Machine Learning Methods for Modeling Hypertension Prevalence in Zambia

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Abstract

Background: Despite advances in medical technology, the global prevalence of high blood pressure (hypertension) continues to rise. Developing countries like Zambia are experiencing increasing rates of hypertension, partly due to rapid lifestyle changes associated with urbanization and modernization. This study investigates key demographic and lifestyle factors associated with hypertension in Zambia.
Method: Data from the 2017 World Health Organization (WHO) STEPS survey was analyzed, including demographic, socioeconomic, behavioral, and biometric variables. Descriptive statistics and chi-square tests were used to summarize the data and find association between hypertension and covariates. Logistic and quantile regression models were employed to assess relationships between predictors and hypertension, while nonparametric smoothing techniques explored the proportion of hypertension prevalence by different levels of predictors. A Random Forest model with a Leave-One-Covariate-Out (LOCO) approach was used to assess variable importance.
Results: Age and body mass index (BMI) were found to be strong predictors of hypertension, particularly in the 90th percentile. Among women, age 45 and older was significantly associated with hypertension; for men, the threshold was age 65. Nonparametric plots revealed higher rates of hypertension among urban residents, individuals with a BMI over 30, and those who consume alcohol. LOCO analysis identified age as the most influential predictor across models.
Conclusion: This study highlights the growing burden of hypertension in Zambia and identifies age and BMI as key contributing factors. The findings emphasize the importance of public health strategies focused on lifestyle modification to mitigate hypertension risk in rapidly modernizing low- and middle-income countries.

1. Introduction

High blood pressure (hypertension) is a key indicator of cardiovascular health and a major risk factor for heart disease, stroke, and mortality (Kendall et al., 2015; Whelton et al., 2017). The prevalence of hypertension has been increasing globally (Kearney et al,. 2005) and is currently about 30%. It is slightly lower for wealthier countries (Mills et al., 2016). Research of US adults has shown that the prevalence of hypertension has increased over time (Bromfield et al., 2014). Understanding the factors associated with hypertension is critical for informing public health interventions, particularly in countries experiencing rapid lifestyle changes.

Previous research from the United States as well as developing countries has identified multiple risk factors for hypertension, including age, obesity, smoking, and alcohol consumption (Kannel, 1987; Mills et al, 2020). Smoking and alcohol use, in particular, are known to contribute not only to cardiovascular disease (Mulenga et al., 2013; Ambrose, 2004; Jackson et al., 1991) but also to respiratory damage (Wistuba, 2002). In Zambia, shifting dietary habits—such as increasing consumption of processed foods—have been linked to rising rates of obesity and chronic disease, highlighting the need for greater dietary diversity (Harris et al., 2019). However, the WHO STEPS 2017 dataset provides limited dietary insights, aside from noting that vegetable oil is the dominant cooking fat. Rush et al. 2018 found that higher consumption of vegetables was correlated with a lower likelihood of hypertension in Zambia.

There has long been substantial research linking various dietary factors to cardiovascular health outcomes. Historically, high salt intake was widely believed to be a major contributor to hypertension; however, recent literature challenges this traditional view, suggesting that the role of salt may have been overstated (DiNicolantonio et al., 2017). Instead, modern studies increasingly identify added sugars, particularly fructose, as a more significant dietary factor associated with the development of hypertension (DiNicolantonio et al., 2014). This shift in understanding highlights the evolving nature of nutrition science and its implications for public health strategies. In the context of Zambia, the country is undergoing rapid socio-economic development, accompanied by significant shifts in lifestyle and dietary habits. As urbanization accelerates, more individuals are adopting sedentary lifestyles and consuming greater amounts of processed foods high in added sugars. These changes are contributing to rising rates of overweight and obesity, particularly in urban and more economically developed areas (Ndahayo et al., 2022). Consequently, the increasing burden of non-communicable diseases such as hypertension represents a major public health challenge that requires targeted interventions focused on promoting healthier dietary patterns and active living.

