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Article

Dietary Acid Load Is Associated with MetS-Related Parameters After Eating Habit Modification in Korean Adults

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Abstract

Background/Objectives: This study examined the association between dietary acid load (DAL) and metabolic syndrome (MetS)-related parameters in Korean adults undergoing eating habit modification. **Methods:** Forty-eight Korean adults (≥ 19 years) with at least one MetS risk factor were recruited via public advertisement. Anthropometric and biochemical parameters, Nutrition Quotient (NQ) scores, and nutrient intake were assessed. DAL was calculated and expressed as potential renal acid load (PRAL) and net endogenous acid production (NEAP). **Results:** A total of 40 participants completed the 8-week intervention. After the intervention, overall improvements were observed in NQ, body composition (body weight, body mass index, and body fat percentage), blood pressure, and glycemic parameters. At baseline, DAL scores were not significantly associated with body composition or glycemic indices. After the intervention, however, these parameters showed significant associations with DAL, which were more pronounced when DAL was expressed as NEAP rather than PRAL. **Conclusion:** Eating habit modification may alter DAL in daily life and is associated with meaningful changes in body composition and other metabolic parameters among Korean adults. NEAP appears to be a more relevant indicator of DAL than PRAL.

Keywords: dietary acid load; metabolic syndrome; body composition; eating habit modification; nutrition quotient; potential renal acid load; net endogenous acid production

1. Introduction

Over the past two decades, the prevalence of metabolic syndrome (MetS) and obesity has increased worldwide, including in Korea [1–4]. Obesity and MetS contribute substantially to morbidity and mortality, and the proportion of deaths attributable to obesity-related conditions continues to rise in many regions. In Korea, where Westernized dietary patterns have become increasingly common, obesity-related health burdens have also grown considerably [1–4].

MetS is defined by the presence of three or more of the following components: elevated waist circumference (WC), elevated triglycerides (TG), reduced high-density lipoprotein cholesterol (HDL-C), elevated blood pressure (BP), and elevated fasting glucose [5]. Both obesity and MetS increase the risk of major chronic diseases, including cardiovascular disease, type 2 diabetes, hypertension, certain cancers, and chronic kidney disease [6]. The etiology of obesity and MetS is multifactorial and involves genetic susceptibility, insulin resistance, circadian rhythm disruption, and lifestyle factors

such as physical inactivity and unhealthy dietary habits characterized by excessive energy intake [6,7].

Dietary factors—including increased intake of saturated fat and energy-dense foods, reduced consumption of fruits and vegetables, and adoption of Westernized eating habits—are recognized as major contributors to obesity and MetS risk [8,9]. When such dietary patterns persist, visceral adiposity increases and may alter adipokine and cytokine secretion, thereby promoting insulin resistance, metabolic dysregulation, and chronic low-grade inflammation [8,9]. Consistent with this, previous studies have reported positive associations between Westernized dietary patterns and cardiometabolic risk markers such as WC, body mass index (BMI), BP, TG, and abdominal obesity [10,11].

In addition to overall dietary quality, dietary acid–base balance has recently gained attention as a potential determinant of cardiometabolic health. Diets rich in animal protein, processed foods, and refined grains—often accompanied by low fruit and vegetable intake—tend to increase dietary acid load (DAL), which may adversely influence metabolic homeostasis [12–15]. DAL can be estimated from nutrient intake and is commonly expressed as potential renal acid load (PRAL) and net endogenous acid production (NEAP) [12]. Acid-producing foods typically include meat, fish, eggs, cheese, and refined grains, which provide acid precursors and contribute to higher PRAL and NEAP scores [16]. In contrast, fruits and vegetables are associated with lower PRAL and NEAP scores and may help maintain acid–base balance [16,17]. Emerging evidence suggests that higher DAL is associated with obesity-related chronic diseases and adverse cardiometabolic outcomes [18–20].

Moreover, although PRAL and NEAP are widely used indices for DAL estimation, their relative sensitivity and metabolic relevance particularly under lifestyle intervention conditions, remain unclear. Importantly, evidence is especially limited in Korean populations, where dietary patterns are undergoing rapid transitions toward Westernized eating habits. Therefore, this study aimed to investigate the association between DAL (assessed by PRAL and NEAP) and MetS-related anthropometric and biochemical parameters among Korean adults undergoing an 8-week eating habit modification intervention, and to evaluate the relative relevance of PRAL versus NEAP as DAL indicators.

