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Phosphorous intake in foods and phosphorus status markers in circulation in the Boston Puerto Rican Health Study

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Abstract

Phosphorus (P) additives may be deleterious for health. We measured the P content of key foods, and associations of P intake with biomarkers in the Boston Puerto Rican Health Study (BPRHS). Direct chemical analysis of 92 foods was done with the molybdenum blue spectrophotometric method and inductively coupled plasma mass spectrometry (ICP-MS). A novel algorithm was used to determine bioavailable, natural, and added P. We estimated P intakes from foods in 1323 participants, aged 45–75 y, and associations of these with serum P, fibroblast growth factor 23 (FGF23), parathyroid hormone (PTH), and Klotho. Relationships between intakes and status markers were assessed with Pearson's correlations and t-tests. Our food analyses generally support P values in the USDA nutrient database, with the exceptions of American and cheddar cheese, which had more P than in the database. Women had higher added P intake than men, and younger participants had higher added P than those older. Total P intake tended to be positively associated with serum P and klotho, and inversely associated with PTH, but relationships were not strong. Puerto Rican adults have high intake of additive P. Culturally sensitive interventions that highlight dietary quality are needed.

Keywords

Phosphorus intake; Food additives; Biomarkers; Food samples; Chemical analysis; Hispanic; Aging; Health Disparities; Bioavailability; Epidemiology; Nutrition; Diet

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Declaration of Competing Interest

None

CRediT authorship contribution statement

Sabrina E Noel: Writing – review & editing. **Dhimiter Bello:** Writing – review & editing, Validation, Supervision, Resources, Formal analysis. **Wenjun Li:** Writing – review & editing, Supervision. **Mahdi Garelnabi:** Writing – review & editing. **Chi N Duong:** Validation. **Oladimeji J Akinlawon:** Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis. **Xiyuan Zhang:** Software, Formal analysis, Data curation. **Katherine L Tucker:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jfca.2024.106681.

1. Introduction

Compounds with added phosphorus (P) are used in diverse applications, making them among the most used additives in the world (Cooke, 2017; Gutiérrez, 2013). Added P is found in foods in the form of phosphoric acid, calcium phosphate, monocalcium phosphate, sodium phosphate, sodium acid pyrophosphate, sodium aluminum phosphate, sodium tripolyphosphate, potassium triphosphate, and others (Calvo et al., 2014; Sullivan et al., 2007). Added P serves several functions in food manufacturing and processing, such as leavening, anti-caking, acidulant, emulsification, and stabilization (Calvo and Uribarri, 2013; Molins, 1990; Moore et al., 2015). On average, individuals are estimated to consume 8–10 pounds of food additives per year (Assembly Standing Committee on Mental Health Mental Retardation and Developmental Disabilities, 2007), as processed foods are commonly consumed. In the U.S, about 23 % of foods contain added P (Moore et al., 2015), and P intake among adults is estimated at 180 % of the recommended value, without fully accounting for added P (Suki and Moore, 2016). A recent study using national data (1988–1994–2001–2016) showed that mean intake of total and natural P increased, but added P intake decreased (from 14.6 % to 11.6 %) over the past few decades, which may be due to, in part to misclassification of foods (e.g., lack of separation of frozen and fresh meat) and measurement error in nutrient databases and calculations of added P (Fulgoni and Fulgoni, 2021).

Importantly, added P has greater bioavailability than natural P, contributing to greater bodily exposure (Gutiérrez et al., 2015). Early findings (from the pre-1970s) suggested that added P appeared to be safe in amounts up to 30–70 mg/kg/d (Onufrak et al., 2008; Yoon et al., 2017), and these additives were classified as generally recognized as safe (GRAS) by the Food and Drug Administration (FDA) (Carrigan et al., 2014). Phosphorus content in the food supply is increasing, with the constant need to improve food stability, taste, and preparation (Calvo et al., 2014). Despite growing concerns, the P content of foods is not required to be reported on food labels (Uribarri and Calvo, 2003), and there are currently no regulations on the amount that foods can contain in the U.S. Prior studies showed underestimation of total dietary P in nutrient databases, compared with direct chemical analysis, (Benini et al., 2011; Carrigan et al., 2014; Sherman and Mehta, 2009; Sullivan et al., 2007). This measurement error may obscure important relationships between dietary P intake and health outcomes.

There is currently no distinction between P intake from additives and natural P in food composition databases. One recent study quantified total, added, and natural P from food, but was not comprehensive (Fulgoni and Fulgoni, 2021). The assumption used in that study exempted added P in frozen meat products and mixed dishes, which are likely important sources of added P. Our group previously developed new P metrics that capture natural and added P from different food sources, and their bioavailability, in an African American cohort (Duong et al., 2022). Serum P, parathyroid hormone (PTH), fibroblast growth factor 23 (FGF23), and Klotho protein are known P biomarkers. It is important to examine how our newly developed P metrics relate to these biomarkers among aging adults, considering their important role in P biochemistry (Kuro-o, 2019). Added phosphate salts are more rapidly and efficiently absorbed (> 90 %) than natural forms (20–60 %), and plant sources have

lower bioavailability than animal sources (Calvo et al., 2014; Cupisti and Kalantar-Zadeh, 2013; Nouri et al., 2010; Takeda et al., 2017; Williams et al., 2014; Winger et al., 2012).

This study aimed to measure the P content of several key foods frequently consumed by Puerto Ricans that may be a potential source of added P, and to update the P measures used in our previously developed algorithm. This is important, as foods consumed differ between populations based on cultural preference and other demographic factors. Second, we aimed to describe P intake, its bioavailability, and P biochemistry status, using a panel of functional P biomarkers – serum P, FGF23, PTH, and Klotho protein – in the Boston Puerto Rican Health Study (BPRHS).

2. Materials and methods

2.1. Selection of food samples

Food sampling was carried out following the United States Department of Agriculture (USDA) national food sampling plan (Pehrsson et al., 2000), but focused on local foods. To ensure equality in the food sample distribution, counties of participants represented in the BPRHS were ranked in descending order, based on population density, and stratified into high, medium, or low population size. Grocery store outlets were selected based on availability of foods consumed by the Puerto Rican population. Six to eight samples of each food product (name brands and generic brands) representing canned legumes, meat, bread, cereal, cheese, and sweets were purchased between October 2021 to May 2022.

