also derives neighborhood-level data based on residential address information [55, 56], including neighborhood collective efficacy and food deserts, allowing for analysis of community traits and eating behaviors. Understanding the complexity of ecological factors that contribute to health disparities can aid in the development of policies and targeted interventions to achieve health equity [57].

Second, unlike other national nutrition surveys that assess diet among different groups of children in each wave [16], the ECHO Program involves enrollment of a single sample with repeated measures of diet and critical child health outcomes. Although early-life exposures, including nutrition, are known to influence an individual's health across the life span [58], the effects of specific perinatal dietary factors on future health are still being uncovered [10]. For example, a recent systematic review conducted by the 2020 Dietary Guidelines Advisory Committee found insufficient evidence to determine the relationship between maternal intake of common food allergens during pregnancy or lactation and children's risk of food allergy or asthma [59]. These analyses and similar analyses with other child health outcomes, such as neurodevelopment, could be investigated using ECHO data. Future work could include a focus on the identification of critical or sensitive periods for nutritional exposures [60] and early-life origins of nutrition-related health disparities [61]. This may be strengthened in the future as ECHO Cycle 2 will follow an interpregnancy preconception cohort of individuals who enrolled while pregnant and who have the potential to become pregnant with a subsequent child [20]. Preconception diet data may aid in identification of critical or sensitive periods prior to conception [62] and further add to the study of diet across preconception and prenatal periods. Moreover, ECHO Cycle 1 data (and future Cycle 2 data) also present opportunities to examine how early-life shapes dietary behaviors. For example, there is interest in how maternal diet during pregnancy and lactation influences child dietary behaviors [63] and how predictors of child diet may vary by socioeconomic status [64]. Given the cultural and socioeconomic diversity in the ECHO Program, this could be a prime opportunity for research.

Another strength of the ECHO Program is that cohort study sites span decades of data collection, with some beginning collection in the 1980s, allowing for examination of secular trends in diet over time. For example, decreases in sugar-sweetened beverage consumption among US children from 2001–2018 were identified using NHANES data [65]. Using ECHO data, similar analyses could be achieved, potentially with an expanded time interval and the inclusion of the same group of children over time. Changes in diet could also be investigated before and after major policy changes or world events. Although other national studies that collect dietary data were paused at the beginning of the COVID-19 pandemic, many cohorts in the ECHO Program continued with remote data collection [17]. The availability of detailed data related to the COVID-19 pandemic, including clinical outcomes and behavioral factors, may be utilized to address questions with high public health relevance. For example, ECHO researchers documented no change in children's sugar-sweetened beverage or discretionary food intake during the COVID-19 pandemic compared with before [66]; however, in the midst of the pandemic, differences in children's intake of sugar-sweetened beverages, fruits, and vegetables were related to financial strain and parental coping strategies [67]. ECHO data could also be used to examine nutritional status as a predictor of pregnant persons' and children's COVID-19 outcomes.

The ECHO Program features rich data collection, including self-reported questionnaires and biological samples. The measurement of biological data, such as nutrient biomarkers, presents an opportunity to examine objective measures of health. Nutrient biomarkers in particular could be used to assess the validity of subjective dietary intake and supplement use data [68], help refine biomarker cutoff values in various population groups [69], or directly examine relationships with health outcomes. ECHO data also includes nutritional and nonnutritional exposures, offering an opportunity to investigate the complex connections between early-life diet and other health factors. For example, ECHO cohorts collect extensive data on environmental exposures, such as air pollutants, heavy metals, per- and polyfluoroalkyl substances, and other chemicals [70]. Compelling biological and experimental evidence suggests that prenatal exposure to chemical toxins and nutritional factors jointly affects health and fetal programming [71–74]. Opportunities for examining the link between prenatal environmental exposures and child neurodevelopment in the ECHO Program have already been outlined [75,76]. As that work develops, the interaction of exposures with prenatal diet is a natural next step. Additionally, although genetic and epigenetic data are not included in publicly available datasets, the unique opportunities for investigating generational epigenetic effects in the ECHO Program have been highlighted [77]. ECHO-affiliated researchers may use these data to examine the interaction of genetic and epigenetic factors with early-life nutritional exposures, offering opportunities to advance the field of personalized nutrition.

Novel and impactful research questions may require sophisticated statistical techniques. Fortunately, ECHO's large sample size paired with the analytic expertise at the centralized ECHO DAC allows for such advanced statistical analyses. For example, ECHO's environmental exposure data have been utilized in exposomic analyses [30] and mixture modeling [78], 2 techniques that could be useful when applied to studies with nutrition-related aims. ECHO-affiliated researchers also have demonstrated expertise in analytic approaches to identify periods of susceptibility in children's development [79], which could be applied to periods of specific import for nutritional intake.

The ECHO Program aims to use these strengths to conduct solution-oriented research. For nutrition, this could include research to promote the development of dietary guidelines and interventions. The 2020–2025 Dietary Guidelines for Americans Scientific Advisory Committee identified numerous gaps in the existing evidence underlying the recommendations specific to pregnant persons, infants and toddlers, and young children [11]. ECHO data can be used to examine these research questions. For example, the Dietary Guidelines committee recommends further research on the relationship between maternal dietary supplement intake of vitamin B12, vitamin D, iron, and choline and maternal and child outcomes; these data are available in the ECHO Program. Epidemiological analyses of dietary data in the ECHO Program can then inform the development and design of interventions for testing in the ECHO Program's Institutional Development Award States Pediatric Clinical Trials Network (ISPCTN) [80], the goals of which are to build national capacity for conducting pediatric clinical trials in underserved rural populations. Thus far, 2 of the 4 completed ECHO ISPCTN trials have had nutrition as a focus. One was designed to determine the pharmacokinetics of vitamin D supplementation in children who have asthma and overweight or obesity [81], and one tested a family-based group program using mobile health technology to improve child weight, nutrition, and physical activity [82]. Careful planning of nutrition-related hypotheses and analysis of cohort data with the intention of informing clinical trials within the ECHO ISPCTN and elsewhere will allow for more rapid translation of observational data to action.

