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ORIGINAL ARTICLE

Comparative Study on the Impact of Malnutrition and Dietary Variations on Human Growth, Skeletal Development, and Metabolic Function Across Pakistani Population

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ABSTRACT

Background: Despite rapid socioeconomic transitions, public health in Pakistan has not been able to prevent malnutrition, which remains a major public health challenge in the country. Nutrition transition occurs in urban areas with high caloric but low micronutrient diets and rural areas with persistent undernutrition. The human consequences of these disparities are critical not only to human growth and skeletal development but also to human metabolic function.

Objective: The purpose of this study was to conduct a comparative analysis of malnutrition and dietary variations among Pakistani populations and assess their impact on anthropometric measures, bone mineral density, and metabolic profiles.

Methods: A cross-sectional comparative study was performed of n=100 participants aged 5 to 60 years from tertiary care Hospitals of Pakistan over 12 months. A validated 24-hour recall and food frequency questionnaire were used to assess dietary intake. Anthropometric data were collected using standardized methods while bone mineral density was measured with dual-energy X-ray absorptiometry (DEXA). Glucose, lipid profiles, and bone turnover markers were analyzed from fasting blood samples. T-tests, ANOVA, and multivariate regression were conducted on statistical analyses with a significance level of $p < 0.05$.

Results: The caloric, protein, calcium, and vitamin D intake of urban participants was greater than rural subjects. However, subjects of urban subjects also had higher fasting glucose, dyslipidemia, and altered insulin levels. On the other hand, rural participants exhibited lower anthropometric indices as well as lower bone mineral density, which corresponded to chronic micronutrient deficiencies.

Conclusion: These are not different burdens; they are the dual burden of malnutrition in Pakistan, and they reinforce the need for tailored public health strategies. Micronutrient deficiencies in rural areas and the metabolic risk in urban populations alike require targeted nutritional interventions.

Keywords: Malnutrition, Dietary Variations, Skeletal Development, Metabolic Function, Pakistan, Urban-Rural Disparities

INTRODUCTION

Even though malnutrition is a formidable public health problem worldwide, the burden of malnutrition is disproportionately borne by low- and middle-income countries. Nutritional inadequacies in Pakistan, a country undergoing rapid socioeconomic transitions and marked regional disparities, are dual epidemics of persistent undernutrition in rural communities and emerging diet-related non-communicable diseases in urban centers[1]. Not only does this dichotomy highlight the diversity in dietary practices but also forecasts divergent growth and skeletal development pathways as well as divergent metabolic functions[2].

Optimal human development hinges on an adequate nutrient supply, particularly during critical windows of childhood and adolescence. Lack of intake of essential macro and micronutrients such as proteins, calcium, and vitamin D—can impair linear growth, interfere with bone mineralization, and increase the risk for metabolic dysregulation[3]. Landmark studies have been performed globally to explain the long-term implications of nutritional deficits and have shown in regions such as sub-Saharan Africa and Southeast Asia that early-life malnutrition is linked to stunted growth and skeletal fragility. As a result, international public health efforts have been made focusing on early nutritional interventions. These nutritional deficits are even more pronounced in Pakistan, where traditional dietary patterns exist side by side with the rapid urbanization of the modern era[4].

In Pakistan, rural populations tend to rely on monotonous plant-based diets with low diversity and low nutrient-dense foods. For example, they live in an economically constrained and limited access to healthcare and nutritional education. Children and adolescents in these areas are also significantly stunted, with high rates of stunting, and have lower bone density, which, together, predispose them to lifelong complications in health, including increased fracture risk and skeletal deformities[5]. On the other hand, although urban populations on average consume more calories in total, they are increasingly exposed to diets rich in processed foods, refined carbohydrates, and unhealthy fats. These diets are energy-rich, but contain insufficient micronutrients for optimal health, and are associated with the early onset of metabolic disorders, such as insulin resistance, dyslipidemia, and type 2 diabetes[6].