2. Materials and Methods

2.1. Study Participants and Study Design

Sixty Korean adults (aged ≥ 19 years) who had no diagnosed chronic diseases and had at least one risk factor of MetS were recruited in this quasi-experimental eating habit modification study through a public advertisement. Initially, they underwent baseline screening. Among them, 12 individuals were excluded because they had one or more chronic diseases such as diabetes, cardiovascular disease, stroke, cancer, thyroid, and kidney or liver disease. The remaining 48 individuals were enrolled in the eating habit modification intervention study for 8 weeks. They were asked to visit the study laboratory after 4 and 8 weeks for follow-up for anthropometric measurements (0, 4, and 8 weeks), biochemical tests (0 and 8 weeks), questionnaire surveys (basic information, 24-h recall record sheets, and nutrition quotient (NQ) at 0, 4, and 8 weeks), and eating habit education. During the intervention, eight participants dropped out of the study because of personal reasons (i.e., work time and travel). Overall, 40 participants were finally included in the analyses. Among them, 35 (81.4%) were female, 2 (4.7%) were current smokers, and 26 (60.5%) were current drinkers. The Institutional Review Board of Dong-A University approved the study protocol (no. 2-1040709-AB-N-202103-HR-016-02). To obtain informed consent, the participants were explained about the objectives and contents of the study.

2.2. Definition of MetS

The participants were considered to have MetS when they had three or more of the five factors listed in the NCEP-ATP III guideline: 1) WC criteria for abdominal obesity proposed by the Korean

Society for the Study of Obesity ≥ 90 cm for men and ≥ 85 cm for women, 2) TG level of ≥ 150 mg/dL, 3) HDL-cholesterol level of < 40 mg/dL for men and < 50 mg/dL for women, 4) BP of $\geq 130/85$ mmHg, 5) fasting blood glucose level of ≥ 100 mg/dL or a history of taking antidiabetic, antihypertensive, or lipid-lowering medications.

2.3. Eating Habit Modification

At the initial visit, study participants attended an one-hour education session on eating habit modification delivered by professional clinical dietitians and received educational materials and books. The sessions covered the definitions of obesity and MetS and the ways to improve eating habits (i.e., appropriate food choice, reduced consumption of foods high in sodium and saturated fatty acid, and guidance on healthy eating-out practices, and food preparation methods). Training for increasing physical activity (light-moderate intensity) in daily life was also provided by health professionals. To increase adherence to the dietary advice, cell phone text messages were also sent to the participants (i.e., low-calorie food selection, stress release, and smart eating-out). This was reinforced by checking their food diary notes.

2.4. Calculation of DAL Scores

We encouraged the study participants to maintain a dietary diaries for at least 3–6 days each month to estimate DAL expressed as NEAP and PRAL scores. NEAP was calculated using protein and potassium intakes, whereas PRAL was calculated using intakes of protein, potassium, phosphorus, magnesium, and calcium [21].

2.5. Nutrition Quotients

The NQ, a dietary index developed by the Korean Nutrition Society, was used to evaluate the nutritional status and meal quality of the study participants. It consists of 21 questions divided into four domains: balance, diversity, moderation, and eating behavior.

2.6. Anthropometric Measurement and Blood Collection

Participants' height was measured manually using an InBody extensometer (InBody Co. BSM170, Ltd., Seoul, Korea). Body weight, body fat percentage, body fat volume (BFM), visceral fat area (VFA), skeletal muscle mass, subcutaneous fat (SFA), and BP were automatically measured using InBody 970 (InBody Co.). WC was measured by a tapeline. The blood samples were collected in serum-separating or ethylenediaminetetraacetic acid tubes after fasting overnight at week 0 and 8 visits, separated into serum or plasma, and then stored below -80 °C before analysis.