Conclusions

ECHO Program cohort study sites have collected a wide array of dietary intake assessments spanning from pregnancy to adolescence, including FFQs, 24-h recalls, and screeners. These longitudinal data come from a geographically, socioeconomically, racially, and ethnically diverse sample of pregnant persons and children across the United States. As ECHO data are publicly available, they present a rich opportunity to advance the field of early-life nutrition and child health for ECHO-affiliated investigators and the broader research community.

Acknowledgments

ECHO collaborators acknowledgments

The authors wish to thank our ECHO Colleagues; the medical, nursing, and program staff; and the children and families participating in the ECHO cohorts. We also acknowledge the contribution of the following ECHO Program collaborators:

ECHO Components—Coordinating Center: Duke Clinical Research Institute, Durham, NC: Smith PB, Newby LK; Data Analysis Center: Johns Hopkins University Bloomberg School of Public Health, Baltimore, MD: Jacobson LP; Research Triangle Institute, Durham, NC: Catellier DJ; Person-Reported Outcomes Core, Northwestern University, Evanston, IL: Gershon R, Cella D; Human Health Exposure Analysis Resource, Wadsworth Center, Menands, NY: Parsons P, Kurunthachalam K; RTI International, Research Triangle Park, North Carolina: Fennell TR, Sumner SJ, Du X; Westat, Rockville, MD: O'Brien, B; University of Minnesota, Minneapolis, MN, Peterson LA; Icahn School of Medicine at Mount Sinai, New York City, NY: Arora M, Teitelbaum SL, Wright RO; Duke University, Durham, NC: Stapleton, HM, Ferguson, PL.

ECHO Awardees and Cohorts—University of Georgia, Athens, GA: Cordero J; University of Michigan, Ann Arbor, MI: Meeker J; Albert Einstein College of Medicine, Bronx, NY: Aschner J; Icahn School of Medicine at Mount Sinai, New York, NY: Teitelbaum SL; Icahn School of Medicine at Mount Sinai, New York, NY and Cohen Children's Medical Center, Northwell Health, New Hyde Park, NY: Stroustrup A; Cincinnati Children's Hospital Medical Center, Cincinnati, OH: Merhar S; Children's Hospital and Clinic Minnesota, Minneapolis, MN: Lampland A; University of Buffalo, Buffalo, NY: Reynolds A; University of Florida, College of Medicine, Jacksonville, FL: Hudak M; University of Rochester Medical Center, Rochester, NY: Pryhuber G; Vanderbilt Children's Hospital, Nashville, TN: Moore P; Wake Forest University School of Medicine, Winston Salem, NC: Washburn L; New York University Grossman School of Medicine, New York, NY: Trasande L; Pennsylvania State University, University Park, PA: Gatzke-Kopp L; University of North Carolina, Chapel Hill, NC: Swingler M; Arnold Palmer Hospital for Children, Orlando, FL: Laham FR; Boston Children's Hospital, Boston, MA: Mansbach JM; Children's Hospital of Los Angeles, Los Angeles, CA: Wu S; Children's Hospital of Philadelphia, Philadelphia, PA: Spergel JM; Children's Hospital of Pittsburgh of UPMC, Pittsburgh, PA: Celedón JC; Children's Mercy Hospital & Clinics, Kansas City, MO: Puls HT; Children's National Hospital, Washington, DC: Teach SJ; Cincinnati Children's Hospital and Medical Center, Cincinnati, OH: Porter SC; Connecticut Children's Medical Center, Hartford, CT: Waynik IY; Dell Children's Medical Center of Central Texas, Austin, TX: Iyer SS; Massachusetts General Hospital, Boston, MA: Samuels-Kalow ME; Nemours Children's Hospital, Wilmington, DE: Thompson AD; Norton Children's Hospital, Louisville, KY: Stevenson MD; Phoenix Children's Hospital, Phoenix AZ: Bauer CS; Oklahoma University – Tulsa, Tulsa, OK: Inhofe NR; Seattle Children's Hospital, Seattle, WA: Boos M; Texas Children's Hospital, Houston, TX: Macias CG; Rhode Island Hospital, Providence RI: Koinis Mitchell D; Rhode Island Hospital, Providence RI: Deoni S, D'Sa V; New York State Psychiatric Institute, New York, NY: Duarte CS; New York State Psychiatric Institute, New York, NY and Columbia University Vagelos College of Physicians and Surgeons, New York, NY: Monk C; Duke University Department of Psychiatry and Behavioral Sciences, Durham, NC: Posner J; University of Puerto Rico, Rio Piedras, PR: Canino G; Avera Research Institute, Sioux Falls, SD: Elliott AJ; Kaiser Permanente Northern California Division of Research, Oakland, CA: Ferrara A; Kaiser Permanente Northern California Division of Research, Oakland, CA: Croen L; Columbia University Medical Center, New York, NY: Herbstman J; University of Wisconsin, Madison WI: Gern J; Icahn School of Medicine at Mount Sinai, New York, NY: Miller R; Columbia University Medical Center, New York, NY: Perera F; Henry Ford Health System, Detroit, MI: Zoratti E; Marshfield Clinic Research Institute, Marshfield, WI: Seroogy C, Bendixsen C; University of Wisconsin, Madison, WI: Jackson D; Boston Medical Center, Boston, MA: Bacharier L, O'Connor G; Children's Hospital of New York, New York, NY: Bacharier L, Kattan M; Johns Hopkins University, School of Medicine, Baltimore, MD: Wood R; Washington University in St Louis, St Louis, MO: Rivera-Spoljaric K, Bacharier L; Cincinnati Children's Hospital Medical Center, Cincinnati, OH: Hershey G; Vanderbilt University, Nashville, TN: Hartert T; Brigham and Women's Hospital, Channing Network Division of Network Medicine, Boston, MA: Gold D; Henry Ford Health System, Detroit, MI: Johnson C; Henry Ford Health System, Detroit, MI: Ownby D; University of Wisconsin, Madison, WI: Singh A; University of Southern California, Los Angeles, CA: Breton C, Bastain T, Farzan S, Habre R; University of California Davis Health, MIND