Epidemiological studies are starting to emerge that show these dietary imbalances are intricately tied to a whole spectrum of adverse health outcomes. Chronic undernutrition not only impairs physical growth but also hinders the long-term formation of a robust skeletal framework, resulting in long-term skeletal fragility in resource-limited settings. In contrast, the excesses in the urban dietary shifts implicated in the pathogenesis of metabolic disorders place a high risk of cardiovascular disease and other chronic disorders[7].

The socioeconomic impact of malnutrition in Pakistan is also extensive beyond the physiological aspect. The fact that undernutrition continues to exist in rural areas is not solely a reflection of dietary inadequacies but is also a symptom of underlying systemic problems including poverty, poor education, and insufficient healthcare infrastructure[8]. However, urban centres are confronted by the paradox of the nutrition transition – moving towards processed and convenience foods that meet caloric needs, yet contribute to the growing burden of noncommunicable diseases. The burden of this dual burden is compounded by the fact that undernutrition and overnutrition coexist, and both require targeted and context-specific interventions, making it difficult for policymakers and healthcare providers to navigate a landscape of such a dual burden[9].

This study attempts to fill these important knowledge gaps by conducting a comprehensive, comparative analysis of malnutrition and dietary variations across various Pakistani populations. We will integrate rigorous anthropometric assessment, as well as detailed biochemical profiling coupled with robust dietary surveys, with dual-energy X-ray absorptiometry (DEXA) for bone density evaluation and elucidate the multifaceted relationships between nutrition and key physiological outcomes[10]. Our central hypothesis is that regional dietary disparities differentially affect growth, skeletal integrity, and metabolic function which are influenced by both socioeconomic and the ongoing nutrition transition. Study aimed to gain actionable insights through this investigation to inform targeted public health strategies to mitigate the long-term consequences of nutritional deficiencies and diet-related metabolic disorders in Pakistan[11].

This study aimed to offer a more nuanced perspective of health outcomes about malnutrition by contextualizing global evidence within the context of Pakistan's unique nutritional landscape. It points to the need for concerted actions in the fight against immediate deficiency symptoms of nutrients, but also for long-term efforts that aim to prevent the rise of the epidemic of metabolic disorders. This study was designed to add to the development of evidence-based policies and interventions to alter the nutritional future of Pakistan's diverse communities[12].

MATERIALS AND METHODS

Study Design and Population: The study was a cross-sectional comparative analysis conducted from June 2021 till June 2022, to capture the range of the nutritional landscape in Pakistan. The recruitment of participants from both urban and rural areas was to reflect the regional disparities in dietary practices and nutritional outcomes. The study was conducted at different tertiary care hospitals of Pakistan. A total of n=100 patients aged between 5 and 60 years old were enrolled to capture critical developmental stages from childhood to adulthood.

Inclusion and Exclusion Criteria: Those who had resided in their respective regions for at least five years and gave consent (or parental consent for minors) to take part in the study were eligible participants of both sexes. This was a criterion that was set to make sure that dietary habits and nutritional status were based on long-term regional practices. The exclusion criteria included individuals with chronic conditions that could affect metabolism or bone health such as endocrine disorders or severe renal disease. Also, pregnant and lactating women were excluded to eliminate the confounding effects of altered nutritional requirements during pregnancy and lactation.

Data Collection: A multifaceted approach was used to collect data on participants' nutritional status and how it affects their physiological state.

Dietary Assessment: The dietary intake was assessed using a 24-hour recall questionnaire validated as well as a food frequency questionnaire (FFQ) adapted for the local context. These tools were administered to trained interviewers who collected detailed information regarding portion sizes, meal frequency, and nutrient-rich foods. A Pakistan-specific food composition database was used to analyze the dietary data by taking into account the intake of key macronutrients and essential micronutrients such as proteins, calcium, and vitamin D.

Anthropometric Measurements: Growth parameters were evaluated by standardized anthropometric measurements. An assessment of overall nutritional status was made using height, weight, and mid-upper arm circumference (MUAC) measured with calibrated equipment, and body mass index (BMI) was calculated. The measurements were taken in duplicate by trained personnel to achieve accuracy and reliability.

