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Prenatal and adolescent blood lead levels in South Africa: Child, maternal and household risk factors in the Birth to Twenty cohort

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ABSTRACT

Introduction: The risk factors for lead exposure in developing countries have not been fully described. This study looks at child, maternal and household factors associated with increased risk of lead exposure at birth and at 13 years of age in the Birth to Twenty cohort.

Methods: Mothers were recruited from antenatal clinics in the Johannesburg-Soweto metropolitan area in 1990 ($n=3273$). Lead levels were analysed in cord blood collected at birth ($n=618$) and at 13 years ($n=1546$). Data on selected child, maternal and household factors were collected using a structured questionnaire in the third trimester and at 13 years of age. Statistical analyses were conducted to determine the associated risk factors.

Results: The mean blood lead level at birth was 5.85 μg/dl, and at 13 years of age it was 5.66 μg/dl. The majority of children had blood lead levels above 5 μg/dl (52% at birth and 56% at 13 years). At birth, being a teenage mother and having low educational status were strong predictors for elevated cord blood lead levels. Being a male child, having an elevated cord blood level, and lack of household ownership of a phone were significant risk factors for high blood lead levels at 13 years.

Conclusion: Significant associations found in the study point to the low socio-economic status of lead-affected mothers and children. These poor circumstances frequently persist into later childhood, resulting in continued high lead levels. Thus broader measures of poverty alleviation and provision of better education may help decrease the risk of exposure.

1. Introduction

Lead is a versatile but highly toxic blue-grey metal found naturally in the earth's crust. Human activities such as burning of fossil fuels, the use of lead in paint, petrol, water pipes, smelting, and applications in the manufacturing industry and informal sector (for example repairs to electrical appliances using lead solder, making of jewellery and stained glass and lead recycling in cottage industries) have resulted in increased lead exposure in the environment, including in homes, schools and the workplace (Mathee et al., 2004; Tong et al., 2000). The harmful effects of lead at levels greater than 10 μg/dl, especially in children, are well established (Hernberg, 2000; Needleman, 2004). A blood lead level above 10 μg/dl is widely considered the value at which action should be taken to prevent further exposure to lead (CDC, 1991). However recent studies have shown that levels <10 μg/dl in children can lead to substantial neuro-behavioural problems, such as a reduction in IQ, decreased math and reading levels and problem behaviours (Bellinger, 2004; Canfield et al., 2003; Bernard, 2003). Some studies have also pointed to an association between bone lead levels of greater than 25 ppm and impulsive, aggressive or delinquent behaviour in children (Needleman et al., 2002, 1996). To date there is no evidence of a safe level for lead exposure at which detrimental effects are negligible (Binns et al., 2007; Gilbert and Weiss, 2006; Koller et al., 2004; Bernard, 2003; Canfield et al., 2003).

In 2000, around 40% of all children globally were estimated to have blood lead concentrations greater than 5 μg/dl, and 20% greater than 10 μg/dl. Based on the limited data available, Fewtrell et al. (2004) showed that over 97% of exposed children are estimated to live in low- and middle-income countries. In resource-rich countries, such as the United States of America (USA), the United Kingdom and parts of Europe (for example, Sweden), the level of lead exposure in the general population has

Abbreviations: BLL, blood lead levels; BTT, Birth to Twenty; WHO, World Health Organisation; μg/dl, micrograms per decilitre; ppm, parts per million

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decreased to a current mean level of approximately 3 μg/dl (Koller et al., 2004; Harper et al., 2003), although there are pockets of urban poor children that still have levels greater than 10 μg/dl (Breysse et al., 2004). In poor countries lead exposure remains a problem (Fewtrell et al., 2004; Falk, 2003). South Africa and most other countries in Africa do not have routine lead screening systems. In an epidemiological survey conducted in South Africa, the mean cord lead level in the early 1990s was 15.5 μg/dl in Durban (Chetty et al., 1993). In 1995 Johannesburg school children aged 6–7 years were shown to have a mean blood lead level of 12 μg/dl. By 2002, the mean blood lead level, in a repeat study involving the same schools, had declined to 9.1 μg/dl (Mathee et al., 2004). In South Africa following epidemiological studies showing substantially elevated lead levels in young urban Cape children (Von Schirnding et al., 1991a), lead-free gasoline was introduced in 1996 and eventually in 2006 all leaded gasoline was eliminated. It is, however, still used in certain paint formulations and applications and in the informal and formal industrial sectors. Thus although blood lead levels are decreasing in South Africa due to the discontinuation of leaded gasoline, lead exposure remains a significant local public health problem (Mathee et al., 2006).

