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Modelling of South African child hypertension-application of panel quantile regression

Anesu Gelfand Kuhudzai[1,2]* and Kolentino Mpeta[1]

[1]Business Statistics and Operations Research Department, Faculty of Economic and Management Sciences, North-West University, Mahikeng, North-West Province, South Africa

[2]Statistical Consultation Services, University of Johannesburg, Johannesburg, Gauteng, South Africa

Abstract

Introduction: Hypertension in children is an emerging public health concern that has traditionally received limited attention, particularly in developing countries such as South Africa.

Objective: This study addresses a methodological gap by modeling pediatric hypertension in South Africa using panel quantile regression analysis, aiming to uncover the heterogeneous effects of key predictors across the blood pressure distribution over time.

Methods: Data were obtained from the South African National Income Dynamics Study Household Surveys conducted in 2014–2015 (Wave 4) and 2017 (Wave 5). We constructed a balanced panel of 103 adolescents (<18 years) who participated in both Waves 4 and 5. Panel quantile regression was applied to examine predictors of blood pressure over time.

Results: The prevalence of child hypertension based on abnormal systolic blood pressure increased slightly from 16.5% in 2014–2015 to 21.4% in 2017. Age, body mass index, gender, exercise frequency, cigarette use, depression, and perceived health status were identified as significant predictors of elevated systolic blood pressure or diastolic blood pressure over time. Fixed-effects and random-effects specifications produced identical point estimates.

Conclusion: These results underscore the importance of targeted interventions that consider modifiable lifestyle and psychosocial factors when addressing hypertension among South African children.

Keywords: Child hypertension; South Africa; Panel quantile regression; Random-effects model; Fixed-effects model

***Corresponding author:**
Anesu Gelfand Kuhudzai
(gelfand9@yahoo.com)

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1. Introduction

1.1. Epidemiology of childhood hypertension

Childhood hypertension is an emerging public health concern, with increasing evidence showing that elevated blood pressure during childhood and adolescence persists into adulthood and substantially increases the risk of cardiovascular disease.[1-4] Globally, lifestyle changes, including reduced physical activity and increasing obesity, have contributed to this trend. In South Africa, childhood hypertension remains under-researched despite a growing prevalence, particularly in disadvantaged communities, where approximately 18% of children exhibit elevated systolic blood pressure (SBP) or diastolic blood pressure (DBP).[5]

1.2. Panel quantile regression

Traditional mean-based regression approaches assume homogeneous effects of predictors across the blood pressure distribution and may obscure important variations among high-risk individuals. Panel quantile regression extends standard quantile regression to longitudinal data, enabling estimation of covariate effects at different points of the conditional distribution while accounting for unobserved individual heterogeneity. This makes the approach especially suitable for analyzing health outcomes that evolve over time and display distributional asymmetry.[6]

1.3. Panel quantile regression and childhood hypertension

Hypertension primarily affects the upper tail of the blood pressure distribution. Panel quantile regression enables the identification of factors that disproportionately influence adolescents with moderately high and severely elevated blood pressure.[7] In the South African context, where socioeconomic and behavioral risk factors vary widely, this distributional perspective provides a more informative basis for policy-relevant inference. This study therefore applies panel quantile regression to model childhood hypertension dynamics using nationally representative longitudinal data.

2. Materials and methods

2.1. Data source and study design

This longitudinal study utilized data from the South African National Income Dynamics Study Waves 4 (2014–2015) and 5 (2017). After data cleaning, a balanced panel comprising 103 adolescents under 18 years was obtained.

2.2. Variables and measurements

Both SBP and DBP were considered outcome variables. Explanatory variables included age, gender, race, body mass index (BMI), pulse rate, exercise frequency, cigarette use, depression, and perceived health status.

2.3. Panel quantile regression model specification

Panel quantile regression is an econometric method that extends traditional quantile regression to panel data, allowing estimation of conditional quantiles of the dependent variable while accounting for both individual- and time-specific heterogeneity.[8] This approach is particularly useful for capturing the varying effects of explanatory variables across different points in the conditional distribution of the dependent variable, providing a comprehensive understanding of the relationships within the data.

Panel data can be classified as balanced or unbalanced. Unbalanced panel data arise when a different number of observations are available for each unit, whereas balanced panel data occur when each unit is observed at every time point.[9] Panel data are structured as a vector of the dependent variable $y^t_{[n]}$ observed on n units and a matrix of p independent variables $X^t_{[nxp]}$, where $t = 1, \ldots, T$ is the number of time points.[10]

For the examination of panel data with fixed effects (FE), a quantile regression model is provided by Koenker[11]:

$$Q_\theta(y^t|\mathrm{x}) = \alpha + \beta(\theta)\mathrm{x}^t + e^t \tag{1}$$

where:

(i) θ represents the vector of quantiles.
(ii) α represents a vector of unknown unit-specific intercepts.
(iii) β represents the vector of quantile-specific slope coefficients.
(iv) x^t represents the vector of independent variables at time t.
(v) y represents the dependent variable at time t.
(vi) e^t is the error term.