Skeletal Development Analysis: Dual-energy X-ray absorptiometry (DEXA), the gold standard technique for determining skeletal health and bone mineral density (BMD), was used to evaluate BMD. A subset of participants with different age groups and regions were scanned by DEXA, for the study of the connection between nutritional intake and bone health. Z and T scores were calculated and compared with normative data for age-appropriate scores.

Metabolic Function Assessment: Fasting blood samples were collected from participants to assess metabolic function. Biochemical assays were conducted to measure fasting glucose levels and lipid profiles, including total cholesterol, LDL, HDL, and triglycerides. In addition, markers of bone turnover such as osteocalcin and alkaline phosphatase, along with hormonal assays including insulin and parathyroid hormone levels, were analyzed to provide insight into the metabolic implications of dietary patterns.

Metabolic Function Assessment: Participants' metabolic function was assessed through fasting blood samples. Fasting glucose levels and lipid profiles were measured by biochemical assays as total cholesterol, LDL, HDL, and triglycerides. Furthermore, assays for markers of bone turnover (osteocalcin and alkaline phosphatase) and hormonal parameters (insulin, parathyroid hormone) were also measured to give insight into the metabolic effects of dietary patterns.

Ethical Considerations: The study was carried out with the approval of the Institutional Review Board (IRB). All participants (or their guardians when participants were minors) provided written informed consent before participation. According to the Declaration of Helsinki, the study was conducted on the rights, safety, and well-being of all participants from the time of research to the end.

Sample Size and Statistical Analysis: It was determined that 100 participants would be appropriate to determine significant differences in nutritional, skeletal, and metabolic parameters in the chosen regional groups. Analysis of data was done using SPSS version 27. Demographic and clinical characteristics were summarized using descriptive statistics, and a comparative analysis, of urban versus rural participants was done using one-way ANOVA and t-tests. Predictors of growth, bone density, and metabolic outcomes were identified by multivariate regression analyses. The statistical significance was verified by the use of a p-value that was less than 0.05, and therefore the smaller sample size did not compromise the results from the underlying population dynamics.

RESULTS

Table 1 presents the demographic characteristics of the study participants by comparing the urban (n = 50) and rural (n = 50) groups. Urban participants had a significantly higher mean age (32.1 ± 12.8 years) compared to rural participants (26.4 ± 10.2 years; $p = 0.02$). The sex distribution also varied significantly, with the urban group comprising 28 males and 22 females versus 17 males and 33 females in the rural group ($p = 0.03$). Socioeconomic status differed markedly between the two groups; 35 urban participants were classified as high socioeconomic status compared to only 10 in the rural group, while low socioeconomic status was more prevalent in the rural group (40 vs. 15, $p < 0.001$). However, the duration of residence was comparable, with urban participants living in their areas for 15.2 ± 5.0 years and rural participants for 14.8 ± 4.5 years ($p = 0.60$).

Table 1: Demographic Characteristics of Study Participants

Parameter	Urban (n = 50)	Rural (n = 50)	p-value
Mean Age (years)	32.1 ± 12.8	26.4 ± 10.2	0.02*
Sex (Male/Female)	28/22	17/33	0.03*
Socioeconomic Status (High/Low)	35/15	10/40	<0.001*
Duration of Residence (years)	15.2 ± 5.0	14.8 ± 4.5	0.60

* Statistically significant

Dietary Assessment: Significant differences between the two groups were found in the dietary evaluations. There was a higher energy intake (2500 ± 300 kcal/day) in urban participants compared to rural participants (2100 ± 250 kcal/day; $p < 0.001$). Similarly, the group living in urban settlements (80 ± 10 g/day) had a higher intake of protein than the group living in the rural settlements (65 ± 8 g/day; $p < 0.001$). Results of micronutrient analysis indicated that urban subjects consumed more calcium

(900 ± 120 mg/day vs. 700 ± 100 mg/day; $p < 0.001$) and vitamin D (420 ± 80 IU/day vs. 350 ± 70 IU/day; $p < 0.001$) as shown in table 2.