Lead exposure and poisoning is preventable, and it is therefore important to determine the most significant predictors of blood lead levels at birth and in later childhood so that appropriate action can continue to be taken. Longitudinal studies examining the potential effects of lead exposure have mainly been conducted in resource rich countries (Canfield et al., 2003; Bellinger and Needleman, 2003). In African countries on the other hand, there is a paucity of research information available on lead exposure at birth and during childhood/adolescence, including with respect to risk factors and health outcomes.

The primary aim of this study was to determine child, maternal and household factors associated with blood lead levels at birth, and at the age of 13 years among urban South African children.

2. Materials and methods

2.1. Study design and sampling

The study used sub-samples from The Birth to Twenty (BTT) cohort at birth (cord blood sub-sample) and at 13 years of age (13 year sub-sample). Birth to Twenty (BTT) is a longitudinal birth cohort study in the metropolitan area of Johannesburg-Soweto, South Africa, which aims to assess the environmental, economic, psychosocial and biological determinants of health, development and well-being amongst the cohort from birth to 20 years of age. The study commenced in 1990.

Participants were included in the BTT cohort if they were born between April and June 1990, and if the mother resided in the Johannesburg-Soweto area for at least 6 months following delivery ($n=3273$). Enrolment into the study began prior to delivery when women were interviewed during their third trimester of pregnancy while attending public antenatal clinics. Attrition from the cohort occurred because the participants moved away from the study area, moved to an unknown address or the mother or child died. The cohort enrolment and attrition is well described in several publications and 72% of the original cohort were being successfully followed up at age 16 (Yach et al., 1990; Richter et al., 2004; Norris et al., 2007; Richter et al., 2007).

Cord blood samples were collected from 862 BTT participants who were enroled for a lead exposure study in the antenatal phase. However, only 618 cases (cord blood sub-sample) fulfilled the enrolment criterion of remaining within the study area for at least six months after delivery: 244 participants moved out of the study area during this period, the mother or child died or the blood sample could not be used for analysis due to clotting (Norris et al., 2007). In 2003, when the children were 13 years of age, 1546 (47%) cohort participants (13 year old sub-sample) had their blood lead levels analysed. The remaining participants ($n=1727$) could not be enroled due to blood sampling errors such as clotting of the blood sample or the participant could not be located during the time period for data collection. Of the 1546 13 year olds, 312 adolescents (13 year with cord blood sub-sample) also had cord blood lead data. Fig. 1 illustrates the sampling scheme of the two lead assessments conducted at birth and at 13 years of age.

2.2. Procedures/data collection

A detailed structured questionnaire was administered to pregnant women by a trained interviewer in their home language to collect data on birth history, maternal factors and household factors such as access to water and electricity, type of dwelling, ownership of assets. At 13 years of age trained interviewers collected data on household factors from caregivers and participants. Cord blood samples were obtained during the fourth stage of delivery and whole venous blood was collected when children were 13 years old. Blood samples were collected in heparinised tubes determined to be free of trace metals. Following preparation, lead concentrations in the whole blood samples were determined using a flameless atomic absorption spectrophotometer equipped with a graphite furnace. Blood lead measurements were performed by the South African Centre for Occupational Health (now called the National Institute for Occupational Health), which participates in an international and national quality control programme for blood lead determinations (Röllin et al., 1988). The coefficient of variation in blood lead samples was 5.8% in 1990. In 1990 the limit of detection of lead in blood was 1 μg/dl and in 2003 the limit of detection equalled 0.1 μg/dl.

2.3. Data analysis

Associations between blood lead levels and independent variables in the two sub-samples were tested in a bivariate analysis using the Student t test, Spearman rho, X^2 and analysis of variance (ANOVA) as appropriate. Multiple regression analyses were used to identify associated risk factors. VIF and tolerance tests in STATA were conducted to identify multicolinearity among the independent. The results show that the mean VIF was less than 10 and the tolerance (1/VIF) was also >0.1 in all three sub-samples. Thus there is no strong evidence of multicolinearity among the independent variables. Independent variables found to have significant relationships with blood lead levels were then used in a logistic regression model. In this model, blood lead levels were dichotomised at 5 μg/dl (≤ 5 μg/dl vs. >5 μg/dl). The level of 5 μg/dl was chosen because it is close to the mean blood lead level in the sample and was also based on the current global discussions around lowering the action level to 5 μg/dl (Gilbert and Weiss, 2006). Blood lead levels were also logarithmically transformed to correct skewed distribution. However analyses using the natural log transformed blood lead levels did not significantly alter the results. Statistical significance was determined at a level of $p<0.05$. All analyses were conducted using STATA 9.