Institute, Sacramento, CA: Hertz-Picciotto I; University of Pittsburgh, Pittsburgh, PA: Hipwell A; University of Washington, Department of Environmental and Occupational Health Sciences, Seattle, WA: Karr C; University of California, San Francisco, San Francisco, CA: Bush N, LeWinn KZ; University of Minnesota, Minneapolis, MN: Nguyen R; University of Rochester Medical Center, Rochester, NY: Barrett E; Seattle Children's Research Institute, Seattle, WA: Sathyanarayana S; Icahn School of Medicine at Mount Sinai, New York, NY: Swan S; University of Tennessee Health Science Center, Memphis, TN: Tylavsky F, Mason A, Zhao Q; Women & Infants Hospital of Rhode Island, Providence RI, Lester B; Children's Mercy, Kansas City, MO: Carter B; Corewell Health, Helen DeVos Children's Hospital, Grand Rapids, MI: Pastyrnak S; Kapiolani Medical Center for Women and Children, Providence, RI: Neal C; Los Angeles Biomedical Research Institute at Harbour-UCLA Medical Center, Los Angeles, CA: Smith L; Wake Forest University School of Medicine, Winston Salem, NC: Helderman J; Prevention Science Institute, University of Oregon, Eugene, OR: Leve L; George Washington University, Washington, DC: Ganiban J; Pennsylvania State University, University Park, PA: Neiderhiser J; University of New Mexico Health Sciences Center, Albuquerque, NM: Lewis J; Brigham and Women's Hospital, Boston, MA: Weiss ST; Golisano Children's Hospital, Rochester, NY: Litonjua A; Boston University Medical Center, Boston, MA: O'Connor G; Kaiser Permanente, Southern California, San Diego, CA: Zeiger R; Oregon Health and Science University, Portland, OR: McEvoy C; Indiana University, Riley Hospital for Children, Indianapolis, IN: Tepper R; John Hopkins Bloomberg School of Public Health, Baltimore, MD: Volk H; Kennedy Krieger Institute, Baltimore, MD: Landa R; University of California Davis Health, MIND Institute, Sacramento, CA: Ozonoff S; University of California Davis Health, MIND Institute, Davis, CA: Schmidt R; University of Washington, Seattle, WA: Dager S; Children's Hospital of Philadelphia - Center for Autism Research, Philadelphia, PA: Schultz R; University of North Carolina at Chapel Hill, Chapel Hill, NC: Piven J; University of Pittsburgh Medical Center, Magee Women's Hospital, Pittsburgh, PA: Simhan H; Baystate Children's Hospital, Springfield, MA: Vaidya R; Beaumont Children's Hospital, Royal Oak, MI: Obeid R; Boston Children's Hospital, Boston, MA: Rollins C; East Carolina University, Brody School of Medicine, Greenville, NC: Bear K; Michigan State University College of Human Medicine, East Lansing, MI: Lenski M; Tufts University School of Medicine, Boston, MA: Singh R; University of Chicago, Chicago, IL: Msall M; University of Massachusetts Chan Medical School, Worcester, MA: Frazier J; Atrium Health Wake Forest Baptist, Winston Salem, NC: Gogcu S; Yale School of Medicine, New Haven, CT: Montgomery A; Boston Medical Center, Boston, MA: Kuban K, Douglass L, Jara H; Boston University, Boston, MA: Joseph R; Henry Ford Health, Detroit, MI: Barone C; Michigan Department of Health and Human Services, Lansing, MI: Fussman C; Michigan State University, East Lansing, MI: Paneth N; University of Michigan, Ann Arbor, MI: Elliott M; Wayne State University, Detroit, MI: Ruden D; University of Illinois, Beckman Institute, Urbana, IL: Schantz S; University of California, San Francisco, San Francisco, CA: Woodruff T; University of Utah, Salt Lake City, UT: Stanford J, Porucznik C, Giardino A; Utah State University, Logan, UT: Innocenti M; University of Utah, Salt Lake City, UT: Silver R; University of Utah, Salt Lake City, UT: Conradt E; Icahn School of Medicine at Mount Sinai, New York, NY: Wright RJ, Wright RO; Boston Children's Hospital, Boston, MA: Bosquet-Enlow M; George Mason University, Fairfax, VA: Huddleston K.

Author contributions

The authors' responsibilities were as follows—KL, DD: conceived of this project. MGB, KL: developed the overall research plan with feedback from TAB, DC, SC, DD, NK, JMK, SM, LM, MM, NM, EO, KMS, KAS; MW, MEN: performed the statistical analysis; MGB: drafted the manuscript based on contributions from TAB, DJC, SSC, DD, NRK, JMK, SM, LEM, MMM, NTM, EO, KMS, KAS, RJW; ANA, CAC, ALD, MMH, CWH, MRK, KK, DM, LM, TGO, TMO, VS, ROW, XZ, YZ: provided substantial feedback on drafts; and all authors: read and approved the final manuscript.