Like many low- and middle-income countries, Zambia is facing a growing burden of noncommunicable diseases, even as infectious diseases remain prevalent (Musonda et al., 2024; Kandala et al., 2008; Wall et al., 2018; White et al., 2012; Kapembwa et al. 2011). Rapid urbanization, changes in dietary patterns, and limited access to preventive healthcare have contributed to rising rates of obesity and hypertension, particularly in urban areas (Rudatsikira et al., 2012; Opie & Seedat 2005).

Using a comprehensive dataset that includes biometric measurements (e.g., height, weight, waist and hip circumference, systolic and diastolic blood pressure) and self-reported behavioral factors (e.g., smoking and alcohol consumption), this study aims to assess the relationship between these variables and hypertension. Findings from this analysis contribute to the broader literature on hypertension by examining its prevalence and risk factors within the Zambian context.

2. Data and Variables

This study utilizes data from the 2017 STEPS World Health Organization (WHO) Zambia survey to examine the factors associated with high blood pressure (HBP) among individuals. The STEPS survey follows a standardized methodology designed to collect data on key non-communicable disease (NCD) risk factors, including sociodemographic characteristics, lifestyle behaviors, and biological markers. The data has 4,302 observations. 62% of those are female.

Dependent Variable

The primary outcome variable in this study is **high blood pressure (HBP)**, defined as a systolic blood pressure of **≥140 mmHg** or a diastolic blood pressure of **≥90 mmHg**. Individuals meeting either criterion are classified as having high blood pressure.

Explanatory Variables

The analysis incorporates a range of independent variables that may influence blood pressure levels. These include: Age Range, Residence, Wealth Index, Education, Marriage status, Tobacco use, Alcohol use, Dietary salt, Exercise amount, Waist to Hip ratio, BMI, Urine sodium level, blood glucose level, and cholesterol level.

3. Statistical Methods

To understand hypertension prevalence in Zambia we used a set of statistical methods including: summary statistics, chi-square test of independence, parametric and non parametric regression, and feature importance for logistic regression models. Bivariate analysis (chi-square test) was used to assess which independent variables will be included in the regression models. Non parametric Kernel regression (Chowdhury 2017; Haskin et al. 2022) was used to construct age-variant curves for portions of hypertension for various covariates. Random Forest with LOCO was used to assess the importance of each variable in the logistic regression model.

4. Results

Table 1: Summary Statistics

	All (%)	Men (%)	Women (%)
Age Range			
18-24	854 (20.67)	315 (20.13)	539 (21.01)
25-34	1157 (28.01)	445 (28.43)	712 (27.75)
35-44	951 (23.02)	366 (23.39)	585 (22.8)
45-54	572 (13.85)	231 (14.76)	341 (13.29)
55-64	399 (9.66)	146 (9.33)	253 (9.86)
65+	198 (4.79)	62 (3.96)	136 (5.3)
Residence			

Rural	1642 (38.17)	560 (34.7)	1082 (40.25)
Urban	2660 (61.83)	1054 (65.3)	1606 (59.75)
Wealth Index			
Poor	1380 (50.36)	547 (49.19)	833 (51.17)
Middle	1058 (38.61)	425 (38.22)	633 (38.88)
Rich	302 (11.02)	140 (12.59)	162 (9.95)
Education			
No school	1546 (35.96)	439 (27.22)	1107 (41.21)
Primary	1862 (43.31)	746 (46.25)	1116 (41.55)
Secondary	564 (13.12)	264 (16.37)	300 (11.17)
College +	327 (7.61)	164 (10.17)	163 (6.07)
Marriage			
Never Married	934 (21.76)	424 (26.29)	510 (19.04)
Married	2621 (61.07)	1069 (66.27)	1552 (57.93)
Cohabitate	6 (0.14)	4 (0.25)	2 (0.07)
Marriage ended	731 (17.03)	116 (7.19)	615 (22.96)
Tobacco			
Smokes	475 (11.04)	414 (25.65)	61 (2.27)
Does not	3826 (88.96)	1200 (74.35)	2626 (97.73)
Alcohol			
Drinks	1047 (74.89)	627 (79.57)	420 (68.85)
Does not	351 (25.11)	161 (20.43)	190 (31.15)
Diet Salt			
Normal	3217 (75.82)	1210 (75.72)	2007 (75.88)
High	1026 (24.18)	388 (24.28)	638 (24.12)
Exercise			
Low exercise	60 (22.73)	37 (19.37)	23 (31.51)
Med exercise	123 (46.59)	92 (48.17)	31 (42.47)
High exercise	81 (30.68)	62 (32.46)	19 (26.03)
Waist to Hip			
Fat	1207 (30.1)	287 (18.32)	920 (37.66)
Not fat	2803 (69.9)	1280 (81.68)	1523 (62.34)
BMI			
below 30 BMI	339 (8.45)	73 (4.66)	266 (10.89)