2.4. Ethics

Ethical approval was obtained from the Human Research Ethics Committee of the University of the Witwatersrand in Johannesburg. Confidentiality was maintained by assigning participant identification numbers that were known only to the data management team, and stored separately from the questionnaires. Prior to the commencement of the study, written informed consent was obtained from each participant's parent or guardian, and at 13 years of age, assent for participation was also obtained from the young participants. As part of the informed consent process, it was explained that participation was voluntary and could be withdrawn at any time without any repercussions.

3. Results

3.1. Sample characteristics

The total BTT cohort consisted of 3273 live singleton births. The demographic characteristics of the cord blood sub-sample ($n=618$) did not differ significantly from the rest of cohort ($n=2655$), except for maternal age ($p<0.001$), birth weight ($p=0.003$) and gestational age ($p<0.001$). There was a higher percentage of teenage mothers in the cord blood sub-sample (19.6% compared to 14.8% in the total BTT cohort). The cord blood sub-sample had a lower percentage (6.5%) of babies with low birth weights (<2500 grams), compared to the total BTT cohort, in which 10.7% of babies had low birth weight. There were no babies with a gestational age of less than 28 weeks in the cord blood sub-sample; however approximately 1% of the total BTT cohort had been born at <28 weeks gestation. The 13 year sub-sample ($n=1546$) did not differ significantly from the remaining subjects in the remaining BTT cohort ($n=1727$) with respect to