2.7. Glycemic Control-Related Parameters and Serum Lipid Profiles

Fasting glucose levels in whole blood were measured using CareSens Dual (i-SENS, Inc., Seoul, Korea). Hemoglobin A1c (HbA1c, %) was measured using SD A1cCare (SD Biosensor, Inc., Suwon, Korea). Serum insulin and C-peptide levels were measured by the immunoassay method using a cobas e 801 analyzer (Roche Ltd., Mannheim, Germany). Homeostasis model assessment insulin resistance (HOMA-IR) was calculated as follows: $HOMA-IR = [\text{fasting insulin } (\mu\text{IU/mL}) \times \text{fasting glucose (mg/dL)}] / 450$. Serum levels of TG, total cholesterol, and LDL-cholesterol were measured using enzymatic assays on a Hitachi LABOSPECT 008AS automatic analyzer (Hitachi, Ltd., Tokyo, Japan). Serum HDL-cholesterol levels were measured using an enzymatic method after the precipitation of chylomicrons with dextran sulfate magnesium.

2.8. Statistical Analysis

The IBM SPSS Statistics version 25.0 (IBM Corp., Armonk, NY, USA) was used for statistical analysis. The Wilcoxon signed-rank test was used to compare the results before and after the intervention. The Friedman test was used to compare the values at weeks 0, 4, and 8 of the

intervention after adjusting for sex, age, cigarette smoking, and alcohol drinking. The Spearman correlation test was used to analyze the relationship between the variables. Partial correlation was also used with adjustment for sex and age. A p-value of <0.05 was considered significant.

3. Results

3.1. Body Composition Parameters of the Study Participants After the 8-Week Intervention

Figure 1 shows significantly improvement in body weight ($P_0 < 0.0001$, $P_1 < 0.0001$), WC ($P_0 = 0.642$, $P_1 = 0.010$), BMI ($P_0 < 0.0001$, $P_1 < 0.0001$), BFM ($P_0 < 0.0001$, $P_1 < 0.0001$), systolic BP ($P_0 = 0.002$, $P_1 = 0.042$), diastolic BP ($P_0 = 0.035$, $P_1 = 0.039$), and SFA ($P_0 < 0.0001$, $P_1 < 0.0001$) after the intervention after the adjustment for sex, age, smoking, and drinking status (P_0 for 4 weeks, P_1 for 8 weeks).