For the examination of panel data with random effects (RE), a quantile regression model is provided by Bache *et al.*[12]:

$$Q_\theta(y^t|\mathrm{x}) = \alpha + \beta(\theta)\mathrm{x}^t + \epsilon + e^t \tag{2}$$

where:

(i) θ represents the vector of quantiles.
(ii) α is the classical average effect.
(iii) β represents the vector of quantile-specific slope coefficients.
(iv) x^t represents the vector of independent variables at time t.
(v) y represents the dependent variable at time t.
(vi) e^t is the error term.
(vii) ϵ is the random deviation of unit intercepts from α.

In convention FE models, assumes individual-specific effects are correlated with the explanatory variables. FE models control for all time-invariant characteristics by using within-entity variation only. In contrast, RE models assumes individual-specific effects are uncorrelated with the explanatory variables treating these effects as random and uses both within-and between-entity variation, making it more efficient if the assumption holds.[11]

2.4. Statistical analysis

Descriptive statistics were computed using SPSS version 30 (IBM, USA). Panel quantile regression models (both the FE and RE models) were estimated in R (R Foundation for Statistical Computing, Austria) using the rqpd package.[11] The rqpd package extends algorithms from the quantreg package for panel data structures. Estimation was performed through linear programming or penalized optimization, depending on the model specification. FE and RE panel quantile regression models were estimated at the 75th and 95th quantiles to capture heterogeneous effects across the upper distribution of blood pressure.

3. Results

3.1. Demographic and lifestyle characteristics

Table 1 summarizes participant characteristics; 43.7% were male and 56.3% were female, with the majority identifying as African. Over time, improvements were observed in healthy BMI status and exercise frequency, whereas cigarette use and moderate depressive symptoms increased. The prevalence of abnormal SBP increased from 16.5% in Wave 4 to 21.4% in Wave 5.

3.2. Panel quantile regression results for systolic blood pressure

Table 2 presents results from panel quantile regression analyses estimating the effects of various risk factors on SBP at the 75th (Q[0.75]) and 95th (Q[0.95]) quantiles. Age and BMI were positively associated with SBP at the 75th percentile. Gender and depression were significant predictors across both upper quantiles, whereas exercise frequency, cigarette use, and perceived health status were significant only at the 95th percentile. FE and RE models yielded identical estimates.

3.3. Panel quantile regression results for diastolic blood pressure

Table 3 presents the estimated effects of various risk factors on DBP at the 75th and 95th percentiles of the distribution. Cigarette use was positively associated with DBP at both upper quantiles, whereas depression was significant only at the 95th percentile. All other covariates were not statistically significant.

4. Discussion

The study identified a modest increase in childhood hypertension prevalence over time, driven primarily by elevated SBP. Panel quantile regression analysis revealed that key demographic, behavioral, and psychosocial factors exert heterogeneous effects across the upper distribution of blood pressure. These results align with previous studies among South African children in disadvantaged areas, which report that 18% of children were classified as hypertensive.[5]

Both the FE and RE panel quantile regression approaches indicated that age and BMI were associated with moderately elevated SBP, whereas lifestyle and psychosocial factors—such as exercise frequency, cigarette use, depression, and perceived health status—had greater influence at higher risk levels. The strong association between cigarette use and both SBP and DBP underscores the importance of early behavioral interventions. The similarity between FE and RE estimates suggests minimal bias from unobserved heterogeneity.

Age and BMI were primarily associated with SBP at the 0.75 quantile, with weaker effects at the 0.95 quantile. Age had a statistically significant effect only at the 75th quantile of SBP, suggesting that SBP increases with age primarily among adolescents with moderately elevated blood pressure, consistent with evidence from rural North India.[13] Similarly, BMI showed a positive and significant association with SBP at the 75th percentile, indicating that higher body weight contributes to elevated SBP in the early stages of hypertension, in line with previous studies linking obesity and blood pressure.[5]

Gender emerged as an important determinant of SBP at both the 75th and 95th quantiles, with males exhibiting higher SBP than females at moderately high and very high levels, consistent with previously reported gender differences in blood pressure.[14] Exercise frequency showed a protective effect at the 95th quantile of SBP, as lack of physical activity was associated with higher SBP among individuals with very high blood pressure, consistent with earlier findings.[15] Cigarette use was positively associated with SBP at the 95th quantile and with DBP at both upper quantiles, supporting prior evidence that smoking elevates blood pressure among adolescents.[16]

Depression displayed a robust positive association with both SBP and DBP across all upper quantiles, indicating a strong association between depressive symptoms and elevated blood pressure levels, as reported by Olive *et al.*[17] Perceived health status was significantly associated with SBP only at the 95th percentile, indicating that poorer self-rated health is associated with severely elevated SBP, potentially reflecting underlying health and lifestyle burdens.[18] In contrast, pulse rate and race were not statistically significant predictors of SBP or DBP at the upper quantiles, diverging from some earlier studies that reported associations between pulse rate, race, and elevated blood pressure among children and adolescents.[4,19]