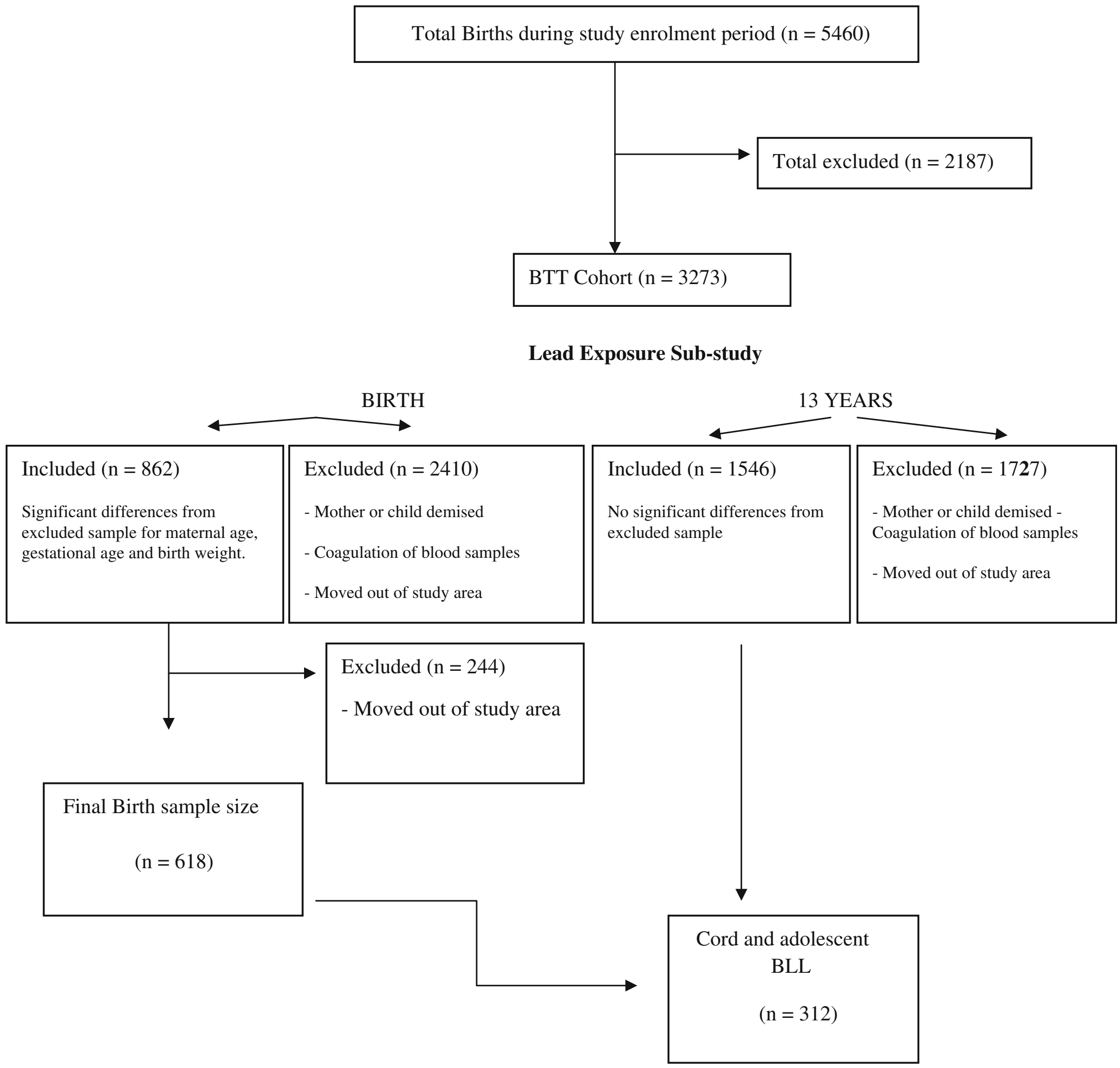

Fig. 1. Sampling scheme.

any of the demographic characteristics. The sub-sample at 13 years with cord blood (13 year with cord blood sub-sample, $n=312$) did not differ significantly from the rest of the 13 year sub-sample.

3.2. Blood lead levels

The mean group blood lead levels at birth (cord blood sub-sample) and at 13 years of age (13 year sub-sample) were 5.9 and 5.7 μg/dl, respectively. The 13 year with cord blood sub-sample had the same mean blood lead level of 5.9 μg/dl at birth and 5.7 μg/dl at 13 years of age. The blood lead distribution ranged from 2 to 17 μg/dl in the cord blood sub-sample, and 1 to 28 μg/dl in the 13-year sub-sample. Even though few newborns (4%) and adolescents (3%) had blood lead levels over the WHO action level of 10 μg/dl, a large number of participants had lead levels above 5 μg/dl (50% in the cord blood sub-sample and 53% in the 13 year sub-sample). As can be seen from Fig. 2, the data were positively skewed.

Tracking the blood lead levels for individual subjects between birth and 13 years ($n=312$) showed that blood lead levels increased in 42.3%, decreased in 56.4% and stayed the same in 1.3% of the children followed up. Longitudinal regression analysis over 13 years showed that the change in blood lead levels over time was not significant ($p=0.1$). However boys at 13 years had significantly higher mean blood lead levels than girls ($p<0.0001$).

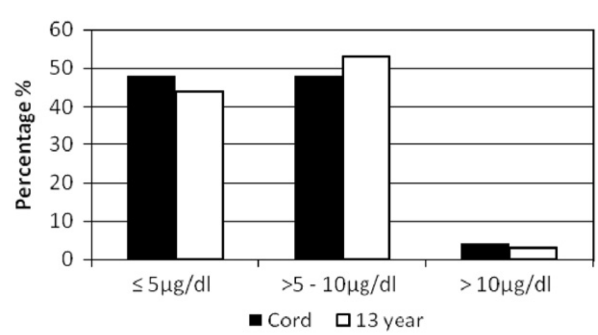

Fig. 2. Blood lead levels at birth and at 13 years of age.

A description of the study sample with the mean blood lead levels in the cord blood sub-sample and in the 13 year sub-sample is given in Table 1. The majority of the population was Black (99.3% at birth and 92.1% at 13 years of age). The mean blood lead levels were highest in the Black population groups at birth, as well as at 13 years of age when compared to the other ethnic groups; however the sample sizes for the other ethnic groups were very

Table 1
Characteristics of the participants in the cohort at birth and at 13 years.