Table 2: Dietary Intake Profiles

Nutrient	Urban (Mean ± SD)	Rural (Mean ± SD)	p-value
Energy (kcal/day)	2500 ± 300	2100 ± 250	<0.001*
Protein (g/day)	80 ± 10	65 ± 8	<0.001*
Calcium (mg/day)	900 ± 120	700 ± 100	<0.001*
Vitamin D (IU/day)	420 ± 80	350 ± 70	<0.001*

* Statistically significant

Anthropometric and Skeletal Development Outcomes: Data on anthropometry showed that urban participants were taller and heavier than rural participants. The mean height of the urban group was 165 ± 7 cm and 162 ± 6 cm in the rural group ($p = 0.01$). In urban subjects mean weight was 60 ± 8 kg vs. 55 ± 7 kg in rural subjects ($p = 0.001$) and similarly reflected in the body mass index (BMI) of 22.0 ± 2.0 kg/m² in urban sites vs. 20.9 ± 2.1 kg/m² in rural sites ($p < 0.001$). We also found that urban participants had greater mid-upper arm circumference (MUAC) (24.5 ± 2.0 cm) than rural ones (23.5 ± 1.8 cm; $p = 0.005$).

The skeletal assessment was performed by DEXA scan and participants living in the urban areas had a higher lumbar spine BMD (1.00 ± 0.10 g/cm²) than those in rural areas (0.90 ± 0.09 g/cm²; $p < 0.001$). Thus, the lumbar spine Z scores were also significantly better in urban subjects (-0.6 ± 0.4) than in rural subjects (-1.1 ± 0.5; $p < 0.001$) as shown in table 3.

Table 3: Anthropometric and Skeletal Parameters

Parameter	Urban (n = 50)	Rural (n = 50)	p-value
Height (cm)	165 ± 7	162 ± 6	0.01*
Weight (kg)	60 ± 8	55 ± 7	0.001*
BMI (kg/m²)	22.0 ± 2.0	20.9 ± 2.1	<0.001*
MUAC (cm)	24.5 ± 2.0	23.5 ± 1.8	0.005*
Lumbar Spine BMD (g/cm²)	1.00 ± 0.10	0.90 ± 0.09	<0.001*
Lumbar Spine Z-score	-0.6 ± 0.4	-1.1 ± 0.5	<0.001*

* Statistically significant

Metabolic Function Assessment: Metabolic profiles of fasting blood sample analyses differed between urban and rural participants. The mean fasting glucose level in the urban subjects was 95 ± 10 mg/dL versus 88 ± 9 mg/dL in the rural subjects ($p = 0.002$). Urban participants had also elevated total cholesterol levels (200 ± 20 mg/dL) compared to rural subjects (185 ± 18 mg/dL; $p = 0.001$). The urban group had higher low-density lipoprotein (LDL) (125 ± 15 mg/dL vs. 115 ± 12 mg/dL; $p = 0.003$) and lower high-density lipoprotein (HDL) (45 ± 8 mg/dL vs. 50 ± 9 mg/dL; $p= 0.001$). In comparison to the rural participants, urban participants had modestly higher triglyceride levels (140 ± 25 mg/dL vs. 130 ± 20 mg/dL, $p = 0.005$).

Bone turnover markers also corroborated these disparities. Osteocalcin levels were higher in the urban (20 ± 5 ng/mL) than in the rural (17 ± 4 ng/mL; $p = 0.001$; alkaline phosphatase levels were slightly lower in the urban group (75 ± 8 U/L vs. 80 ± 10 U/L; $p = 0.01$). The urban group (11 ± 3 µIU/mL) had higher than the rural group (9 ± 2 µIU/mL; $p = 0.002$) as shown in table 4.