2.2. Reagents and supplies

All reagents used were analytical grade. Double deionized water (Milli-Q system water; Millipore, Bedford, MA, USA), nitric acid (70 % HNO_3, Fisher Scientific, Fair Lawn, NJ, USA), hydrogen peroxide (50 % H_2O_2, Fisher Scientific), phosphorus standard solution for colorimetric (1000 mg/L, Hach, Loveland, CO, USA), P standard for Inductively coupled plasma mass spectrometry (ICP-MS) (1 mg/L, Sigma-Aldrich, St. Louis, MO, USA), hydroquinone (Sigma-Aldrich), ammonium molybdate tetrahydrate (Sigma-Aldrich), and concentrated sulfuric acid (Sigma-Aldrich), anhydrous sodium sulfite (EMD Millipore, Billerica, MA) were used. A certified reference material SRM 1546a, meat homogenate from the National Institute of Standards and Technology (NIST) was used for independent validation of analytical results.

2.3. Chemical analysis

2.3.1. Sample homogenization—A half or quarter of a serving size (based on the food label) of each food product was weighed, minced, and placed in polypropylene containers. An appropriate amount of water was added to heterogenous food products and homogenized with a tissue homogenizer (model PRO250; PRO Scientific Inc., Oxford, CT, USA). A 1 g aliquot from the homogenized sample was taken for P analysis and was stored at −20°C until further processing. The remainder of the homogenized sample was stored at −20°C for future use.

2.3.2. Digestion protocol—For sample digestion, one gram of each analytical sample was weighed directly into a 110 mL polytetrafluoroethylene (PTFE) Mars6 Xpress Plus reaction vessel. Eight milliliters of HNO_3 and 2 mL of H_2O_2 were added into each tube, then closed. This mixture was subjected to a P digestion program at 180 °C with 15 mins ramp to temperature, at maximum power of 1000 W over 30 mins. Upon digestion program execution and cooling at room temperature, digested samples were adjusted to 100 mL using deionized water. A 15 mL aliquot of the dilute solution was then stored in clean 15 mL VWR polypropylene centrifuge tubes and stored at 4 °C until further analysis. Due to the wide range of P content in foods, colorimetric P analysis was first performed on all food samples as a quick check of P content and as a means of determining an optimal sample dilution factor for subsequent ICP-MS analyses.

2.3.3. Colorimetric analysis—The well-established molybdenum blue colorimetric method, described previously (Gliszczyńska-Świgło and Rybicka, 2021), was used for colorimetric analysis of P in foods. Anhydrous ammonium molybdate (5 g) was dissolved in 60 mL de-ionized water and mixed with a solution of 15 mL concentrated sulfuric acid diluted in 40 mL deionized water to make a 5 % molybdate sulfuric (VI) acid solution. This mixture was stored in a beaker wrapped with aluminum foil at 4 °C, which is stable for up to 4 weeks. Another 0.5 g hydroquinone (benzene-1,4-diol) was dissolved in 100 mL deionized water with concentrated sulfuric acid (10 μL) to make a 0.5 % hydroquinone solution. This, also stored at 4 °C in a beaker wrapped with aluminum foil and has been shown to be stable for 4 weeks. A fresh 20 % sodium sulfite (Na_2SO_3) solution was prepared daily by dissolving 20 g Na_2SO_3 in 100 mL deionized water. To measure the total P in each sample, a flat bottom 48-well Costar cluster plate was used. Each well except the blank contained 0.08 mL of sample, 0.08 mL of de-ionized water (or 0.16 mL de-ionized water as a blank), 0.08 mL of 5 % molybdate sulfuric (VI) acid solution, 0.08 mL of 0.5 % hydroquinone solution, and 0.08 mL of 20 % sodium sulfite. The plate containing the mixture, as described above, was left in the dark for 30 mins and absorbance was read in a spectrophotometer (TECAN Infinite Pro M200, Männedorf, Switzerland) for each sample in triplicate at wavelength of 823 nm. The absorbance of all sample solutions, including control samples, were read and P was estimated using the calibration curve for P.

Quantitation of P in samples was based on a nine point external standard calibration in the range 0.39–100 μg/mL. A linear calibration curve, $y = 0.0074 \times x + 0.1034$, was obtained for P, with a correlation coefficient of 0.9993. The limit of detection (LOD) and limit of quantitation (LOQ) values were calculated as 3.40 and 10.4 μg/mL, respectively.

2.3.4. ICP-MS analysis—ICP-MS analysis of P was conducted in an Agilent 7900 ICP-MS (Agilent Technologies, Tokyo, Japan). Diluted digested samples (digest solutions) were further diluted (1:100 or 1:10 v/v) to fit the optimal calibration range of ICP-MS analysis (1–1000 ppb). Digest solutions with undetectable P concentration from the colorimetric method were analyzed with ICP-MS without further dilution. Instrument parameters were as follows: RF power, 1550 W; Nebulizer gas flow 1.03 L/min; nebulizer mode: Micro mist; and RF power 1550 W. A nine-point calibration curve in the linear range of 3.91–1000 ng/mL was generated for P quantitation. The linear equation for P was: $y = 4.588 \times x +$

178.9 (R^2 > 0.999). The method LOD was estimated to be 0.04–0.4 μg/g sample for 10× and 100× dilution, respectively. The ICP-MS instrument LOD was estimated to be ~0.2 ppb (ng/mL). All samples were above method LOQ (~0.6 ppb).

The colorimetric analysis was used for triaging purposes and to calculate dilution factors for ICP-MS to ensure P in samples for ICP-MS analysis was within the linear range of the calibration curve (above). This effort would avoid contamination of the instrument from very concentrated samples and eliminate the need for multiple analyses of samples at different dilutions. For these reasons P data by the colorimetric method are not reported. Strong correlation (r = 0.91) was found between P values by the ICP-MS and colorimetric method (excluding 12 samples that were below the colorimetric method's LOD).