	At birth ($n=618$)	Mean BLL at birth (μg/dl)	P value	13 years ($n=1546$)	Mean BLL at 13 years (μg/dl)	P value
INDIVIDUAL FACTORS						
Gestational age						
≤28 weeks	0			10 (0.6%)	6.68	
≥29 weeks	617 (100%)	5.80		1424 (92%)	5.71	0.29
Sex						
Male	312 (50.5%)	5.89	0.61	713 (46.1%)	6.51	
Female	306 (49.5%)	5.81		751 (48.6%)	4.96	<0.01*
Birth weight						
≤2500 g	40 (6.5%)	6.12		169 (10.9%)	5.87	
≥2500 g	577 (93.4%)	5.83	0.74	1295 (83.8%)	5.69	0.53
Population group						
Asian	1 (0.2%)	–		14 (0.9%)	5.27	
Black	630 (99.3%)	5.89		1424 (92.1%)	5.80	
White	3 (0.5%)	4.67	0.33	26 (1.7%)	4.69	0.12
MATERNAL FACTORS						
Age in years						
Mean	24.8			26.05		
Range	14–43			14–46		
Teenage pregnancy	121(19.6%)	5.96		247 (16.0%)	5.76	
Adult (>19 years)	497 (80.4%)	5.40	0.02*	1215 (83.0%)	5.53	0.79
Education						
None	9 (1.5%)	8.73		12 (0.8%)	6.80	
Primary	87 (14.1%)	6.33		156 (10.1%)	5.76	
Secondary	452 (73.1%)	5.81		1069 (69.1%)	5.69	
Tertiary	55 (8.9%)	5.32	<0.01*	123 (7.9%)	5.68	0.45
Marital status						
Married	177 (28.6%)	5.80		531 (34.3%)	5.51	
Single	439 (71.1%)	5.87	0.72	932 (59.7%)	5.84	0.01*
Parity						
Mean	2			2		
Range	1–8			1–9		
≤3	543 (87.7%)	5.83		1216 (83.1%)	5.70	
>3	75 (12.1%)	5.97	0.01*	248 (16.9%)	5.79	0.29
Type of home						
Formal	520 (84.2%)	5.80		1238 (82.4%)	5.72	
Informal	67 (10.9%)	5.85	0.85	94 (6.1%)	5.91	0.45
Ownership of home						
Owned	126 (20.4%)	5.67		328 (21.2%)	5.65	
Rented	459 (74.3%)	5.82	0.42	998 (64.6%)	5.75	0.49
Access to water						
Indoor access	241 (39%)	5.75		609 (39.4)	5.71	
Access outside house	319 (51.6%)	5.75	0.99	507 (32.8%)	5.64	0.62
Access to electricity						
Yes	545 (88.2%)	5.78		1243 (80.4%)	5.49	
No	51 (8.2%)	6.07	0.31	62 (4.0%)	5.73	0.46
Assets owned						
TV						
Yes	375 (60.7%)	5.76		929 (60.1%)	5.77	
No	180 (29.1%)	5.93	0.33	284 (18.4%)	5.74	0.83
Car						
Yes	119 (19.3%)	5.82		335 (21.7%)	5.85	
No	435 (70.4%)	5.82	0.99	879 (56.9%)	5.44	0.01*
Fridge						
Yes	370 (59.9%)	5.76		891 (57.6%)	5.86	
No	186 (30.1%)	5.95	0.27	322 (20.8%)	5.70	0.32
Washing machine						
Yes	52 (8.4%)	5.77		180 (11.6%)	5.79	
No	503 (81.4%)	5.83	0.81	1034 (66.9%)	5.51	0.18
Phone						
Yes	267 (43.2%)	5.63		663 (42.9%)	5.94	
No	287 (46.4%)	6.02	0.02*	550 (35.6%)	5.59	0.01*

* Indicates significant bivariate associations.

small. Being male was associated with higher mean blood lead levels in the 13 year sub-sample with a mean blood lead level of 6.5 μg/dl, compared to 4.9 μg/dl in females.

In the cord blood sub-sample and the 13 year sub-sample, children of teenage mothers had a higher mean blood lead level compared to mothers of 20 years and older, and lower educational

Table 2
Characteristics of the 13 year cord blood subsample (the longitudinal sample) $n=312$.