30 to 40 BMI	2558 (63.79)	1121 (71.54)	1437 (58.82)
above 40 BMI	1113 (27.76)	373 (23.8)	740 (30.29)
Urine Sodium			
Normal	2648 (89.19)	1055 (91.18)	1593 (87.91)
High	321 (10.81)	102 (8.82)	219 (12.09)
Blood Glucose			
Normal	2704 (74.94)	1059 (76.79)	1645 (73.8)
Prediabetes	474 (13.14)	163 (11.82)	311 (13.95)
Diabetic	430 (11.92)	157 (11.39)	273 (12.25)
Cholesterol			
Normal	3401 (91.25)	1341 (94.64)	2060 (89.18)
High	326 (8.75)	76 (5.36)	250 (10.82)

The median (IQR) age was 34 (25-46). The median (IQR) SBP and DBP were 126 (115-138) and 78 (71-87). The median BMI was 36.042 (32.771-40.589). In addition, 35.96% never completed primary school, and 38.17% were residing in rural areas. Very few women smoke which aligns with research from Indonesia (Ng et al.,2006).

Table 2: Bivariate Analysis (Chi-squared Test)

	Men				Women		
	High Blood Pressure				High Blood Pressure		
	0	1	P-Value		0	1	P-Value
Age Range				**Age Range**			
18-24	215	93	0.000386	18-24	429	89	0
25-34	297	133		25-34	569	115	
35-44	226	123		35-44	422	140	
45-54	149	75		45-54	214	124	
55-64	83	54		55-64	122	124	
65+	24	35		65+	43	90	
Region				**Region**			
Rural	357	184	0.913517	Rural	758	279	0.98569

Urban	674	341		Urban	1140	422	
Wealth Index				**Wealth Index**			
Poor	416	210	0.513974	Poor	743	262	0.249557
Middle	307	149		Middle	493	174	
Rich	85	52		Rich	105	50	
Education				**Education**			
No school	265	157	0.102411	No school	753	317	0.009121
Primary	494	222		Primary	821	262	
Secondary	175	85		Secondary	218	70	
College +	97	60		College +	106	51	
Marriage				**Marriage**			
Never Married	280	131	0.776265	Never Married	392	100	0
Married	676	354		Married	1131	369	
Cohabitate	3	1		Cohabitate	1	1	
Marriage ended	71	39		Marriage ended	372	227	
Tobacco				**Tobacco**			
Smokes	259	142	0.447149	Smokes	39	20	0.287221
Does not	772	383		Does not	1859	681	
Alcohol				**Alcohol**			
Drinks	380	223	0.697073	Drinks	301	110	0.357982
Does not	99	53		Does not	128	57	
Diet Salt				**Diet Salt**			
Normal	773	390	0.807444	Normal	1413	529	0.355134
High	248	130		High	462	156	
Exercise				**Exercise**			
Low exercise	26	11	0.836897	Low exercise	19	4	0.389376
Med exercise	64	26		Med exercise	24	6	
High exercise	45	15		High exercise	17	1	
Waist to Hip				**Waist to Hip**			
Fat	155	131	3.00E-06	Fat	597	317	0
Not fat	876	394		Not fat	1144	367	
BMI				**BMI**			
below 30 BMI	56	16	0	below 30 BMI	213	52	0
30 to 40 BMI	780	335		30 to 40 BMI	1095	336	