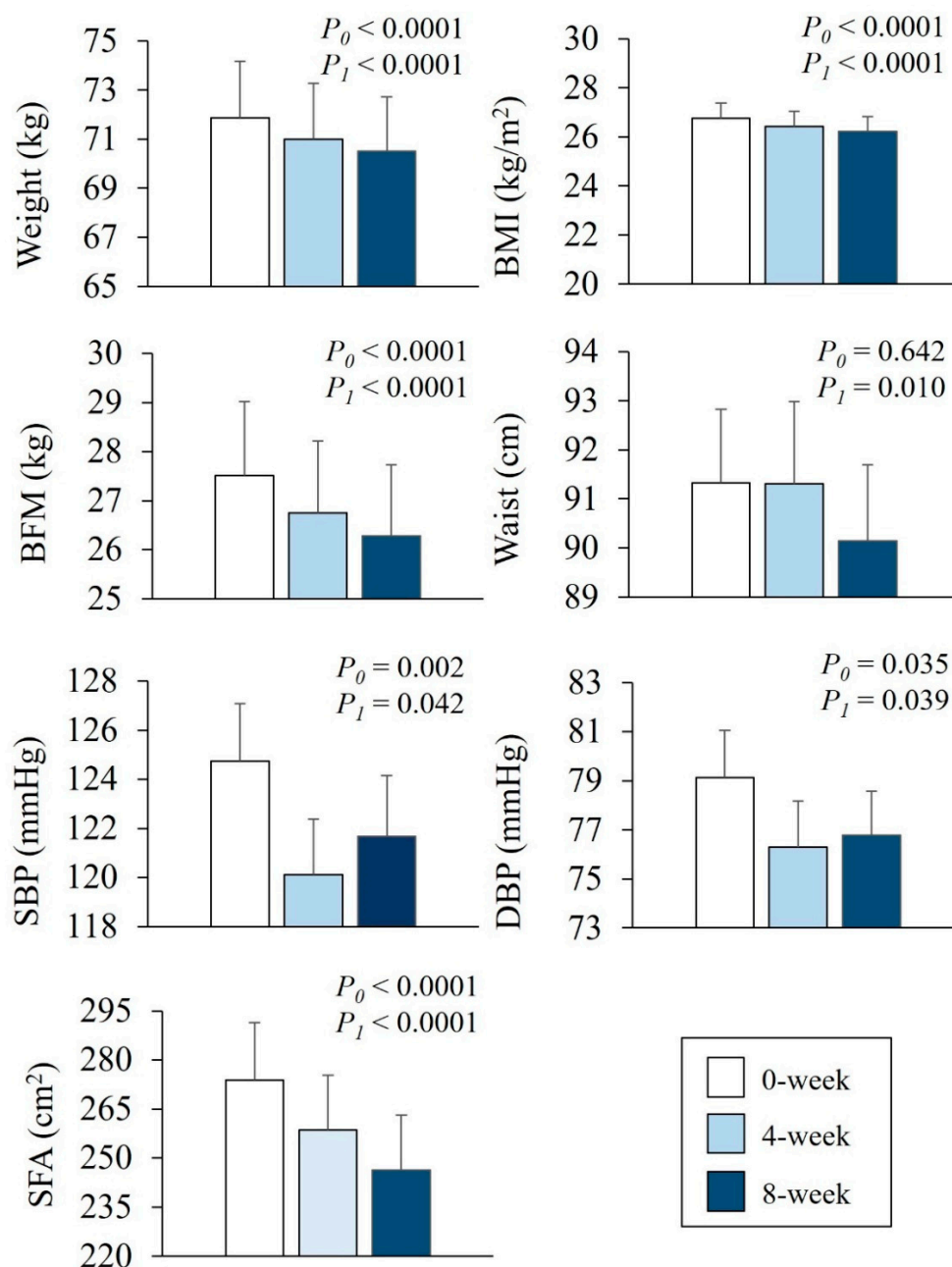


Figure 1. Body composition measures of the study participants over the 8-week intervention period. Means \pm standard error. Tested by the Friedman test (nonparametric repeated measures analysis of variance) with adjustment for age, sex, cigarette smoking, and alcohol drinking. P_0 , P-values compared between the values at 0

and 4 weeks. P_i , P -values compared between the values at 0 and 8 weeks. BFM, body fat mass; BMI, body mass index; DBP, diastolic blood pressure; SBP, systolic blood pressure; SFA, subcutaneous fat area.

3.2. NQ and DAL Scores of the Study Participants at Baseline and After 8-Week Intervention

After the 8 weeks of intervention, the mean values of the total NQ scores (51.0 ± 1.84 and 57.5 ± 1.62 , $P < 0.0001$) were significantly improved along with all of its components, except for diversity, i.e., balance (31.1 ± 2.76 and 35.9 ± 2.25 , $P = 0.013$), moderation (70.0 ± 2.29 and 77.0 ± 2.08 , $P = 0.007$), behavior (41.2 ± 2.75 and 52.9 ± 1.88 , $P < 0.0001$), and diversity (56.5 ± 2.55 and 60.0 ± 2.98 , $P = 0.178$). However, no significant difference was found in the mean values of the DAL scores after the intervention, although the NEAP scores showed a slightly decreasing trend (NEAP scores: 67.8 ± 7.67 and 62.1 ± 3.88 mEq/day, $P=0.717$; PRAL scores: 14.1 ± 3.35 and 15.6 ± 2.17 mEq/day, $P=0.717$).

3.3. Correlation Between DAL Scores and Anthropometric Parameters During the Intervention Period

At baseline, DAL scores expressed as both NEAP and PRAL were not significantly correlated with most anthropometric parameters, however, NEAP scores were negatively correlated with WC after adjustment (Figure 2). After 4 weeks, both PRAL and NEAP scores showed significant positive correlations with body composition parameters including BMI, WC, and SFA. However, the statistical significance disappeared after adjustment (Figure 3). After 8 weeks, PRAL and NEAP scores were significantly and positively correlated with BMI, WC, VFA and SFA. but the significant association between PRAL scores and WC, and between PRAL and SFA disappeared after adjustment (Figure 4).