Funding

Research reported in this publication was supported by the Environmental influences on Child Health Outcomes (ECHO) program, Office of the Director, National Institutes of Health, under Award Numbers U2COD023375 (Coordinating Center), U24OD023382 (Data Analysis Center), U24OD023319 with co-funding from the Office of Behavioral and Social Science Research (PRO Core), U24ES026539 (HHEAR O'Brien), U2CES026533 (HHEAR Peterson), U2CES026542 (HHEAR Parsons, Kannan), UH3OD023251 (Alshawabkeh), UH3OD023320 (Aschner), UH3OD023332 (Trasande), UH3OD023253 (Camargo), UH3OD023248 (Dabelea), UH3OD023313 (Koinis Mitchell), UH3OD023328 (Duarte), UH3OD023318 (Dunlop), UH3OD023279 (Elliott), UH3OD023289 (Ferrara), UH3OD023282 (Gern), UG3/UH3OD023287 (Breton/Maldonado), UH3OD023365 (Hertz-Picciotto), UH3OD023244 (Hipwell), UH3OD023275 (Karagas), UH3OD023271 (Karr), UH3OD023347 (Lester), UH3OD023389 (Leve), UH3OD023344 (MacKenzie), UH3OD023268 (Weiss), UH3OD023288 (McEvoy), UH3OD023342 (Lyall), UH3OD023349 (O'Connor), UH3OD023286 (Oken), UH3OD023348 (O'Shea), UH3OD023285 (Kerver), UH3OD023290 (Herbstman), UH3OD023272 (Schantz), UH3OD023249 (Stanford), UH3OD023305 (Trasande), and UH3OD023337 (Wright).

Role of funder

The sponsor, National Institutes of Health (NIH), participated in the overall design and implementation of the ECHO Program, which was funded as a cooperative agreement between NIH and grant awardees. The sponsor approved the Steering Committee-developed ECHO protocol and its amendments, including COVID-19 measures. The sponsor had no access to the central database, which was housed at the ECHO Data Analysis Center. Data management and site monitoring were performed by the ECHO Data Analysis Center and Coordinating Center. All analyses for scientific publication were performed by the study statistician, independently of the sponsor. The lead author wrote all drafts of the manuscript and made revisions based on co-authors' and the ECHO Publication Committee's (a subcommittee of the ECHO Steering Committee) feedback without input from the sponsor. The study sponsor did not review nor approve the manuscript for submission to the journal.

Disclaimer

The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

Data availability

Select deidentified data from the ECHO Program are available through NICHD's Data and Specimen Hub (DASH) (https://dash.nichd.nih.gov). Information on study data not available on DASH, such as some Indigenous datasets, can be found on the ECHO study DASH webpage (https://dash.nichd.nih.gov/study/417122).

Conflict of interest

The authors report no conflicts of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cdnut.2023.102019.

References

[1] A.D.L. Bailey, V.L. Fulgoni III, N. Shah, A.C. Patterson, F. Gutierrez-Orozco, R.S. Mathews, et al., Nutrient intake adequacy from food and beverage intake of US children aged 1-6 years from NHANES 2001-2016, Nutrients 13 (3) (2021) 827, https://doi.org/10.3390/nu13030827.

[2] R.L. Bailey, S.G. Pac, V.L. Fulgoni III, K.C. Reidy, P.M. Catalano, Estimation of total usual dietary intakes of pregnant women in the United States, JAMA Netw. Open 2 (6) (2019) e195967, https://doi.org/10.1001/jamanetworkopen.2019.5967.

[3] K.A. Sauder, R.N. Harte, B.M. Ringham, P.M. Guenther, R.L. Bailey, A. Alshawabkeh, et al., Disparities in risks of inadequate and excessive intake of micronutrients during pregnancy, J. Nutr. 151 (11) (2021) 3555–3569, https://doi.org/10.1093/jn/nxab273.

[4] R.L. Bailey, J.D. Ard, T.A. Davis, T.S. Naimi, B.O. Schneeman, J.S. Stang, et al., A proposed framework for identifying nutrients and food components of public health relevance in the Dietary Guidelines for Americans, J. Nutr. 151 (5) (2021) 1197–1204, https://doi.org/10.1093/jn/nxaa459.

[5] Y. Wang, D. Guglielmo, J.A. Welsh, Consumption of sugars, saturated fat, and sodium among US children from infancy through preschool age, NHANES 2009-2014, Am. J. Clin. Nutr. 108 (4) (2018) 868–877, https://doi.org/10.1093/ajcn/nqy168.

[6] A.D. Guerrero, P.J. Chung, Racial and ethnic disparities in dietary intake among California children, J. Acad. Nutr. Diet. 116 (3) (2016) 439–448, https://doi.org/10.1016/j.jand.2015.08.019.

[7] S.I. Kirkpatrick, K.W. Dodd, J. Reedy, S.M. Krebs-Smith, Income and race/ethnicity are associated with adherence to food-based dietary guidance among US adults and children, J. Acad. Nutr. Diet. 112 (5) (2012) 624–635.e6, https://doi.org/10.1016/j.jand.2011.11.012.

[8] S.W. Ng, J.M. Poti, B.M. Popkin, Trends in racial/ethnic and income disparities in foods and beverages consumed and purchased from stores among US households with children, 2000-2013, Am. J. Clin. Nutr. 104 (3) (2016) 750–759, https://doi.org/10.3945/ajcn.115.127944.

[9] A.R. Quiñones, A. Botoseneanu, S. Markwardt, C.L. Nagel, J.T. Newsom, D.A. Dorr, et al., Racial/ethnic differences in multimorbidity development and chronic disease accumulation for middle-aged adults, PLOS ONE 14 (6) (2019) e0218462, https://doi.org/10.1371/journal.pone.0218462.

[10] N.E. Marshall, B. Abrams, L.A. Barbour, P. Catalano, P. Christian, J.E. Friedman, et al., The importance of nutrition in pregnancy and lactation: lifelong consequences, Am. J. Obstet. Gynecol. 226 (5) (2022) 607–632, https://doi.org/10.1016/j.ajog.2021.12.035.