	%	Mean BLL (μg/dl) at birth	*P* value	Mean BLL (μg/dl) at 13 years	*P* value
INDIVIDUAL FACTORS					
Gestational age					
≤ 28 weeks	0 (0%)				
≥ 29 weeks	312 (100%)	5.91	–	5.67	–
Sex					
Male	153 (49.0%)	5.89		6.56	
Female	159 (51.0%)	5.94	0.83	4.81	< 0.0001*
Population group					
Asian	1 (0.3%)	9		3.33	
Black	311 (99.7%)	5.90		5.68	–
White	0 (0%)	–		–	
MATERNAL FACTORS					
Age in years					
Mean	24.9				
Range	14–43				
Teenage pregnancy	64 (20.5%)	5.55		5.28	
Adult (> 19 years)	248 (79.5%)	6.01	0.67	5.78	0.13
Education					
None	3 (1%)	6.33		7.50	
Primary	33 (10.6%)	6.03		5.73	
Secondary	237 (76%)	5.91		5.56	
Tertiary	34 (10.9%)	5.14	0.02*	6.19	0.02*
Marital status					
Married	81 (26%)	5.99		5.39	
Single	230 (73.7%)	5.88	0.68	5.77	0.21
Parity					
Mean	2				
Range	1–8				
≤ 3	274 (87.8%)	5.89		5.65	
> 3	38 (12.2%)	6.05	0.65	5.82	0.68
HOUSEHOLD FACTORS					
Type of home					
Formal	281 (90.1%)	5.87		5.72	
Informal	23 (7.4%)	5.78	0.84	5.24	0.36
Ownership of home					
Owned	70 (22.4%)	5.64		5.65	
Rented	233 (74.7%)	5.91	0.31	5.70	0.89
Access to water					
Indoor access	135 (43.3%)	5.87		5.76	
Access outside the house	153 (49.0%)	5.74	0.55	5.67	0.73
Access to electricity					
Yes	292 (93.6%)	5.80		5.71	
No	15 (4.8%)	6.80	0.05	5.01	0.27
Assets owned					
TV					
Yes	215 (68.9%)	5.76		5.72	
No	81 (26%)	6.12	0.15	5.52	0.53
Car					
Yes	68 (21.8%)	5.84		5.19	
No	228 (73.1%)	5.87	0.91	5.81	0.06
Fridge					
Yes	220 (70.5%)	5.75		5.75	
No	77 (24.7%)	6.23	0.06	5.47	0.39
Washing machine					
Yes	30 (9.6%)	6.27		5.38	
No	267 (85.6%)	5.83	0.24	5.71	0.47
Phone					
Yes	159 (51%)	5.66		5.49	
No	137 (43.9%)	6.14	0.03*	5.87	0.19

* Indicates significant results.

attainment was associated with higher blood lead levels. In the 13 year with cord blood sub-sample 25% of the teenage moms had children with cord and 13 year blood lead levels of > 5 μg/dl. However the mean blood lead levels of children in the 13 year with cord blood sub-sample was higher in the adult mothers compared to the children of the teenage mothers. Table 2 illustrates the characteristics of the 13 year with cord blood sub-sample.

3.3. *Factors associated with blood lead levels*

Maternal, child and household factors are illustrated in Tables 1 and 2. The analysis of household factors showed that most participants lived in formal, rented housing, and only a small proportion of households owned relatively high cost items such as washing machines and cars. Access to commodities such as a telephone was also low. The homes of the majority of participants

Table 3
Multiple regression analysis.

	At birth ($n=618$)			At 13 years ($n=1546$)			13 year cord sub-sample		
	β	SE	*P* value	β	SE	*P* value	β	SE	*P* value
Individual factors									
Gestational age	0.04	0.03	0.16	−0.01	0.01	0.24	0.17	0.12	0.16
Sex	−0.03	0.17	0.85	−1.53	0.14	<0.001*	−1.71	0.28	<0.01*
Birth weight	0.00	0.00	0.94	−0.00	0.00	0.31	−0.00	0.00	0.45
Race	−0.03	0.35	0.93	−0.02	0.13	0.89	−0.61	0.59	0.29
Maternal factors									
Parity	−0.11	0.99	0.28	0.10	0.08	0.19	−0.06	0.17	0.70
Age	0.05	0.02	0.01*	−0.01	0.15	0.54	0.02	0.03	0.52
Education	−0.47	0.25	0.05*	−0.22	0.16	0.16	0.02	0.29	0.95
Marital status	0.08	0.21	0.69	0.15	0.18	0.38	0.26	0.37	0.47
Household factors									
Formal housing	0.30	0.33	0.34	−0.33	0.31	0.28	−0.34	0.58	0.56
Lack of home ownership	0.19	0.21	0.37	0.37	0.17	0.03*	0.05	0.34	0.87
Access to indoor running water	0.00	0.18	0.96	−0.14	0.16	0.36	−0.23	0.30	0.44
Access to electricity	0.91	0.36	0.01*	0.03	0.38	0.92	0.75	0.71	0.29
TV ownership	0.01	0.21	0.98	0.19	0.18	0.28	0.53	0.34	0.13
Fridge ownership	0.11	0.21	0.60	0.03	0.19	0.87	0.45	0.36	0.21
Washing machine ownership	0.12	0.31	0.69	−0.14	0.23	0.55	−0.22	0.50	0.66
Car ownership	−0.34	0.22	0.11	−0.31	0.18	0.08	−0.48	0.37	0.21
Phone ownership	0.41	0.19	0.03*	−0.32	0.16	0.05*	−0.54	0.32	0.09
Cord lead							0.16	0.07	0.03*

* $P<0.05$ for association between blood lead and potential risk factor.

Table 4
Logistic regression model examining the predictors of high (>5 μg/dl) cord blood lead levels.