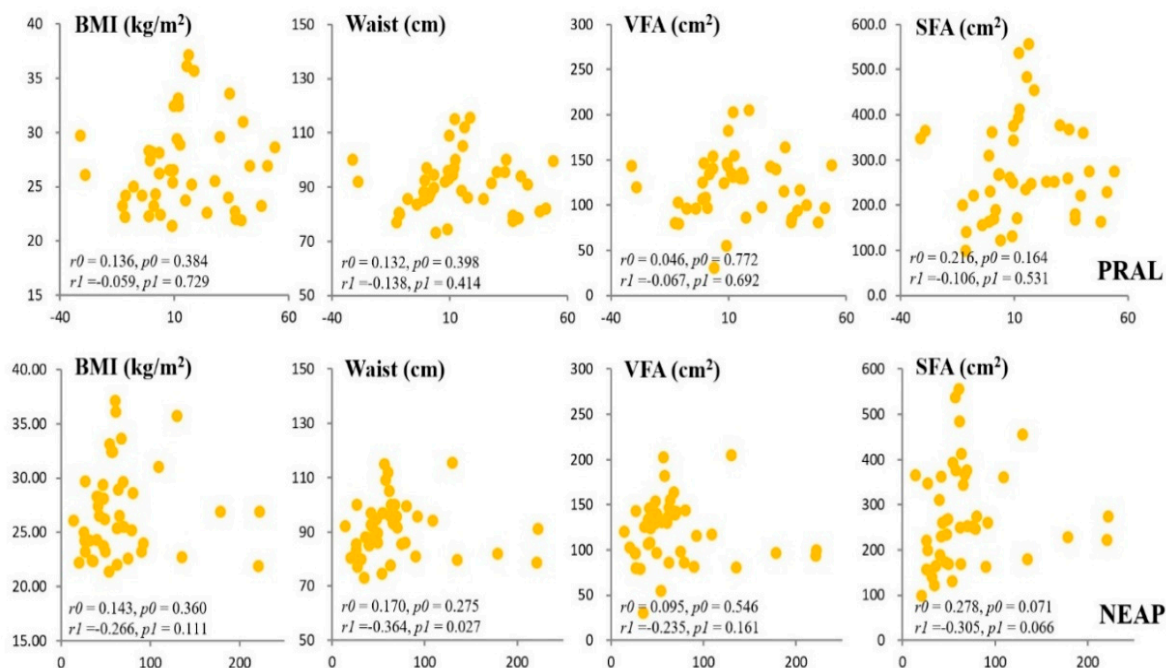


Figure 2. Correlations between dietary acid load scores (PRAL and NEAP) and anthropometric measures at baseline. r , correlation coefficient; r_0 and p_0 , tested by the *Spearman* correlation analysis (unadjusted); r_1 and p_1 , tested by the *partial* correlation analysis (adjusted for age and sex). BMI, body mass index; SFA, subcutaneous fat area; VFA, visceral fat area.