above 40 BMI	195	174		above 40 BMI	433	296	
Urine Sodium				**Urine Sodium**			
Normal	673	361	0.200467	Normal	1121	447	0.202826
High	72	28		High	161	51	
Blood Glucose				**Blood Glucose**			
Normal	715	321	0.000574	Normal	1194	424	1.10E-05
Prediabetes	98	65		Prediabetes	220	86	
Diabetic	86	70		Diabetic	161	109	
Cholesterol				**Cholesterol**			
Normal	885	433	0.002626	Normal	1491	535	0
High	36	37		High	141	106	

Table 2 shows the chi squared test of independence between the dependent variable, hypertension and a set of independent variables: Age Range, Residence, Wealth Index, Education, Marriage status, Tobacco use, Alcohol use, Dietary salt, Exercise amount, Waist to Hip ratio, BMI, Urine sodium level, blood glucose level, and cholesterol level. For men; age, waist to hip ratio, BMI, glucose, and cholesterol had a p-value < 0.05. For women; age, education, marriage status, waist to hip ratio, BMI, glucose and cholesterol had a p-value < 0.05.

Table 3: Logistic Regression

	Men		Women	
	Odds Ratio	P Value	Odds Ratio	P Value
(Intercept)	0.22068	0	0.0913	0
Age 25-34	1.07935	0.66942	0.92099	0.64439
Age 35-44	1.24222	0.24582	1.25002	0.22688
Age 45-54	1.00536	0.97996	2.17832	9.00E-05
Age 55-64	1.33298	0.24184	3.73092	0
Age 65+	3.05699	0.00091	8.03661	0
Primary			0.95039	0.67418
Secondary			1.18264	0.39645
College +			1.3376	0.20028
Married			0.9711	0.86485
Cohabitate			4.37184	0.35989
Marriage ended			1.06684	0.74723
Fat	1.44987	0.01721	1.28285	0.02366
BMI 30 to 40 BMI	1.46195	0.21231	1.99675	0.00063
BMI 40+ BMI	2.65262	0.00217	3.84028	0
Prediabetes	1.4156	0.0468	1.11238	0.46962
Diabetic	1.47965	0.04085	1.3587	0.05653
cholesterol High	1.45451	0.15164	1.41982	0.03271

Table 3 shows the logistic regression models for predicting hypertension for men and women. The independent variables that had a p-value < 0.05 in the chi-squared test of independence were used in the logistic regression models. For men, an age of 65+ is statistically significant (alpha level = 0.05). However, for women, age ranges of 44-55, 54-65, 65+ are all significant. Waist to hip ratio is significant for both men and women. A BMI > 40 is significant for men and a BMI between 30 to 40 and also a BMI > 40 is significant for women. Being diabetic is significant for both men and women, and prediabetes is significant for men (alpha level = 0.1). High cholesterol is only statistically significant for women. The logistic regression shows that on average, men are more likely to have hypertension than women, and this is consistent with previous research from other countries (Minh et al., 2006).

Table 4: Quantile Regression (90th percentile Systolic Blood Pressure)

	Men		Women	
	Estimate	P Value	Estimate	P Value
(Intercept)	110.33344	0	83.1567	0
age	0.32501	0.00249	0.80015	0
w2h	-8.23417	0.75793	22.98899	0.01855
bmi	0.98897	0.00063	0.52483	1.00E-05
glucose	0.87913	0.16625	0.03545	0.89836
cholesterol	-0.93911	0.1343	-0.19016	0.49632

Table 4 shows the quantile regression for the 90th percentile systolic age is significantly for both men and women. Waist to hip ratio and BMI is statistically significant for women but for men only BMI is significant.