Variable	OR	CI	*P* value
Maternal factors			
Teenage mothers	1.85	1.19–2.88	<0.01*
Low educational level	1.75	1.04–2.97	0.03*

* $P<0.05$ for association between blood lead and potential risk factor.

Table 5
Logistic regression model examining the predictors of high (>5 μg/dl) blood lead levels at 13 years of age.

Variable	OR	CI	*P* value
Individual characteristics			
Male gender	3.01	2.41–3.77	<0.0001*
Cord lead level[a]	1.91	1.10–3.32	0.02*
Socio-economic			
Lack ownership of a phone	1.25	0.99–1.58	0.05*

* $P<0.05$ for association between blood lead and potential risk factor.
[a] Sample size=312 participants with cord lead and adolescent lead levels.

were served with electricity, but only 39% of participants lived in homes with indoor access to water.

With respect to the cord blood sub-sample lead levels, bivariate analyses showed that lower maternal age at birth ($p=0.02$) and lower maternal education were significantly ($p<0.01$) associated with higher cord blood lead levels. Higher parity levels ($p=0.01$) and not owning a phone ($p=0.02$) were also significantly associated with higher cord blood lead levels. In the 13 year sub-sample, male gender of the child ($p<0.001$), the mother being a single parent ($p=0.01$) and lack of ownership of a car ($p=0.01$) or telephone ($p=0.01$) were significantly associated with higher blood lead levels. Bivariate analysis conducted with respect to the 13 year with cord blood sub-sample ($n=312$) showed that the cord blood lead levels and blood lead levels at 13 years were significantly associated with each other ($p=0.02$).

Table 3 illustrates the multiple regression analyses conducted with respect to the cord and 13-year blood lead levels. As can be seen, lower maternal age and low maternal education as well as access to electricity were strong predictors of elevated blood lead levels at birth. In the 13 year sub-sample, the sex of the child, lack of home ownership and lack of telephone ownership were strong predictors for elevated blood lead levels. In the longitudinal analysis of the 13 year with cord blood sub-sample the regression analysis showed that sex of the child and cord lead levels were strong predictors of elevated blood lead levels at 13 years. Log transformation of the blood lead distributions did not alter the observed associations between lead levels and the risk factor variables.

A logistic regression model was created using significant independent variables at birth and at 13 years of age. Table 4 shows that in the cord blood sub-sample, maternal age and maternal education were the most important predictors of cord blood lead levels. At 13 years, gender and cord lead levels, as well as lack of ownership of a telephone were the strongest predictors of blood lead levels (Table 5).

4. Discussion

This is the first study to explore lead exposure among children in South Africa longitudinally. The study findings demonstrated that the majority of newborns, followed up to 13 years of age and reassessed, had blood lead levels below the CDC action level of 10 μg/dl; however, over 50% had levels above 5 μg/dl at both ages. The mean blood lead level in the cord blood sub-sample was 5.9 μg/dl, and in the 13 year sub-sample it was 5.7 μg/dl. The blood lead levels are similar at birth and at 13 years possibly because the level of environmental exposure remained the same. While there are well known problems associated with inter-country and inter-laboratory comparisons, the cord blood lead distribution obtained for this study appeared to be similar to that determined in other urban settings such as the USA in the 1980s and the 1990s (Bellinger et al., 1994; Ernhart et al., 1986). The blood lead levels of young BTT adolescents, however, were much higher than those found in urban settings in developed resource rich countries (Koller et al., 2004). In the USA the mean blood lead level in the 1–5 year age group was 2 μg/dl (Koller et al., 2004). This mean blood level was also found in Sweden (Strömberg et al., 2003). Thus the reason for the higher levels found in South Africa could be due to the continued exposure to environmental lead, amongst others, through the continued use of lead-based paint (Mathee et al., 2007), increased urbanisation, the growing informal sector (cottage industries) using lead and leaded gasoline in South Africa during the period of the study. The use of leaded petrol was only phased out in South Africa in 2006. Studies conducted around the world have shown that blood lead levels have declined following the phase-out of leaded gasoline (Mathee et al., 2006; Thomas et al., 1999). However blood lead distributions in low- and middle-income countries usually still exceed that of the West (Koller et al., 2004; Falk, 2003).