[11] Dietary Guidelines Advisory Committee, Scientific Report of the 2020 Dietary Guidelines Advisory Committee: Advisory Report to the Secretary of Agriculture and the Secretary of Health and Human Services, U.S. Department of Agriculture, Washington, DC, 2020.

[12] K.J. Brunst, R.O. Wright, K. DiGioia, M.B. Enlow, H. Fernandez, R.J. Wright, et al., Racial/ethnic and sociodemographic factors associated with micronutrient intakes and inadequacies among pregnant women in an urban US population, Public Health Nutr 17 (9) (2014) 1960–1970, https://doi.org/10.1017/s1368980013003224.

[13] M.N. Kooijman, C.J. Kruithof, C.M. van Duijn, L. Duijts, O.H. Franco, M.H. van IJzendoorn, et al., The Generation R Study: design and cohort update 2017, Eur. J. Epidemiol. 31 (12) (2016) 1243–1264, https://doi.org/10.1007/s10654-016-0224-9.

[14] A. Fraser, C. Macdonald-Wallis, K. Tilling, A. Boyd, J. Golding, G. Davey Smith, et al., Cohort profile: the Avon Longitudinal Study of Parents and Children: ALSPAC mothers cohort, Int. J. Epidemiol. 42 (1) (2013) 97–110, https://doi.org/10.1093/ije/dys066.

[15] P. Magnus, C. Birke, K. Vejrup, A. Haugan, E. Alsaker, A.K. Daltveit, et al., Cohort profile update: the Norwegian Mother and Child Cohort study (MoBa), Int. J. Epidemiol. 45 (2) (2016) 382–388, https://doi.org/10.1093/ije/dyw029.

[16] N. Ahluwalia, J. Dwyer, A. Terry, A. Moshfegh, C. Johnson, Update on NHANES dietary data: focus on collection, release, analytical considerations, and uses to inform public policy, Adv. Nutr. 7 (1) (2016) 121–134, https://doi.org/10.3945/an.115.009258.

[17] E.A. Knapp, A.M. Kress, C.B. Parker, G.P. Page, K. McArthur, K.K. Gachigi, et al., The Environmental influences on Child Health Outcomes (ECHO)-wide cohort, Int. J. Epidemiol. 192 (8) (2023) 1249–1263, https://doi.org/10.1093/aje/kwad071.

[18] M.W. Gillman, C.J. Blaisdell, Environmental influences on Child Health Outcomes, a research program of the National Institutes of Health, Curr. Opin. Pediatr. 30 (2) (2018) 260–262, https://doi.org/10.1097/MOP.0000000000000600.

[19] M. Gillman, Environmental Influences on Child Health Outcomes (ECHO)-wide Cohort (Version 1), NICHD Data and Specimen Hub, 2022.

[20] Environmental influences on Child Health Outcomes (ECHO)-wide Cohort Data Collection Protocol, Version 2.1, National Institutes of Health, Bethesda.

[21] A.F. Subar, S.I. Kirkpatrick, B. Mittl, T.P. Zimmerman, F.E. Thompson, C. Bingley, et al., The Automated Self-Administered 24-hour dietary recall (ASA24): a resource for researchers, clinicians, and educators from the National Cancer Institute, J. Acad. Nutr. Diet. 112 (8) (2012) 1134–1137, https://doi.org/10.1016/j.jand.2012.04.016.

[22] S.I. Kirkpatrick, A.F. Subar, D. Douglass, T.P. Zimmerman, F.E. Thompson, L.L. Kahle, et al., Performance of the Automated Self-Administered 24-hour Recall relative to a measure of true intakes and to an interviewer-administered 24-h recall, Am. J. Clin. Nutr. 100 (1) (2014) 233–240, https://doi.org/10.3945/ajcn.114.083238.

[23] Diet History Questionnaire, Version 2.0, National Institutes of Health, Epidemiology and Genomics Research Program, National Cancer Institute, Bethesda, MD, 2010.

[24] K.W. Cullen, K. Watson, I. Zakeri, Relative reliability and validity of the Block Kids Questionnaire among youth aged 10 to 17 years, J. Am. Diet. Assoc. 108 (5) (2008) 862–866, https://doi.org/10.1016/j.jada.2008.02.015.

[25] Background [Internet]. National Cancer Institute [cited 9 February], Dietary Screener Questionnaire in the NHANES 2009-10, 2023. Available from: https://epi.grants.cancer.gov/nhanes/dietscreen/.

[26] S.B. Fein, J. Labiner-Wolfe, K.R. Shealy, R. Li, J. Chen, L.M. Grummer-Strawn, Infant Feeding Practices Study II: study methods, Pediatrics 122 (suppl 2) (2008) S28–S35, https://doi.org/10.1542/peds.2008-1315c.

[27] US Department of Agriculture, US Department of Health and Human Services, Dietary Guidelines for Americans, 2020–2025, 9th ed., United States Department of Agriculture, Bethesda, MD, 2020.

[28] L.P. Jacobson, B. Lau, D. Catellier, C.B. Parker, An Environmental influences on Child Health Outcomes viewpoint of data analysis centers for collaborative study designs, Curr. Opin. Pediatr. 30 (2) (2018) 269–275, https://doi.org/10.1097/MOP.0000000000000602.

[29] N. Potischman, J.L. Freudenheim, Biomarkers of nutritional exposure and nutritional status: an overview, J. Nutr. 133 (3) (2003) 873S–874S, https://doi.org/10.1093/jn/133.3.873S.