Figure 1: Age-variant Kernel smoothing regression curves for proportion of Hypertentsive men and women based on covariates

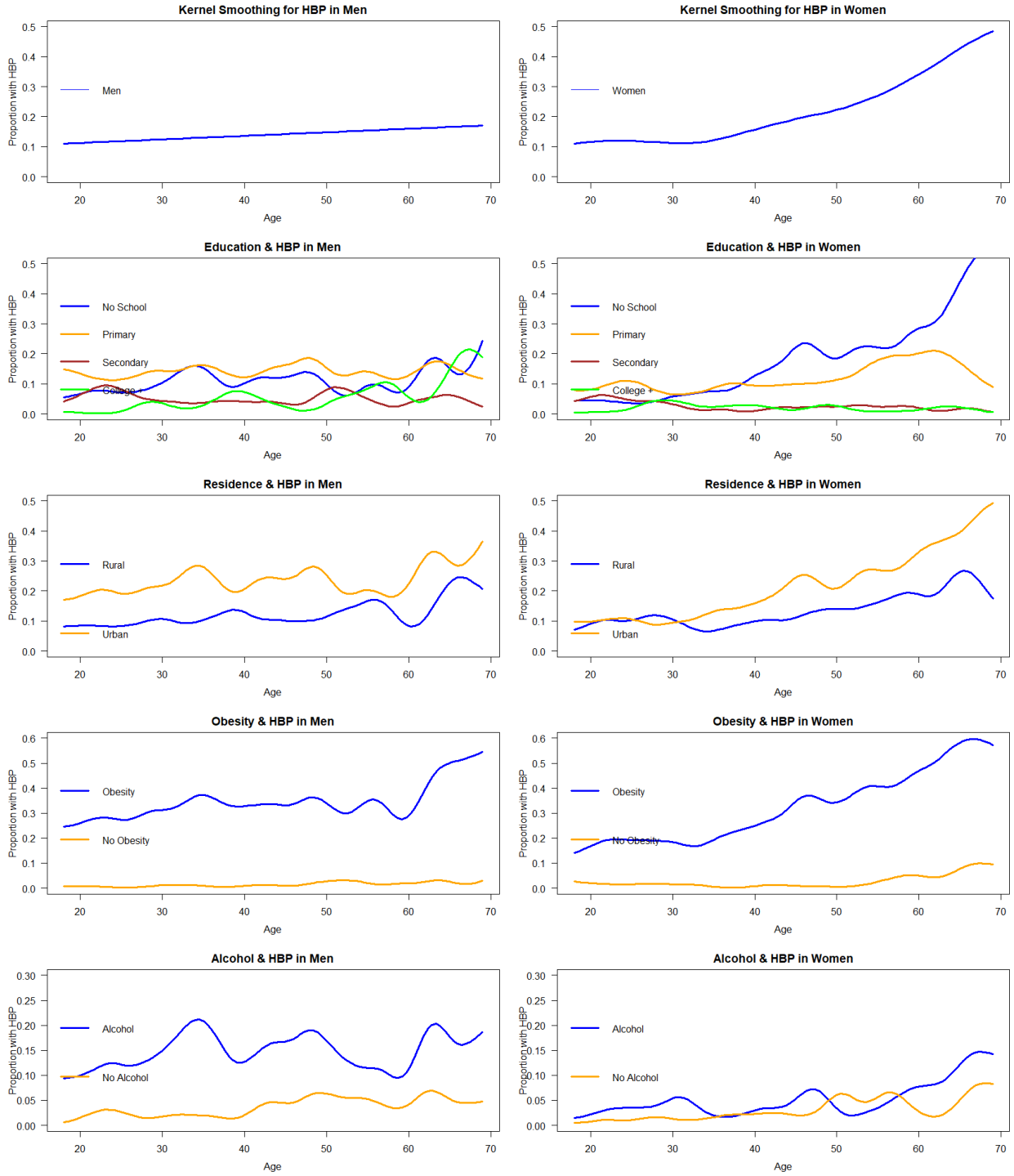
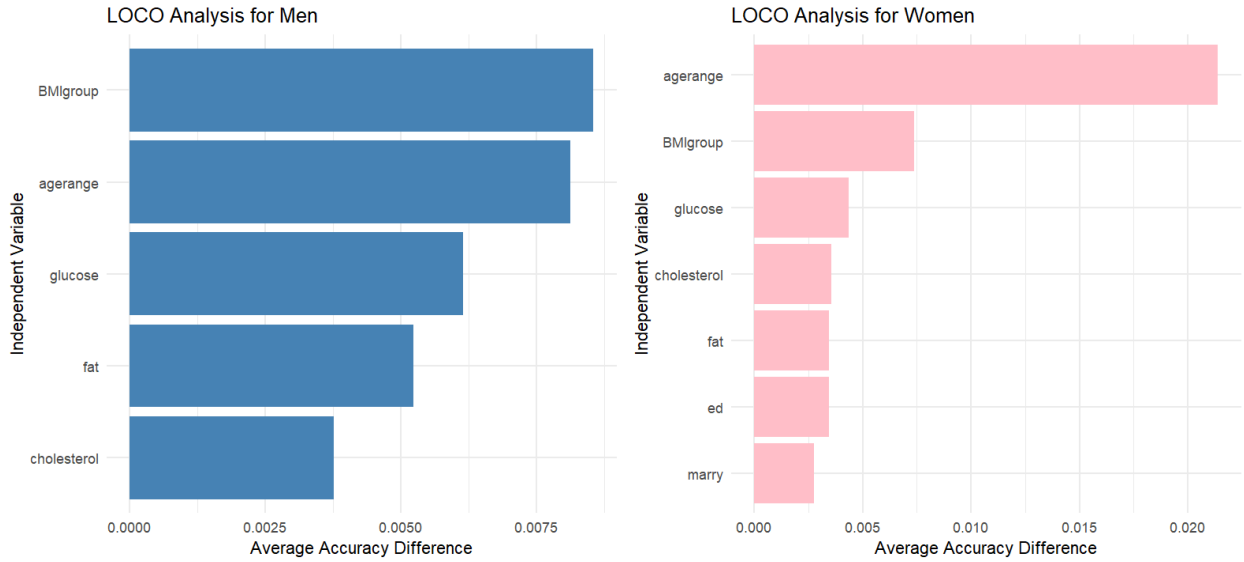