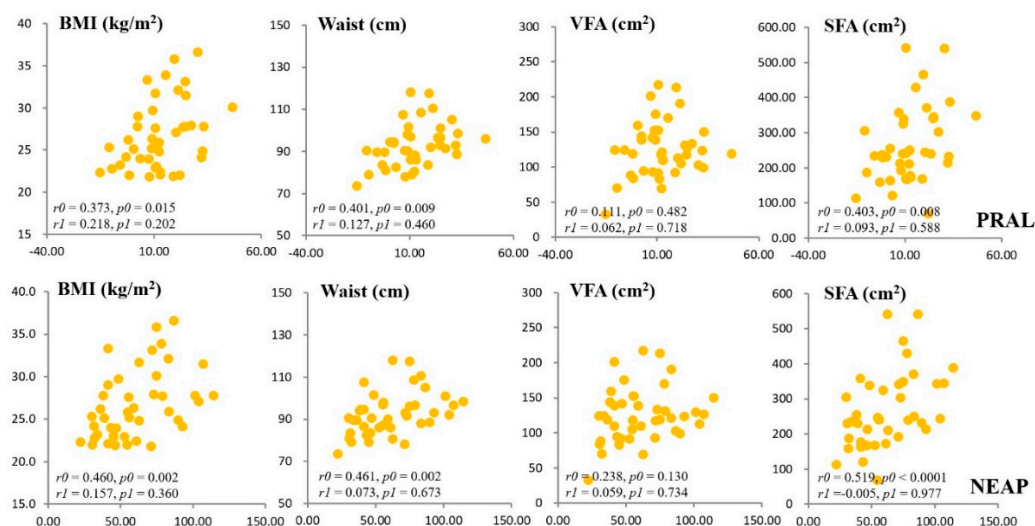


Figure 3. Correlations between dietary acid load scores (PRAL and NEAP) and anthropometric measures after 4 weeks of intervention. r , correlation coefficient; r_0 and p_0 , tested by the *Spearman* correlation analysis (unadjusted); r_1 and p_1 , tested by the *partial* correlation analysis (adjusted for age and sex). BMI, body mass index; SFA, subcutaneous fat area; VFA, visceral fat area.

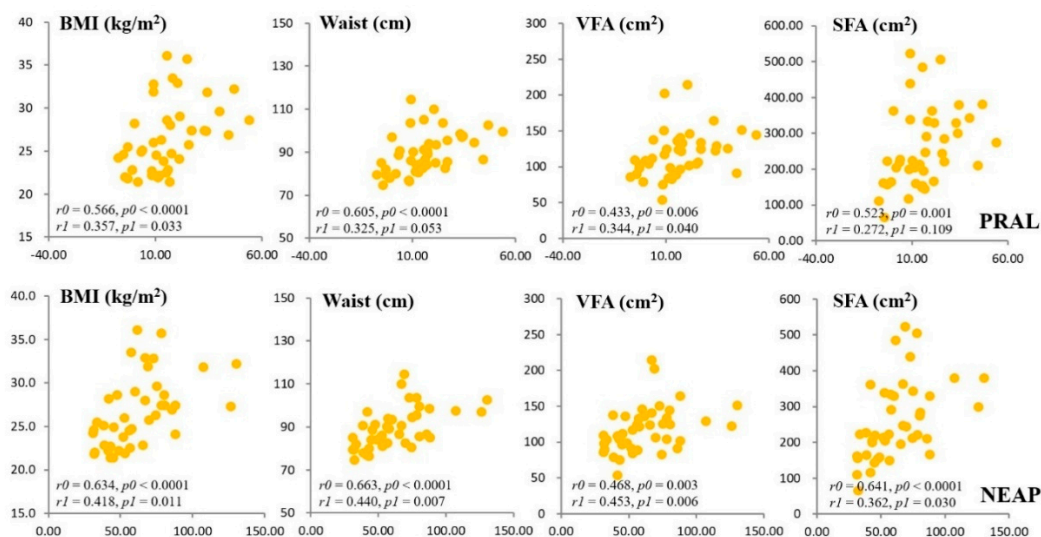


Figure 4. Correlations between dietary acid load scores (PRAL and NEAP) and anthropometric measures at baseline after 8 weeks of intervention. r , correlation coefficient; r_0 and p_0 , tested by the *Spearman* correlation analysis (unadjusted); r_1 and p_1 , tested by the *partial* correlation analysis (adjusted for age and sex). BMI, body mass index; SFA, subcutaneous fat area; VFA, visceral fat area.

3.4. Correlation Between DAL Scores and Biochemical Parameters During the Intervention Period

At baseline, PRAL and NEAP scores were not significantly correlated with fasting insulin, HDL-C, or C-peptide levels (Figure 5A); however, significant association with these biochemical parameters were observed at week 8 (Figure 5B). Notably, after adjustment, the associations remained significant when DAL was expressed as NEAP, but not when expressed as PRAL (Figure 5B). NEAP scores were significantly correlated with fasting glucose at baseline and with HOMA-IR at week 8; however, these associations were no longer significant after adjustment. In contrast, neither PRAL nor NEAP scores were significantly correlated with other lipid profiles, including TG, LDL-C, and total cholesterol, throughout the intervention period.