[30] S.M. Viet, J.C. Falman, L.S. Merrill, E.M. Faustman, D.A. Savitz, N. Mervish, et al., Human Health Exposure Analysis Resource (HHEAR): a model for incorporating the exposome into health studies, Int. J. Hyg. Environ. Health 235 (2021) 113768, https://doi.org/10.1016/j.ijheh.2021.113768.
[31] G. Block, M. Woods, A. Potosky, C. Clifford, Validation of a self-administered diet history questionnaire using multiple diet records, J. Clin. Epidemiol. 43 (12) (1990) 1327–1335, https://doi.org/10.1016/0895-4356(90)90099-b.
[32] W.C. Willett, L. Sampson, M.J. Stampfer, B. Rosner, C. Bain, J. Witschi, et al., Reproducibility and validity of a semiquantitative food frequency questionnaire, Am. J. Epidemiol. 122 (1) (1985) 51–65, https://doi.org/10.1093/oxfordjournals.aje.a114086.
[33] J. Reedy, J.L. Lerman, S.M. Krebs-Smith, S.I. Kirkpatrick, T.E. Pannucci, M.M. Wilson, et al., Evaluation of the Healthy Eating Index-2015, J. Acad. Nutr. Diet. 118 (9) (2018) 1622–1633, https://doi.org/10.1016/j.jand.2018.05.019.
[34] F.K. Tabung, S.A. Smith-Warner, J.E. Chavarro, K. Wu, C.S. Fuchs, F.B. Hu, et al., Development and validation of an empirical dietary inflammatory index, J. Nutr. 146 (8) (2016) 1560–1570, https://doi.org/10.3945/jn.115.228718.
[35] P.R. Conlin, The dietary approaches to stop hypertension (DASH) clinical trial: implications for lifestyle modifications in the treatment of hypertensive patients, Cardiol. Rev. 7 (5) (1999) 284–288, https://doi.org/10.1097/00045415-199909000-00013.
[36] Dietary Assessment Primer [Internet], National Cancer Institute, 2023 cited 10 February, https://dietassessmentprimer.cancer.gov/.
[37] A. Schatzkin, V. Kipnis, R.J. Carroll, D. Midthune, A.F. Subar, S. Bingham, et al., A comparison of a food frequency questionnaire with a 24-hour recall for use in an epidemiological cohort study: results from the biomarker-based Observing Protein and Energy Nutrition (OPEN) study, Int. J. Epidemiol. 32 (6) (2003) 1054–1062, https://doi.org/10.1093/ije/dyg264.
[38] R.S. Gibson, Principles of Nutritional Assessment [Internet]. [cited 13 February], 3rd Edition, 2023. Available from: https://nutritionalassessment.org/.
[39] J.A. Tooze, V. Kipnis, D.W. Buckman, R.J. Carroll, L.S. Freedman, P.M. Guenther, et al., A mixed-effects model approach for estimating the distribution of usual intake of nutrients: the NCI method, Stat. Med. 29 (27) (2010) 2857–2868, https://doi.org/10.1002/sim.4063.
[40] A.F. Subar, F.E. Thompson, V. Kipnis, D. Midthune, P. Hurwitz, S. McNutt, et al., Comparative validation of the Block, Willett, and National Cancer Institute food frequency questionnaires: the Eating at America's Table Study, Am. J. Epidemiol. 154 (12) (2001) 1089–1099, https://doi.org/10.1093/aje/154.12.1089.
[41] Y. Park, K.W. Dodd, V. Kipnis, F.E. Thompson, N. Potischman, D.A. Schoeller, et al., Comparison of self-reported dietary intakes from the Automated Self-Administered 24-h recall, 4-d food records, and food-frequency questionnaires against recovery biomarkers, Am. J. Clin. Nutr. 107 (1) (2018) 80–93, https://doi.org/10.1093/ajcn/nqx002.
[42] S. Mahabir, D.J. Baer, C. Giffen, A. Subar, W. Campbell, T.J. Hartman, et al., Calorie intake misreporting by diet record and food frequency questionnaire compared to doubly labeled water among postmenopausal women, Eur. J. Clin. Nutr. 60 (4) (2006) 561–565, https://doi.org/10.1038/sj.ejcn.1602359.
[43] A.F. Subar, V. Kipnis, R.P. Troiano, D. Midthune, D.A. Schoeller, S. Bingham, et al., Using intake biomarkers to evaluate the extent of dietary misreporting in a large sample of adults: the OPEN study, Am. J. Epidemiol. 158 (1) (2003) 1–13, https://doi.org/10.1093/aje/kwg092.
[44] L.S. Freedman, J.M. Commins, J.E. Moler, L. Arab, D.J. Baer, V. Kipnis, et al., Pooled results from 5 validation studies of dietary self-report instruments using recovery biomarkers for energy and protein intake, Am. J. Epidemiol. 180 (2) (2014) 172–188, https://doi.org/10.1093/aje/kwu116.
[45] T.A. Bekelman, C.K. Martin, S.L. Johnson, D.H. Glueck, K.A. Sauder, K.K. Harrall, et al., A comparison of the remote food photography method and the Automated Self-Administered 24-h dietary assessment tool for measuring full-day dietary intake among school-age children, Br. J. Nutr. 127 (8) (2022) 1269–1278, https://doi.org/10.1017/S0007114521001951.
[46] T.A. Bekelman, S.L. Johnson, R.I. Steinberg, C.K. Martin, K.A. Sauder, S. Luckett-Cole, et al., A qualitative analysis of the remote food photography method and the Automated Self-Administered 24-hour Dietary Assessment Tool for assessing children's food intake reported by parent proxy, J. Acad. Nutr. Diet. 122 (5) (2022) 961–973, https://doi.org/10.1016/j.jand.2021.11.001.