Figure 1 shows the proportion of hypertension by age for different covariates. Education shows different results for men compared to women. For men, education levels and the proportion of hypertension cannot be disentangled; however, for women, by age 70, all of the women are not

educated or completed primary school. Urban dwellers have higher rates of hypertension compared to rural inhabitants. High BMI is positively correlated with hypertension which aligns with previous research (Brown et al., 2000). Men who consume alcohol have a higher prevalence of hypertension compared to non alcohol drinkers. This is consistent with previous research (Briasoulis et al., 2012) As age increases the prevalence of hypertension drops at age 35 and again at age 50. These drops could be due to the loss of life as a result of consumption of alcohol or a change in lifestyle. By age 70 those with hypertension mostly consume alcohol. For women, the distinction between drinkers and non drinkers is less drastic. This could be due to women drinking less than men; prevalence of consuming alcohol is less for women than men (McCaul et al., 2019; Dawson & Archer 1992).

Figure 2: Random Forest LOCO model analysis



The LOCO compares the accuracy of the full model and the reduced model. The results show that the largest decrease in accuracy occurs when removing age from the model. Therefore, age is variable with the most explanatory power in the model. BMI is almost as important as age for men.

5. Conclusion

The findings of this study align with previous research using WHO data on Zambia (Goma et al., 2011), reinforcing the strong association between age and hypertension, with body mass index (BMI) emerging as another significant predictor. As Zambia and other developing nations undergo rapid lifestyle transitions—characterized by decreased physical activity and increased consumption of inexpensive, processed foods—the burden of hypertension is likely to rise. Public health initiatives focused on promoting healthy diets, physical activity, and early screening for cardiovascular risk factors are essential to mitigate this growing epidemic and support sustainable, healthy development.

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