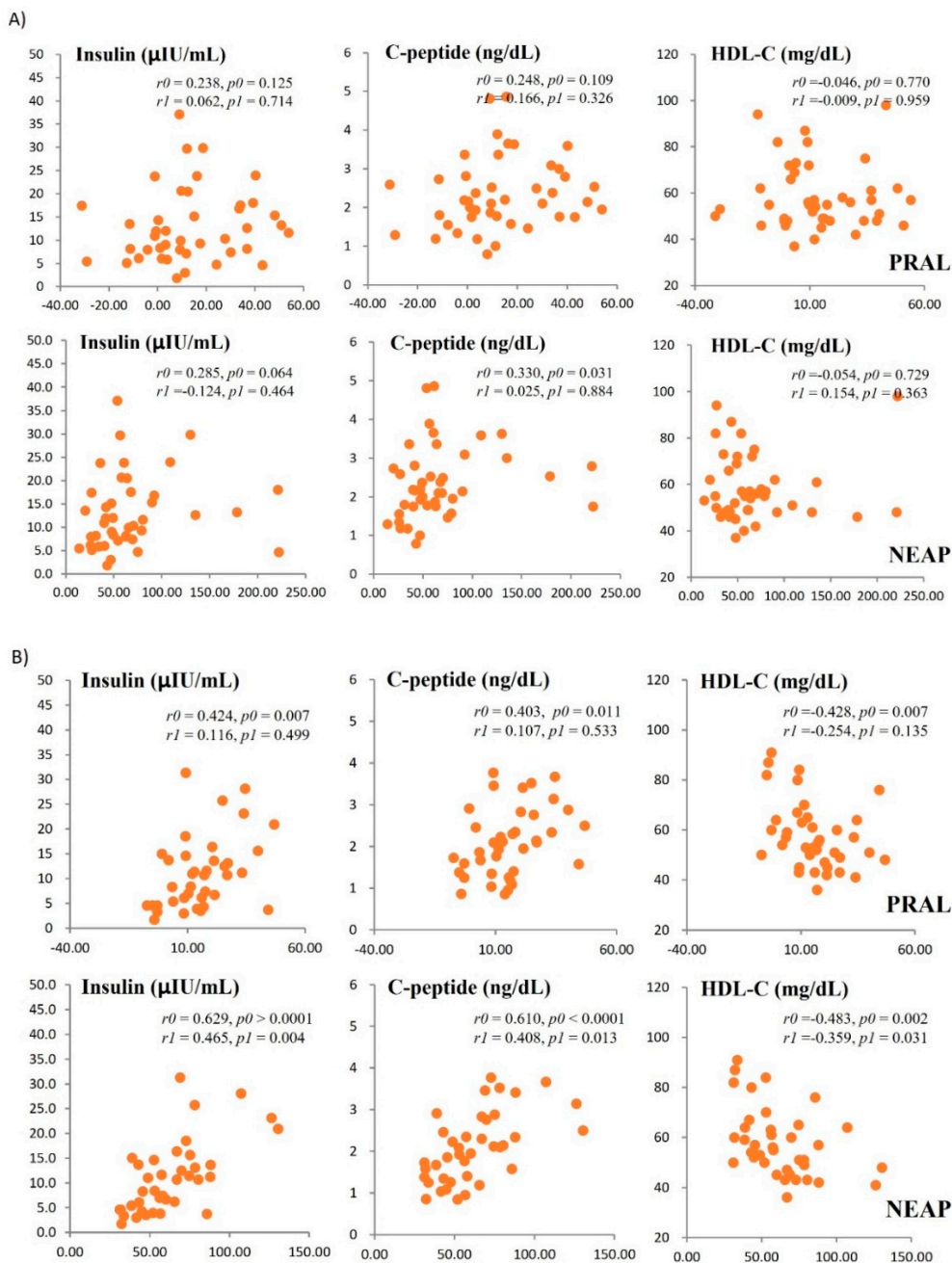


Figure 5. Correlation between dietary acid load scores (PRAL and NEAP) and glycemic control-related parameters and HDL-cholesterol at baseline (A) and during the 8-week intervention period (B). r , correlation coefficient; r_0 and p_0 , tested by the *Spearman* correlation analysis (unadjusted); r_1 and p_1 , tested by the *partial* correlation analysis (adjusted for age and sex). C, cholesterol.