[47] K. Adhikari, S.B. Patten, A.B. Patel, S. Premji, S. Tough, N. Letourneau, et al., Data harmonization and data pooling from cohort studies: a practical approach for data management, Int. J. Popul. Data Sci. 6 (1) (2021) 1680, https://doi.org/10.23889/ijpds.v6i1.1680.
[48] C.R. Lesko, L.P. Jacobson, K.N. Althoff, A.G. Abraham, S.J. Gange, R.D. Moore, et al., Collaborative, pooled and harmonized study designs for epidemiologic research: challenges and opportunities, Int. J. Epidemiol. 47 (2) (2018) 654–668, https://doi.org/10.1093/ije/dyx283.
[49] B.H. Willis, R.D. Riley, Measuring the statistical validity of summary meta-analysis and meta-regression results for use in clinical practice, Stat. Med. 36 (21) (2017) 3283–3301, https://doi.org/10.1002/sim.7372.
[50] N.J. Perkins, S.R. Cole, O. Harel, E.J. Tchetgen Tchetgen, B. Sun, E.M. Mitchell, et al., Principled approaches to missing data in epidemiologic studies, Am. J. Epidemiol. 187 (3) (2018) 568–575, https://doi.org/10.1093/aje/kwx348.
[51] E. Smirnova, Y. Zhong, R. Alsaadawi, X. Ning, A.M. Kress, J. Kuiper, et al., Missing data interpolation in integrative multi-cohort analysis with disparate covariate information, Biostatistics 0 (0) (2022) 1–29, https://doi.org/10.1093/biostatistics/samplebibtex.
[52] M.E. Romano, J.P. Buckley, A.J. Elliott, C.C. Johnson, N. Paneth, program collaborators for Environmental influences on Child Health Outcomes, SPR perspectives: scientific opportunities in the Environmental influences on Child Health Outcomes Program, Pediatr. Res. 92 (5) (2022) 1255–1261, https://doi.org/10.1038/s41390-021-01577-5.
[53] K.Z. LeWinn, E. Caretta, A. Davis, A.L. Anderson, E. Oken, program collaborators for Environmental influences on Child Health Outcomes, SPR perspectives: environmental influences on Child Health Outcomes (ECHO) program: overcoming challenges to generate engaged, multidisciplinary science, Pediatr. Res. 92 (5) (2022) 1262–1269, https://doi.org/10.1038/s41390-021-01598-0.
[54] T.A. Bekelman, D. Dabelea, J.M. Ganiban, A. Law, A. McGovern Reilly, K.N. Althoff, et al., Regional and sociodemographic differences in average BMI among US children in the ECHO program, Obesity (Silver Spring) 29 (12) (2021) 2089–2099, https://doi.org/10.1002/oby.23235.
[55] I.M. Aris, W. Perng, D. Dabelea, A.M. Padula, A. Alshawabkeh, C.M. Vélez-Vega, et al., Associations of neighborhood opportunity and social vulnerability with trajectories of childhood body mass index and obesity among US children, JAMA Netw. Open 5 (12) (2022) e2247957, https://doi.org/10.1001/jamanetworkopen.2022.47957.
[56] S.E. Martenies, M. Zhang, A.E. Corrigan, A. Kvit, T. Shields, W. Wheaton, et al., Associations between combined exposure to environmental hazards and social stressors at the neighborhood level and individual perinatal outcomes in the ECHO-wide cohort, Health Place 76 (2022) 102858, https://doi.org/10.1016/j.healthplace.2022.102858.
[57] S. Friel, L. Hattersley, L. Ford, K. O'Rourke, Addressing inequities in healthy eating, Health Promot. Int. 30 (suppl 2) (2015) ii77–ii88, https://doi.org/10.1093/heapro/dav073.
[58] J. Baird, C. Jacob, M. Barker, C.H. Fall, M. Hanson, N.C. Harvey, et al., Developmental Origins of Health and Disease: a lifecourse approach to the prevention of non-communicable diseases, Healthcare (Basel) 5 (1) (2017) 14, https://doi.org/10.3390/healthcare5010014.
[59] S. Donovan, K. Dewey, R. Novotny, J. Stang, E. Taveras, R. Kleinman, et al., Maternal diet during pregnancy and lactation and risk of child food allergies and atopic allergic diseases: a systematic review, Alexandria, VA, in: USDA Nutrition Evidence Systematic Reviews, 2020. Available from: https://www.ncbi.nlm.nih.gov/books/NBK578647/.
[60] W.H. Dietz, Critical periods in childhood for the development of obesity, Am. J. Clin. Nutr. 59 (5) (1994) 955–959, https://doi.org/10.1093/ajcn/59.5.955.
[61] P. Braveman, C. Barclay, Health disparities beginning in childhood: a life-course perspective, Pediatrics 124 (suppl 3) (2009) S163–S175, https://doi.org/10.1542/peds.2009-1100D.
[62] J. Stephenson, N. Heslehurst, J. Hall, D.A.J.M. Schoenaker, J. Hutchinson, J.E. Cade, et al., Before the beginning: nutrition and lifestyle in the preconception period and its importance for future health, Lancet 391 (10132) (2018) 1830–1841, https://doi.org/10.1016/s0140-6736(18)30311-8.
[63] A.K. Ventura, S. Phelan, K. Silva Garcia, Maternal diet during pegnancy and lactation and child food preferences, dietary patterns, and weight outcomes: a review of recent research, Curr. Nutr. Rep. 10 (4) (2021) 413–426, https://doi.org/10.1007/s13668-021-00366-0.
[64] D.M. Zarnowiecki, J. Dollman, N. Parletta, Associations between predictors of children's dietary intake and socioeconomic position: a