2.3.5. Quality assurance—For chemical analysis, several quality assurance elements were incorporated, including several procedural blanks, instrument blanks, NIST SRM 1546a, phosphorus standard solution, random true duplicate sample analyses for 35 % of all samples, and data acquisition in triplicates. Procedural blanks and the NIST SRM 1546a were inserted into the same testing process as the samples. P standards for colorimetric and ICP-MS were diluted serially with de-ionized water at various concentrations to fit the standard curve of the spectrophotometer (9 data points, range: 0.39–100μg/mL P) and ICP-MS (9 data points, 3.91–1000 ng P/mL). The solutions were vortexed to ensure complete mixing.

The relative standard deviation from independent replicate analysis of food samples had an arithmetic mean of 7.7 % and standard deviation of the mean of 0.38 % (range 0.5 %– 25 %). Sample homogeneity is likely the major component of this variability. The quantitation accuracy was confirmed with the SRM 1564a. The P content in the SRM 1546a was 1640 μg/mg, which falls within the reported range of 1651 +/− 32 μg/mg (1619 – 1683). The coefficient of variation of independent replicates was under 6.9 %.

2.4. BPRHS study design

2.4.1. Study population—These analyses were conducted using data from the BPRHS and the Boston Puerto Rican Osteoporosis Study (BPROS), an ancillary study to the BPRHS. The BPRHS is a longitudinal cohort study designed to determine factors contributing to health disparities experienced by U.S. mainland Puerto Rican adults. As previously described (Tucker et al., 2010), the recruitment of participants was from areas of high Hispanic density in the Greater Boston area selected using data from the year 2000 Census. Households with Puerto Rican adults aged 45 – 75 y were identified and one eligible adult from each qualified household was randomly selected. Recruitment of participants was through door-to-door approaches and community activities. Exclusion criteria were inability to answer questions due to a serious health condition, plans to move from the area within 2 y, or Mini-Mental State Exam (MMSE) score ≤ 10. Of 1504 participants with complete baseline interviews, participants with missing: FFQ data (n = 19), body mass index (n = 17), educational status (n = 2), or poverty status (n = 82); or with reported energy intakes < 600 or > 4800 kcal/d (n =61) were excluded; therefore 1323 were included in final analyses (Fig. 1). To examine associations with biochemical markers,

additional analysis was conducted for a subset of participants with serum P, FGF23 and Klotho (n = 418), and PTH (n = 701) measures. Another subset, of 353 participants with complete PTH and other P status biomarkers, was further examined to test the correlation between the biomarkers.

2.4.2. Dietary data—Interviews were conducted in the home by bilingual interviewers in Spanish or English, based on preference of the participant. Questionnaires were designed based on measures from National Health and Nutrition Examination Survey (NHANES) III (Dreon et al., 1993; McDowell et al., 1990), Hispanic Health and Nutrition Examination Survey (HHANES) (Delgado et al., 1990; McDowell and Loria, 1989), and the National Health Interview Survey Supplement on Aging (Block and Subar, 1992). Dietary intake was assessed at all visits using a food frequency questionnaire (FFQ) adapted for use with this population (Tucker et al., 1998) and validated with plasma measures of vitamin B6 (Ye et al., 2010), B12 (Kwan et al., 2002), vitamin E (Gao et al., 2006), plasma carotenoids (Bermudez et al., 2005), erythrocyte ω-3, and trans-FA (Bigornia et al., 2016). Average daily nutrient intakes were calculated using the Nutritional Data System for Research (NDS-R version 2016, University of Minnesota).

2.4.3. Estimation of bioavailable phosphorus—Estimation of bioavailable P in foods listed on the FFQ was calculated using an algorithm that estimates distinct P metrics for individual foods. A detailed methodology has been described previously (Duong et al., 2022). First, we attributed P content to added or natural sources. As the USDA nutrient database (Food Data Central, FDC) does not discriminate by source of P, a comprehensive list of added vs. natural P and their estimated bio-availabilities were developed, guided by published literature (Calvo et al., 2014; Kalantar-Zadeh et al., 2010; Nouri et al., 2010; Shastak and Rodehutscord, 2015). These were linked to each line item (foods) on the FFQ. Foods containing no P were excluded. Unprocessed or minimally processed foods with no P additives were assigned 0 g for added P. Foods with minimal or zero natural P were assigned 100 % total P as added P. When available, specific proportions from published literature were assigned for added P or by using added P percentages of similar products.

To the extent possible, unknown added P proportions were estimated by subtracting natural from total P and by comparing the P to protein ratio (P:Protein) in processed and unprocessed forms of similar foods in the database. Percent added P in processed mixed dishes were estimated by comparing its total P content to the sum of its corresponding raw ingredients. To determine the level of processing, details were inferred from the literature or by direct analysis of commonly used local products. Lastly, the product of the appropriate added or natural P proportion of the individual food items and their bioavailable weights were estimated. Weighted intakes reflecting bioavailability were derived from the literature or based on expert consensus. Total bioavailable P was calculated with an equation using approximate bioavailability weights for differing sources. All forms of P intake including original total, natural, added, and bioavailable total, natural, and added P (P indicators) were estimated, top coded at three standard deviations and adjusted for total energy intake using the residual method (Willett et al., 1997).

2.4.4. Phosphorus biomarkers—Blood samples were drawn by a certified phlebotomist at each visit after a 12-hour fast and immediately taken to the University of Massachusetts Lowell in coolers with dry ice; cooled to 4 °C and separated within 2 hours in a refrigerated centrifuge. Plasma aliquots were saved in 1 mL cryogenic, screw-cap tubes, and stored at −70 °C. Serum P was determined by Colorimetry with ammonium molybdate (Fiske and Subbarow, 1925) on an EasyRA clinical chemistry analyzer (Medica Corporation, USA). The CV range was 0.68–1.03 %. Plasma fibroblast growth factor 23 C-terminal (FGF23) (Gutiérrez et al., 2015) was estimated using enzyme-labeled immunometric assay (ELISA) assay kit (Eagle Biosciences Inc, USA). Intra- and Inter-assay CVs were ≤ 12 % and ≤ 10 %, respectively. Plasma parathyroid hormone (PTH) was measured with ELISA kit (Abcam, USA). Intra- and Inter-assay CVs were ≤ 1.5 % and 3.8 %, respectively. Plasma Klotho was measured with ELISA kit (Assay Solution Inc, USA). Intra- and Inter-assay CVs were < 10 % and < 8 %, respectively.