Table 1. Demographic and lifestyle characteristics (Waves 4 and 5)

Risk factor	Category	Wave 4 (2014–2015)	Wave 5 (2017)
Gender	Male	45 (43.7%)	45 (43.7%)
	Female	58 (56.3%)	58 (56.3%)
Race	African	82 (79.6%)	82 (79.6%)
	Coloured	21 (20.4%)	21 (20.4%)
Age	14 years	103 (100%)	0 (0.0%)
	17 years	0 (0.0%)	103 (100%)
Body mass index	Underweight	26 (25.2%)	12 (11.7%)
	Healthy	63 (61.2%)	71 (68.9%)
	Overweight	11 (10.7%)	14 (13.6%)
	Obese	2 (1.9%)	3 (2.9%)
	Very Obese	1 (1.0%)	3 (2.9%)
Exercise frequency	Never/less than once a week	76 (73.8%)	63 (61.2%)
	Once a week	5 (4.9%)	9 (8.7%)
	More than once a week	22 (21.4%)	31 (30.1%)
Depression	Rarely or none of the time (less than 1 day)/some or little of the time (1–2 days)	98 (95.1%)	96 (93.2%)
	Occasionally or a moderate amount of time (3–4 days)	2 (1.9%)	6 (5.8%)
	All of the time (5–7 days)	3 (2.9%)	1 (1.0%)
Cigarette use	No	99 (96.1%)	95 (92.2%)
	Yes	4 (3.9%)	8 (7.8%)
Perceived health status	Very good/excellent	86 (83.5%)	83 (80.6%)
	Good	14 (13.6%)	17 (16.5%)
	Poor/fair	3 (2.9%)	3 (2.9%)
DBP	Normal DBP	87 (84.5%)	88 (85.4%)
	Abnormal DBP	16 (15.5%)	15 (14.6%)
SBP	Normal SBP	86 (83.5%)	81 (78.6%)
	Abnormal SBP	17 (16.5%)	22 (21.4%)

Abbreviation: DBP: Diastolic blood pressure; SBP: Systolic blood pressure.

Table 2. Panel quantile regression estimates for systolic blood pressure risk factors

Risk factor	Fixed-effects model		Random-effects model	
	Q(0.75)	Q(0.95)	Q(0.75)	Q(0.95)
Age	1.38**	0.39	1.38**	0.39
Body mass index	0.93**	0.27	0.93**	0.27
Pulse rate	−0.02	0.04	−0.02	0.04
Gender	−11.68***	−10.23***	−11.68***	−10.23***
Race	2.73	−3.42	2.73	−3.42
Exercise frequency	−0.20	−1.93***	−0.20	−1.93***
Cigarette use	4.89	8.15***	4.89	8.15***
Depression	3.49**	7.36***	3.49**	7.36***
Perceived health status	0.61	4.65**	0.61	4.65**

Note: $^{**}p < 0.01$ and $^{***}p < 0.001$.

Table 3. Panel quantile regression estimates for diastolic blood pressure risk factors

Risk factor	Fixed-effects model		Random-effects model	
	Q(0.75)	Q(0.95)	Q(0.75)	Q(0.95)
Age	−0.20	−1.49	−0.20	−1.49
Body mass index	0.26	0.03	0.26	0.03
Pulse rate	0.004	0.01	0.004	0.01
Gender	0.28	−0.002	0.28	−0.002
Race	1.20	2.42	1.20	2.42
Exercise frequency	0.53	0.75	0.53	0.75
Cigarette use	7.22***	11.69**	7.22***	11.69**
Depression	0.27	3.41**	0.27	3.41**
Perceived health status	1.02	−1.97	1.02	−1.97

Note: ** $p < 0.01$ and *** $p < 0.001$.

Overall, these findings highlight the value of distributional methods in pediatric hypertension research and support targeted interventions addressing modifiable risk factors among high-risk adolescents.

5. Conclusion

Panel quantile regression provides valuable insights into the heterogeneous determinants of childhood hypertension in South Africa. The findings indicate that risk factors influence blood pressure differently across severity levels, highlighting the need for targeted prevention strategies that address lifestyle and psychosocial determinants early in life.

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Conflict of interest

The authors declare that they have no conflicts of interest.

Author contributions

Conceptualization: Anesu Gelfand Kuhudzai
Investigation: Anesu Gelfand Kuhudzai
Methodology: Anesu Gelfand Kuhudzai
Formal analysis: Anesu Gelfand Kuhudzai
Supervision: Kolentino Mpeta
Writing – original draft: Anesu Gelfand Kuhudzai
Writing – review & editing: All authors

Ethics approval and consent to participate

The South African National Income Dynamics Study was conducted with ethical approval from the Ethics Committee of Faculty of Commerce, University of Cape Town (ethical approval no.: REC 20202/04/017). All participants provided informed consent prior to participation.

Consent for publication

Not applicable as this study utilised secondary data obtained from the South African National Income Dynamic Study Wave 4 and Wave 5.

Availability of data

The dataset analyzed during the current study is available from the corresponding author upon reasonable request.

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