systematic review of the literature, Obes. Rev. 15 (5) (2014) 375–391, https://doi.org/10.1111/obr.12139.

[65] L. Ricciuto, V.L. Fulgoni, P.C. Gaine, M.O. Scott, L. DiFrancesco, Trends in added sugars intake and sources among US children, adolescents, and teens using NHANES 2001-2018, J. Nutr. 152 (2) (2022) 568–578, https://doi.org/10.1093/jn/nxab395.

[66] T.A. Bekelman, Y. Dong, A.J. Elliott, A. Ferrara, K. Friesen, M. Galarce, et al., Health behavior changes during the COVID-19 pandemic: a longitudinal analysis among children, Int. J. Environ. Res. Public Health 19 (15) (2022) 9220, https://doi.org/10.3390/ijerph19159220.

[67] T.A. Bekelman, E.A. Knapp, Y. Dong, D. Dabelea, T.M. Bastain, C.V. Breton, et al., Sociodemographic variation in children's health behaviors during the COVID-19 pandemic, Child, Obes 19 (4) (2023) 226–238, https://doi.org/10.1089/chi.2022.0085.

[68] M.C. Ocké, R.J. Kaaks, Biochemical markers as additional measurements in dietary validity studies: application of the method of triads with examples from the European Prospective Investigation into Cancer and Nutrition, Am. J. Clin. Nutr. 65 (4) (1997) 1240S–1245S, https://doi.org/10.1093/ajcn/65.4.1240S, suppl.

[69] R. Raghavan, F.S. Ashour, R. Bailey, A review of cutoffs for nutritional biomarkers, Adv. Nutr. 7 (1) (2016) 112–120, https://doi.org/10.3945/an.115.009951.

[70] J.P. Buckley, E.S. Barrett, P.I. Beamer, D.H. Bennett, M.S. Bloom, T.R. Fennell, et al., Opportunities for evaluating chemical exposures and child health in the United States: the Environmental influences on Child Health Outcomes (ECHO) Program, J. Expo. Sci. Environ. Epidemiol. 30 (3) (2020) 397–419, https://doi.org/10.1038/s41370-020-0211-9.

[71] C.C. Lim, R.B. Hayes, J. Ahn, Y. Shao, D.T. Silverman, R.R. Jones, et al., Mediterranean diet and the association between air pollution and cardiovascular disease mortality risk, Circulation 139 (15) (2019) 1766–1775, https://doi.org/10.1161/CIRCULATIONAHA.118.035742.

[72] L.R. Lipton, K.J. Brunst, S. Kannan, Y.M. Ni, H.B. Ganguri, R.J. Wright, M. Bosquet Enlow, Associations among prenatal stress, maternal antioxidant intakes in pregnancy, and child temperament at age 30 months, J. Dev. Orig. Health Dis. 8 (6) (2017) 638–648, https://doi.org/10.1017/S2040174417000411.

[73] S. Péter, F. Holguin, L.G. Wood, J.E. Clougherty, D. Raederstorff, M. Antal, et al., Nutritional solutions to reduce risks of negative health impacts of air pollution, Nutrients 7 (12) (2015) 10398–10416, https://doi.org/10.3390/nu7125539.

[74] X. Zhang, Y.M. Chiu, S. Kannan, W. Cowell, W. Deng, B.A. Coull, et al., Joint associations among prenatal metal mixtures and nutritional factors on birth weight z-score: evidence from an urban U.S. population, Environ. Res. 208 (2022) 112675, https://doi.org/10.1016/j.envres.2022.112675.

[75] H.E. Volk, F. Perera, J.M. Braun, S.L. Kingsley, K. Gray, J. Buckley, et al., Prenatal air pollution exposure and neurodevelopment: a review and blueprint for a harmonized approach within ECHO, Environ. Res. 196 (2021) 110320, https://doi.org/10.1016/j.envres.2020.110320.

[76] S.L. Schantz, B. Eskenazi, J.P. Buckley, J.M. Braun, J.N. Sprowles, D.H. Bennett, et al., A framework for assessing the impact of chemical exposures on neurodevelopment in ECHO: opportunities and challenges, Environ. Res. 188 (2020) 109709, https://doi.org/10.1016/j.envres.2020.109709.

[77] C.V. Breton, R. Landon, L.G. Kahn, M.B. Enlow, A.K. Peterson, T. Bastain, et al., Exploring the evidence for epigenetic regulation of environmental influences on child health across generations, Commun. Biol. 4 (1) (2021) 769, https://doi.org/10.1038/s42003-021-02316-6.

[78] C.G. Howe, S.S. Nozadi, E. Garcia, T.G. O'Connor, A.P. Starling, S.F. Farzan, et al., Prenatal metal(loid) mixtures and birth weight for gestational age: a pooled analysis of three cohorts participating in the ECHO program, Environ. Int. 161 (2022) 107102, https://doi.org/10.1016/j.envint.2022.107102.

[79] J.P. Buckley, G.B. Hamra, J.M. Braun, Statistical approaches for investigating periods of susceptibility in children's environmental health research, Curr. Environ. Health Rep. 6 (1) (2019) 1–7, https://doi.org/10.1007/s40572-019-0224-5.

[80] R.D. Annett, S. Bickel, J.C. Carlson, K. Cowan, S. Cox, M.J. Fisher, et al., Capacity building for a new multicenter network within the ECHO IDeA States Pediatric Clinical Trials Network, Front. Pediatr. 9 (2021) 679516, https://doi.org/10.3389/fped.2021.679516.

[81] L. James, B.P. O'Sullivan, M. Majure, J. Lang, S. Ounpraseuth, C. Hornik, et al., Protocol for the Vitamin D Oral Replacement in Asthma (VDORA) study, Contemp. Clin. Trials 120 (2022) 106861, https://doi.org/10.1016/j.cct.2022.106861.

[82] A.M. Davis, G. Beaver, M. Dreyer Gillette, E.L. Nelson, K. Fleming, R. Swinburne Romine, et al., iAmHealthy: rationale, design and application of a family-based mHealth pediatric obesity intervention for rural children, Contemp. Clin. Trials 78 (2019) 20–26, https://doi.org/10.1016/j.cct.2019.01.001.