2.4.5. Participant characteristics—Data on age, education (≤ 8th grade, 9–12 th grade or GED, some college or college degree, or some graduate school), household income, and household size were obtained from participants during home visits. Poverty status was determined using the poverty threshold published annually by the US Census Bureau. This was estimated by comparing total household income of each participant to the threshold based on the age of household head, household size, and year of interview. A participant was classified as living in poverty if total household income was below this threshold.

2.4.6. Anthropometric measures—Standing height and weight were measured in duplicate in the home during each interview, and body mass index (BMI) was derived by dividing weight (kg) by height (m) squared.

2.4.7. Statistical analysis—Mean intake of the differing forms of P was examined by sex, age, BMI, poverty status and education level. T-tests or one-way analysis of variance (ANOVA) were used to compare differences between groups. The P biomarkers (serum P, FGF23, PTH, and Klotho) were described among participants without evidence of kidney disease (self-reported kidney disease, estimated glomerular filtration rate [eGFR] < 60 mL/min/1.73 m^2, or missing eGFR). Adjusting for age and BMI, mean biomarkers were compared between sex using least squares general linear models. Partial Pearson correlations were used to assess relationships between the P indicators, adjusted for age, sex, and total energy intake, and between biomarkers of P status, adjusted for age, sex, and BMI. Statistical analyses were performed using SAS statistical software (SAS version 9.4; SAS Institute Inc.).

3. Results

3.1. P in foods using colorimetric and ICP-MS analysis

Table 1 shows the P content (mean, SD, min, max) from each analyzed food product, using ICP-MS with the total P content of a corresponding food from Food Data Central. Concise descriptions of each food sample are in Table S1. American cheese and cheddar cheese had more P, as analyzed, relative to the values in FDC. P was highest in dairy products

(range: 282 ± 227–919 ± 25 mg/100 g), meat (range: 164 ± 23–314 ± 41 mg/100 g), baked sweets (214 ± 45 mg/100 g), legumes (103 ± 14 mg/100 g), and cereal grains (range: 37.2 ± 14.3–320 ± 59 mg/100 g). As changing these values in the database did not result in intakes that differed from those using original USDA values, we did not adjust the database based on our values for the final analysis.

3.2. P intake in the BPRHS

The major food sources of total P intake in this population included milk (~20 %), cheese (~8 %), fish (~7 %), poultry and rice (~6 %), beans and beef (~5 %), processed meat and white bread (~4 %) (Table 2). Major contributors to added P intake included poultry (~14 %), processed meat (~13 %), beef (~11), fish (~10 %), yogurt (~7 %), pork and cheese (~6 %), and white bread (~5 %). Major sources of natural P intake included milk (~23 %), cheese (~8 %), fish, rice (each ~7 %), beans (~6 %), poultry (5 %), beef, white bread (each ~4 %), and eggs, hot breakfast cereal, and processed meat (each ~3 %). Major sources of bioavailable P intake included milk (~19 %), meat turnovers, fish, cheese, and poultry (each ~8 %), beef, processed meat (each ~5 %), rice and white bread (~4 %).

After applying the algorithm described above, the mean original total, natural, and added P intakes were 1484 ± 341, 1233 ± 321, and 238 ± 87 mg/d, respectively (Table 3). The mean bioavailable total, natural, and added P intakes were 909 ± 253, 680 ± 219, and 239 ± 83 mg/d, respectively. Original and bioavailable added P were higher among women than men (241 ± 85 vs. 230 ± 91 mg/d, $P = 0.035$, and 242 ± 81 vs. 231 ± 86 mg/d, $P = 0.035$) (Table 4). Original and bioavailable added P intakes were higher among younger, vs. older, women (247 ± 89 vs. 232 ± 79 mg/d, $P < 0.01$, and 248 ± 84 vs. 233 ± 75 mg/d, $P < 0.01$, respectively), and younger, vs. older, men (242 ± 97.6 vs. 211 ± 75 mg/d, $P = 0.001$, and 243 ± 93 vs. 213 ± 71 mg/d, $P = 0.001$, respectively). Older, vs. younger, women had higher original and bioavailable total P (1538 ± 334 vs. 1464 ± 333 mg/d, $P < 0.001$, and 937 ± 250 vs. 896 ± 242 mg/d, $P < 0.0001$, respectively) and original and bioavailable natural P intake (1296 ± 308 vs. 1205 ± 319 mg/d, $P < 0.0001$, and 716 ± 220 vs. 659 ± 210 mg/d, $P < 0.0001$, respectively) (Table 4). Older, vs. younger, men had higher original natural P (1255 ± 359 vs. 1188 ±307 mg/d, $P = 0.05$) while younger. vs. older, men had higher original and bioavailable added P (242 ± 98 vs. 211 ± 75 mg/d, $P = 0.001$, and 243 ± 93 vs. 213 ± 71 mg/d, $P = 0.001$, respectively).

Women with obesity consumed higher added P than those with overweight or ideal weight (244 ± 84 vs. 241 ± 85 and 222 ± 94 mg/d, respectively, $P = 0.05$) (Table 5), and had higher intake of bioavailable added P (245 ± 80 vs. 242 ± 80 and 224 ± 89 mg/d, $P = 0.05$). Original natural P intake was higher among men with obesity than those with overweight or ideal weight (1259 ± 363 vs. 1180 ± 285 and 1165 ± 310 mg/d, respectively, $P = 0.05$). No clear associations were observed in comparing the means of P intake measures with educational attainment and poverty status (Table 6).