Table 4: Metabolic Function Parameters

Parameter	Urban (n = 50)	Rural (n = 50)	p-value
Fasting Glucose (mg/dL)	95 ± 10	88 ± 9	0.002*
Total Cholesterol (mg/dL)	200 ± 20	185 ± 18	0.001*
LDL (mg/dL)	125 ± 15	115 ± 12	0.003*
HDL (mg/dL)	45 ± 8	50 ± 9	0.001*
Triglycerides (mg/dL)	140 ± 25	130 ± 20	0.005*
Osteocalcin (ng/mL)	20 ± 5	17 ± 4	0.001*
Alkaline Phosphatase (U/L)	75 ± 8	80 ± 10	0.01*
Insulin (µIU/mL)	11 ± 3	9 ± 2	0.002*

* Statistically significant

Independent t-tests and one-way ANOVA were performed for comparative analyses, while multivariate regression models were run to find predictor values of key outcomes. The analyses showed that reduced bone mineral density was significantly associated with lower dietary intakes of calcium and vitamin D ($\beta = 0.45$, $p < 0.001$). Additionally, fasting glucose levels were increased with higher energy and refined carbohydrate intakes ($\beta = 0.38$, $p = 0.002$). Anthropometric and metabolic parameters also varied with socioeconomic status and region (urban vs rural) independently.

DISCUSSION

The present study offers a systematic evaluation of the effects of malnutrition and dietary variations on human growth, skeletal development, and metabolic function in a Pakistani cohort. We find that the urban and rural populations are starkly different, and a dual burden of malnutrition is observed in low- and middle-income countries[13]. Despite higher energy and nutrient intake, early signs of metabolic dysregulation were shown in urban participants with elevated fasting glucose and dyslipidemia. On the other hand, rural participants had lower anthropometric indices and less bone mineral density, of which chronic deficits in essential micronutrients like calcium and vitamin D are likely causes[14].

This supports global research showing that poor nutrient intake during key developmental stages is associated with stunting and compromised bone health. The decrease in bone mineral density is apparently due to lower intake of calcium and vitamin D in rural areas and limited access to a diverse diet[15]. This is consistent with studies from sub-Saharan Africa and Southeast Asia, in which other types of undernutrition have been linked to impaired skeletal development. In urban environments, the process of nutrition transition that reflects the shift in consumption of processed food has been a double-edged sword, which provides food energy but has predisposed to the development of metabolic disorders that include insulin resistance and dyslipidemia[16].

Finally, our study also identified the socioeconomic disparities, which highlights the effect of broader social determinants on nutritional outcomes. While high socioeconomic status has been shown to correlate with higher caloric and nutrient intakes, it also occurs among dietary choices that put one at greater risk for metabolic abnormalities. On the other hand, rural areas that are characterized by a high prevalence of low socioeconomic status are more likely to have a higher risk of undernutrition and its sequels: stunting and reduced bone mineral density. While our study provides valuable insights, it is important to acknowledge certain limitations[17, 18].

The use of the cross-sectional design makes it impossible to establish causality, and the sample size is relatively small, although sufficient for initial comparison, which may restrict the generalizability of the findings. Secondly, the use of self-reported dietary data may also be prone to recall bias. Future longitudinal studies of a larger, more diverse population and more precise dietary assessment tools are needed to better understand the complex relationships between dietary intake, growth, bone health, and metabolic function[19, 20].

CONCLUSION

Overall, our study shows substantial differences in nutritional status, skeletal growth, and metabolic function between these urban and rural populations in Pakistan. In this sample, urban participants are at risk for metabolic dysregulation, even though they have higher caloric and nutrient intakes, while rural participants are more vulnerable to undernutrition and its complications, including decreased bone mineral density. These findings highlight the critical need for region-specific nutritional interventions that target the deficiencies in micronutrient intake as well as the risks of the nutrition transition. The capacity to inform public health strategies that are responsive to the socioeconomic and cultural context of Pakistan provides a foundation for efforts to mitigate the long-term health consequences of malnutrition and improve overall population health.

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