4. Discussion

Previous studies have shown that chronic metabolic disorders including obesity and cardiovascular diseases are associated with DAL scores such as NEAP and PRAL [18–20,26]. Women with higher NEAP scores showed higher levels of body weight, WC, and TG levels, and overweight/obese adolescents with higher PRAL and NEAP scores exhibited higher fasting glucose levels [19,24]. However, one study reported that cardiovascular disease risk was significantly associated with NEAP, but not with PRAL [27]. Consistent with these findings, both NEAP and PRAL were associated with metabolic parameters after the intervention in this present study; however, NEAP appeared to be more sensitive DAL indicator than PRAL. Whereas most previous studies on

the association between DAL and MetS have been cross-sectional, our intervention study evaluated this relationship following eating habit modification.

In this present study, body composition parameters such as BMI, body fat, SFA, and whole-blood glucose were significantly improved after the intervention. BP and HbA1c levels were also significantly improved at week 4, and insulin resistance decreased significantly at week 8. Correlations between DAL scores (NEAP and PRAL) and MetS-related parameters, which were not significant at baseline, reached statistical significance after the intervention. These findings indicate that eating habit modification may improve MetS-related parameters, potentially through changes in DAL (NEAP and PRAL). In addition, the results imply that at least one month of customized education focusing on eating behavior modification may substantially improve NQ scores and contribute to improvements in DAL-related metabolic outcomes.

In a randomized clinical trial involving a 16-week plant-based dietary intervention, PRAL and NEAP scores were positively correlated with body weight and body fat [18]. Another study reported that insulin resistance due to impaired glucose homeostasis may be effectively managed by consuming a diet rich in alkaline vegetables and fruits [22]. Conversely, Westernized dietary patterns have been shown to increase the levels of TG, systolic BP, and blood glucose while decreasing HDL-C levels, thereby elevating the risk of obesity and metabolic diseases [25]. Animal-derived foods such as cheese, eggs, fish, meat, and refined grains, increase acid production because they are rich in sulfur-containing amino acids, phosphorus, and chloride. On the other hand, fruits and vegetables, which contain relatively higher levels of glutamate and citrate, induce base production to help maintain acid–base equilibrium in the body [28]. Therefore, diets characterized by high intake of acid-producing foods and low intake of alkaline foods may increase endogenous acid production and, consequently, elevate DAL scores. Such disturbances in acid–base balance may lead to metabolic acidosis and increase the risk of hypertension, insulin resistance, and cancer [13,23,29]. In healthy individuals, acid–base homeostasis is maintained through buffering systems in the blood, respiration, and renal excretion.

This study suggests that eating habit modification in daily life may influence DAL scores and, thereby, contribute to favorable changes in body composition and metabolic parameters. Accordingly, reducing the intake of high-fat and/or high-carbohydrate foods that may promote dietary acidification and increasing the consumption of vegetables and fruits may help maintain metabolic health.

However, this study has several limitations. First, more than 80% of the study population were women. Although sex was adjusted for in the analyses, further studies need to include a sufficient number of men, because metabolic status may differ by sex due to biological and hormonal factors. Second, after adjustment for sex and age, PRAL showed weaker correlations with metabolic parameters than NEAP. It is assumed that NEAP scores calculated based on protein and potassium intake more simply and sensitively reflect dietary modification than PRAL scores calculated with multiple nutrients including protein, calcium, potassium and magnesium. It also needs to be further elucidated in future studies.

5. Conclusions

This study suggests that eating habit modification in daily life may influence DAL scores, and thereby contribute to significant change in body composition and other metabolic parameters. Further large-scale studies with long-term interventions are needed to confirm these findings.

Author Contributions: Study concept and design: OYK; acquisition of data: YJK, and OYK; analysis and interpretation of data: YJK, CK JP, MC, WSA, and OYK; drafting of the manuscript: YJK, and OYK; critical revision of the manuscript: OYK; statistical analysis: YJK, CK and JP; obtained funding: OYK; administrative, technical, or material support: MC, WSA, and OYK; and study supervision: OYK. All authors have read and approved the final manuscript.

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Institutional Review Board Statement: The Institutional Review Board of Dong-A University approved the study protocol (no. 2-1040709-AB-N-202103-HR-016-02).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data supporting the conclusions of this article will be available from the corresponding author upon reasonable request.

Conflicts of interest: The authors declare no conflict of interest.

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