Mean serum P concentration was 3.2 mg/dL, which is within the normal range (2.5–4.5 mg/dl) (Bazydlo et al., 2014), and mean FGF23, PTH, and Klotho concentrations were 1.7 pmol/L, 50.6 pg/mL, and 988 pg/mL, respectively. After excluding participants with evidence of kidney disease (self-reported kidney disease or eGFR < 60 mL/min/1.73 m^2),

women, vs. men, had higher serum P (3.27 ± 0.05 vs. 3.03 ± 0.07, $P < 0.001$), FGF23 (1.75 ± 0.10 vs. 1.38 ± 0.14, $P = 0.02$), and PTH (51.2 ± 1.31 vs. 46.8 ± 1.78, $P = 0.03$) (Table 7).

Serum P tended to be associated with intakes of total and bioavailable total P, while PTH was negatively associated with all P intakes ($P = 0.05–0.17$). Klotho tended to be positively associated with total and natural P ($P = 0.11$ and 0.09, respectively, but not with added P (Table 8). As expected, FGF23 was associated positively with PTH (r = 0.09, $P = 0.09$) and negatively with Klotho (r = −0.10, $P = 0.04$) (Table 9).

4. Discussion

Unlike previous reports that food databases may underestimate the P content of foods (Benini et al., 2011; Carrigan et al., 2014; Sherman and Mehta, 2009; Sullivan et al., 2007) the P content in food products reported in FDC were, for the most part, within the range of the chemically analyzed P content. Rather, variation within category was high.

The first aim of this study was to update the P values used in our algorithm, by checking analyzed values of key foods consumed that may be sources of added P. In contrast with most earlier studies, where underestimations were reported in the nutrient database (Benini et al., 2011; Carrigan et al., 2014; Sherman and Mehta, 2009; Sullivan et al., 2007), our food analysis supported the FDC database values, with few exceptions. The leading sources of total P intake in this population were protein rich foods, including milk, cheese, fish, poultry, beef, and processed meats; and grains including rice, beans or legumes, and white bread. Top added P sources were like those of total P, with the addition of yogurt and pork, and exception of milk, rice, and beans. Prior studies similarly found that dairy, meat, and grains were major sources of total P intake (Duong et al., 2022; Fulgoni and Fulgoni, 2021; McClure et al., 2017).

The P intake variables were modeled to adjust for energy intake. This approach has been shown to reduce bias from under or over reporting on the FFQ (Willett et al., 1997). The total dietary P intake in this study (mean ± SD, 1484 ± 341 mg/d) was more than twice the US recommended dietary allowance (RDA) (700 mg/d) and is greater than NHANES 2005–2006 estimates (mean 1359 mg/d) for ages 20 y and older (Fulgoni and Fulgoni III, 2021). The added P intake (238 ± 86.9 mg/d) also exceeds NHANES 2005–2006 derived added P intake (mean 183 mg/d) (Fulgoni and Fulgoni III, 2021).

In this sample of Puerto Rican adults, woman had higher intake of total P than men; and younger (45 - < 60 y) men and women had higher P intake, compared to those ≥ 60 y. Though there remains contradictory evidence on the impact of sex on dietary P intake (Chang et al., 2014), our results support findings that consumption of total P among women has increased over time (Fulgoni and Fulgoni III, 2021). Further, several studies have found that women are more likely than men to have higher serum P attributable to dietary intake (de Boer et al., 2009; Dhingra et al., 2010; Foley et al., 2009). Older women and men had higher natural P intake compared with younger participants. This suggests that older adults in this cohort may have better dietary quality compared to those who are younger. Dietary quality is associated with acculturation. Americans consume large amounts of processed

foods, many of which contain added P (León et al., 2013). Among Mexican Americans, acculturation has been shown to have a negative influence on dietary quality (Ayala et al., 2008; Pérez-Escamilla and Putnik, 2007), due to exposure to the “USA mainstream culture” (Pérez-Escamilla, 2009). We previously found that younger adults in this population were more acculturated than older adults, based on language and psychological acculturation (Tucker et al., 2010), consistent with higher natural P intake among older adults and higher added P intake among younger adults, who are more likely to use processed foods.

Further, we found that women with obesity consumed more added P than those who were overweight or normal weight. The prevalence of obesity in this population is greater among women than men (60.5 % vs. 43 %), and among those < 60 y (Tucker et al., 2010). Further, more women than men had abdominal obesity (Tucker et al., 2010).

Added P has greater bioavailability than natural P (> 90 % vs. 20–60 %) (Calvo et al., 2014; Cupisti and Kalantar-Zadeh, 2013; Nouri et al., 2010; Takeda et al., 2017; Williams et al., 2014; Winger et al., 2012), thus, increased intake of added P may raise FGF23, a potent phosphaturic agent. Several studies have described a positive association between BMI and FGF23 (Mirza et al., 2011; Zaheer et al., 2017). Hu et al. (2018) found that BMI and abdominal obesity were independently correlated with FGF23 in 591 postmenopausal women. Though obesity is marked by expression of elevated FGF23, the mechanisms in which FGF23 increases BMI remains to be elucidated. Another possibility is that BMI may be influenced indirectly, as added P tends to be from processed food sources. This is particularly concerning as this population suffers disproportionately from obesity and other comorbid conditions, compared to other Hispanic groups and non-Hispanic Whites. (Andrews and Elixhauser, 2000; Tucker, 2005; Tucker et al., 2000)

Serum P, FGF23, and PTH were higher among women, compared to men, consistent with the findings on dietary intake. However, in the assessment of added P and the P biomarkers, only weak associations were observed. P status is a function of multiple factors, including age, sex, diet, hormones, transporters, effector organs, genetics and others (Lederer, 2014). The mechanism of interaction of these factors remains unknown, and additional studies are needed to understand how these factors leads to blood concentrations of P biomarkers.

Contrary to expectation, total P intake was inversely correlated with PTH, and serum P was inversely correlated with PTH. However, as expected, FGF23 correlated negatively with Klotho. Elevated serum P, PTH and FGF23, with decline in Klotho concentration have been observed with increased P intake among kidney disease patients (Cannata-Andía et al., 2014). However, the P biomarkers analyzed here were for participants without evidence of kidney disease. Circulating P in human plasma is about 72 % organic and 28 % inorganic P, with inorganic P comprising 20 % protein bound (Peacock, 2021). P-bound proteins such as albumin were not accounted for in our analysis and have the potential to affect the observed relationship with circulating P (Webster et al., 2016). Also, phosphate-binding medication use and health conditions such as kidney and bone status, and estrogenic status may influence the observed relationship (Peacock, 2021; Webster et al., 2016).

High P intake (Calvo et al., 2014) suggests use of added P in food processing, hence, increased exposure to added P by consumers. Although adequate P status is required for calcium balance, and ideal intestinal P to calcium absorption improves bone mineralization and turnover (Masuyama et al., 2003), excess P due to the use of P additive in food processing and supplements may lead to hormonal imbalance in P homeostasis and disruption in kidney function (Calvo and Uribarri, 2013; Kemi et al., 2009). Further analysis of these relationships is needed.

Strengths of this study include the use of our novel algorithm to distinguish natural from added P intake in a Puerto Rican cohort and comparing the P intake measures with a panel of P biomarkers. Dietary intake was assessed with a validated FFQ adapted for this population. This enabled assessment of P intake by source. Although our analyzed food values support the existing nutrient database, a limitation of this study is the relatively small number of food products selected for direct chemical analysis. It is possible that variation exists in the estimated dietary P in the nutrient database that was not identified. Also, the type and amount of added P used during food processing appears to vary greatly between brands and products, limiting precision of estimation from FFQs. Future studies may analyze more food samples and obtain more precise descriptions of foods consumed. This may help capture a wider range of low-quality processed foods consumed which are not accounted for when averaging out nutrient estimates in the nutrient database.

5. Conclusion

The P content of the food samples analyzed in this study generally support the values in the existing nutrient database. High total and added P intakes were observed among Puerto Rican adults. Total and added P intake had similar food sources, thus, more studies are needed to understand how this relates to health outcomes. Interventions that promote increased consumption of quality diets are needed in this population, especially among individuals at a high risk of chronic kidney disease.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data Availability

Data will be made available on request.

Abbreviations:

BPRHS	Boston Puerto Rican Health Study
ANOVA	one-way analysis of variance
CVD	Cardiovascular disease
SRM	certified reference material
EGFR	estimated glomerular filtration rate
FDA	Food and Drug Administration
ELISA	enzyme-labeled immunometric assay
FFQ	food frequency questionnaire
FGF23	fibroblast growth factor 23
GRAS	generally recognized as safe
HHANES	Hispanic Health and Nutrition Examination Survey
ICP-MS	Inductively coupled plasma mass spectrometry
LOD	limit of detection
LOQ	limit of quantitation
MMSE	Mini-Mental State Exam
NIST	National Institute of Standards and Technology
NHANES	National Health and Nutrition Examination Survey
NDS-R	Nutrition Data System for Research
PTH	parathyroid hormone
P	Phosphorus
PSS	Phosphorus standard solution
PTFE	polytetrafluoroethylene
RDA	recommended dietary allowance

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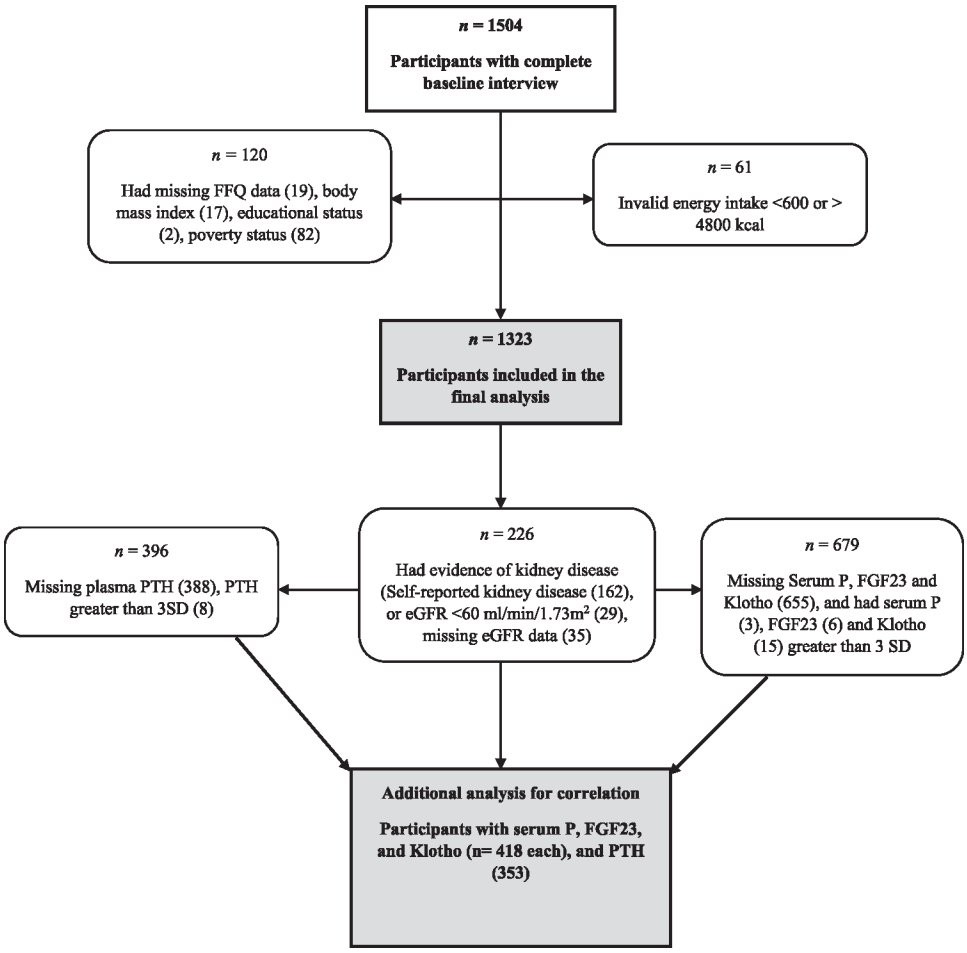

Fig. 1.
Flow Chart of Participants in the Boston Puerto Rican Health Study.

Table 1

Phosphorus value of food samples using ICP-MS.

Food			**Phosphorus (mg/100 g)**			**USDA[a]**
Food group	Product	N	Min	Max	Mean±SD	
Cereal grains	Bread	6	85.9	102	93.6 ± 6.3	113
	Corn flakes	7	20.7	56.7	37.2 ± 14.3	89
	Oats, whole grain, rolled, old fashioned	6	227	380	320 ± 59	410
Legumes	Canned beans	6	87.1	128	103 ± 14	153
Dairy	American cheese	2	902	937	919 ± 25	641
	Cheddar cheese	2	558	709	634 ± 107	458
	Cream cheese	4	107	610	282 ± 227	107
Meat	Chicken drumstick	6	132	200	164 ±23	176
	Chicken breast	7	187	297	229 ± 42	183
	Codfish	3	52.7	541	247 ± 259	203
	Whiting	1	178	178	178	222
	Pollock	1	238	238	238	221
	Ham	7	174	277	222 ± 37	276
	Shrimp	6	121	336	214 ± 91	214
	Salmon	4	162	391	239 ± 103	200
	Farmed salmon	2	285	343	314 ± 41	240
	Tuna, canned	6	139	239	184 ± 41	237
	Sardines	7	170	425	287 ± 104	490
Sweets	Doughnuts	7	140	284	214 ± 45	178

[a]Corresponding phosphorus value in the United States Department of Agriculture (USDA) Food Data Central

Table 2

Top contributors to total, added, natural, and bioavailable phosphorus intake in the Boston Puerto Rican Health Study[a] (n = 1491).

Food Groups	Total P intake (mg/d)	Contribution to total P (%)	Contribution to added P (%)	Contribution to natural P (%)	Contribution to bioavailable P (%)
Milk	54.5	19.5	1.5	22.6	19.0
Cheese	5.0	7.8	5.6	8.2	7.7
Fish	3.5	7.3	10.1	6.8	8.0
Chicken/turkey	3.6	6.4	14.4	5.0	7.5
Rice	5.9	5.8	1.1	6.6	4.3
Beans/legumes	5.1	5.3	0.0	6.3	1.7
Beef	2.2	4.6	10.6	3.6	5.3
Processed meat, sausage, frank	2.8	4.0	12.5	2.5	5.1
White bread	2.6	3.8	5.3	3.5	4.1
Eggs	3.0	3.0	1.5	3.2	2.7
Yogurt	10.2	2.7	7.0	1.9	2.9
Hot breakfast cereal	5.9	2.3	0.8	2.6	1.0
Pork	3.4	2.2	5.7	1.6	2.6
White potatoes	2.6	1.9	0.8	2.1	1.4
Other vegetables	0.3	1.6	0.0	1.8	0.8
Ice cream, sherbet, frozen yogurt	2.2	1.3	1.2	1.3	1.3
Pizza	4.9	1.3	1.3	1.3	1.3
Whole grain breads	3.2	1.2	1.3	1.2	1.1
Cereal (cold, ready-to-eat)	0.2	1.2	0.6	1.3	0.6
Citrus fruit juices	4.6	1.2	0	1.4	1.0
Tortillas/tacos/turnovers	1.3	1.1	0.9	1.2	8.2
Soups	0.9	1.1	1.0	1.1	0.9
Cakes, cookies, pies, doughnuts	0.6	1.1	2.7	0.8	1.2
Liver and organ meats	4.0	1.0	2.6	0.8	1.2
Alcohol beverages	1.7	1.0	0.1	1.2	0.8

[a]Ranking using 64 food groups; items provide minimum of 1 % to total phosphorus intake.

Table 3

Distribution of baseline BPRHS study participants by phosphorus intake (mg/d) (n = 1323)[a,b].

Intake	Mean	SD	Q1	Q2	Q3	Range	n >3 SD
Original P							
Total P	1484	341	1283	1426	1634	204 – 3498	12
Natural P	1233	321	1039	1172	1361	−26 – 3109	11
Added P	238	87	187	231	278	−62 – 712	17
Bioavailable P							
Total P	909	253	766	871	1003	174 – 2449	18
Natural P	680	219	556	635	751	−30 – 1882	18
Added P	239	83	190	232	277	−46 – 689	17

[a]Energy adjusted variables, using the residual method; negative values may appear due to this adjustment

[b]Abbreviations: Boston Puerto Rican Health Study (BPRHS), P (phosphorus), SD (standard deviation)

Table 4

Descriptive characteristics of baseline BPRHS study participants by phosphorus intake (mg/d) (n = 1323).

Characteristics		n	Original mean (SD)			Bioavailable mean (SD)		
			Total[a]	Natural[a]	Added[a]	Total[a]	Natural[a]	Added[a]
Female		952	1493 (335)	1240 (317)	241 (85.2)	912 (246)	682 (215)	242 (81.0)
Male		371	1461 (354)	1214 (329)	230 (90.6)	901 (270)	676 (230)	231 (86.0)
	p [b]		*0.13*	*0.18*	*0.035*	*0.46*	*0.70*	*0.035*
Age	45–59	805	1460 (333)	1200 (315)	246 (91.1)	900 (248)	662 (213)	246 (86.6)
	60–75	518	1521 (349)	1284 (323)	226 (78.3)	923 (260)	708 (227)	228 (74.4)
	p [b]		*<0.01*	*<0.001*	*<0.001*	*0.1*	*<0.001*	*<0.001*
Female	45–59	579	1464 (333)	1205 (319)	247 (88.6)	896 (242)	659 (210)	248 (84.1)
	60–75	373	1538 (334)	1296 (308)	232 (79.0)	937 (250)	716 (220)	233 (75.1)
	p [b]		*<0.001*	*<0.001*	*<0.01*	*0.01*	*<0.001*	*<0.01*
Male	45–59	226	1451 (335)	1188 (307)	242 (97.6)	909 (263)	670 (221)	243 (92.7)
	60–75	145	1477 (383)	1255 (359)	211 (74.9)	888 (281)	686 (243)	213 (71.1)
	p [b]		*0.49*	*0.05*	*0.001*	*0.47*	*0.50*	*0.001*

[a] Energy adjusted variables, using the residual method

[b] P difference in population means (t-test)

Table 5

Baseline body mass index (BMI) category for participants of the BPRHS by phosphorus intake (mg/d) (n = 1323).

Sex	Body mass index[1]	n	Original mean (SD)			Bioavailable mean (SD)		
			Total[2]	Natural[2]	Added[2]	Total[2]	Natural[2]	Added[2]
Female	Normal	103	1447 (333)	1211 (304)	222 (94)	868 (241)	655 (196)	224 (89)
	Overweight	256	1497 (361)	1244 (347)	241 (85)	905 (237)	676 (215)	242 (80)
	Obesity	593	1499 (323)	1244 (306)	244 (84)	923 (250)	689 (219)	245 (80)
	p[2]		*0.33*	*0.62*	*0.05*	*0.1*	*0.30*	*0.05*
Male	Normal	66	1405 (354)	1165 (310)	231 (98)	868 (268)	650 (221)	233 (93)
	Overweight	134	1430 (310)	1180 (285)	228 (92)	875 (256)	651 (214)	229 (87)
	Obesity	171	1507 (382)	1259 (363)	231 (87)	933 (279)	706 (242)	233 (83)
	p[2]		*0.06*	*0.05*	*0.93*	*0.1*	*0.06*	*0.93*

[1] Normal BMI is <25 kg/m^2; overweight is 25–<30; obesity is>30

[2] Energy adjusted variables, using the residual method.

[2] P difference in population means (ANOVA)

Table 6

Phosphorus intake (mg/d) by baseline socioeconomic characteristics for participants of the BPRHS (n = 1323).

		n	Original mean (SD)			Bioavailable mean (SD)		
			Total[a]	Natural[a]	Added[a]	Total[a]	Natural[a]	Added[a]
Educational status	≤8th grade	621	1481 (336)	1232 (312)	235 (88.2)	913 (261)	687 (226)	236 (83.8)
	9–12 th grade	502	1479 (337)	1227 (318)	239 (84.5)	910 (254)	679 (218)	240 (80.3)
	Some college or above	200	1507 (365)	1250 (355)	246 (88.5)	896 (222)	662 (203)	246 (84.1)
	P [b]		*0.57*	*0.70*	*0.27*	*0.72*	*0.38*	*0.27*
Poverty status (Poverty threshold)	Below	775	1484 (343)	1235 (325)	234 (86.8)	914 (256)	688 (225)	236 (82.5)
	Above	548	1484 (338)	1230 (315)	243 (86.8)	902 (249)	669 (211)	244 (82.5)
	P [c]		*0.99*	*0.78*	*0.07*	*0.38*	*0.12*	*0.07*

[a] Energy adjusted variables, using the residual method

[b] P difference in population means (ANOVA)

[c] P difference in population means (t-test)

Table 7

Baseline distribution of P status biomarkers stratified by sex among BPRHS study participants.

P biomarkers	Women Mean (SE)[a]	Men Mean (SE)[a]	P [b]
Serum P, mg/dL (n=418)	3.27 (0.05)	3.03 (0.07)	< 0.001
FGF23, pmol/L (n=418)	1.75 (0.10)	1.38 (0.14)	0.02
PTH, pg/mL (n=701)	51.2 (1.31)	46.8 (1.78)	0.03
Klotho, pg/mL (n=418)	993 (184)	872 (261)	0.67

[a] Least-squares means and standard errors, using the residuals from the regression models adjusting for age, sex and body mass index

[b] P difference in least-squares means (general linear models)

Table 8

Pearson correlations of baseline P status biomarkers and total, added, natural, and bioavailable P intake (mg/d) among BPRHS participants[a].

P biomarkers	Original phosphorus variables						Bioavailable phosphorus variables					
	Total[b]		Natural[b]		Added[b]		Total[b]		Natural[b]		Added[b]	
	r	*P*	r	*P*	r	*P*	r	*P*	r	*P*	r	*P*
Serum P, mg/dL (n=418)	0.08	*0.10*	0.05	*0.23*	0.02	*0.63*	0.07	*0.15*	0.05	*0.33*	0.02	*0.63*
FGF23, pmol/L (n=418)	−0.07	*0.18*	−0.07	*0.16*	0.02	*0.68*	−0.07	*0.16*	−0.08	*0.12*	0.02	*0.68*
PTH, pg/mL (n=701)	−0.07	*0.05*	−0.06	*0.12*	−0.05	*0.17*	−0.07	*0.05*	−0.06	*0.10*	−0.05	*0.17*
Klotho, pg/mL (n=418)	0.08	*0.11*	0.08	*0.09*	0.02	*0.68*	0.06	*0.19*	0.06	*0.20*	0.02	*0.68*

[a] BPRHS participants without evidence of kidney disease

[b] Variable adjusted for age, sex, and total energy intake using the residuals from the regression models

Table 9

Pearson correlations among baseline phosphorus status biomarkers among BPRHS participants[a] (n = 418).

P biomarkers[b]	Serum P		FGF23		PTH[c]		Klotho	
	r	*P*	r	*P*	r	*P*	r	*P*
Serum P, mg/dL	1		0.03	*0.58*	− 0.12	*0.03*	0.04	*0.37*
FGF23, pmol/L			1		0.07	*0.18*	−0.10	*0.035*
PTH, pg/mL					1		0.02	*0.76*
Klotho, pg/mL							1	

[a] BPRHS participants without evidence of kidney disease

[b] Variable adjusted for age, sex, and BMI using the residuals from the regression models

[c] Correlation with parathyroid hormone (n = 353)