At birth, lower maternal age, specifically having a teenage mother, was significantly associated with higher cord lead levels ($p<0.01$). Teenage mothers were 1.85 times more likely to have babies with higher cord blood lead levels than their counterparts over the age of 20 years. Teenage pregnancies have been associated with higher lead levels amongst mothers in the USA (Lane et al., 2008; Nevin, 2000). In the study conducted by Lane et al. (2008) 74.6% of the sample of teenage mothers had a blood lead level <20 μg/dl. The higher the blood lead level, the greater the risk of teenage pregnancy. It is postulated that lead exposure may decrease "cognitive and judgement capacity", leading in turn to an increased risk of teenage pregnancy (Lane et al., 2008). It has been reported that more than 30% of South African 19 year olds have given birth at least once (Kaufman et al., 2001). However the majority of the BTT sample had blood lead levels <10 μg/dl; thus lead exposure may not contribute significantly to elevated levels of teenage pregnancy in the country.

Lower maternal education levels have been widely associated with an increased risk for lead exposure. For example, the education level of the caregiver was found to be a strong risk factor in a Mexican study of children aged 1–6 years old (Albalak et al., 2003). Lower maternal educational status is an indirect measure of poorer socio-economic status. Another indicator of socio-economic status is asset ownership. In this study the lack of ownership of a telephone was significantly related to higher blood lead levels at 13 years of age ($p=0.05$). Poorer communities have been shown to be at much higher risk for adverse environmental exposures, including lead exposure in South Africa and in other resource poor countries (Von Schirnding et al., 1991b , Wright et al., 2005; Mathee et al., 2002; Rahbar et al., 2002; Tong et al., 2000). Poorer communities usually have lower quality housing, live near busy roads, have jobs in dirtier occupations such as lead mining and vehicle repair workshops, and conduct informal industries in their homes that may use lead products (Von Schirnding et al., 1991b, Tong et al., 2000; Nriagu et al., 1996, 1997).

At 13 years of age, male gender was a very strong risk factor for higher blood lead levels. This has not been found in some previous studies of preschool-aged children (Guttinger et al., 2008; Albalak et al., 2003; Melman et al., 1998). However, in the US National Health and Nutrition Examination Survey III (NHANES), of all children tested from 5 to 18 years of age, male children had higher blood lead levels (Fox and Cole, 2004). The reason for this effect was not postulated in the above NHANES study. This effect may be due to the activities of male children such as greater outdoor activities, thus exposing them to higher levels of environmental lead and also increased participation in cottage industries using lead.

Maternal factors such as maternal age and education level did not play a significant role at 13 years of age. In the current study, cord blood lead levels were significantly related to blood lead levels at 13 years of age. Children with high lead levels at birth were 1.9 times more likely to have higher levels later in life. The results from this study suggest that in this setting, the risk factors for high blood levels at birth probably persist through later childhood and adolescence, with new risk factors emerging during adolescence. Home visits paid to two of the adolescents with the highest blood lead concentrations revealed their use of lead solder to repair electrical appliances, television sets and music equipment for the purpose of income generation.

Even though the study was prospective, one limitation was that it was not designed to look at all risk factors for lead exposure; thus information regarding other potential risk factors, such as paternal history, parental occupational exposure to lead, passive smoking and the physical state of the homes such as peeling paint, was not available for analysis. However peeling paint and very dilapidated homes were not major factors of importance in Soweto at the time of the study. Attrition in the sample due to death or moving away from the area could be related to lead exposure and thus the possibility of participation bias must also be noted. The cord blood sub-sample had some significant demographic differences from the rest of the BTT cohort with a higher percentage of teenage mothers and a lower percentage of preterm and low birth weight babies. This may have resulted in sample bias, and the findings from this period may not be representative of the entire cohort. Improvements in detecting low levels of blood lead over the 13-year period of the study may have resulted in the recording of lower blood lead levels at 13 years, i.e. <2 μg/dl.

5. Conclusion

This study has highlighted several risk factors for elevated lead exposure at birth and at 13 years of age in the Johannesburg-Soweto area that requires attention. At birth, maternal education and age were found to be strong risk factors for high cord blood lead levels, potentially reflecting the effects of maternal risk exposure in childhood and continued exposure during adulthood. At 13 years of age the lack of asset ownership (telephones), having had an elevated cord blood level and male sex were the strongest risk factors for lead exposure. A range of significant associations found in the study point to the low socio-economic status of affected mothers and children. The fact that elevated cord blood levels predict higher lead levels at adolescence among a sub-group of children demonstrates that the poor circumstances in which some children reside persist over time. Thus screening and treatment of children for lead exposure need to be conducted alongside socio-environmental upliftment programmes. This study also highlights the need for interventions, such as educational campaigns and health promotion initiatives, targeted at high risk communities. Most importantly measures to alleviate poverty would impact positively on blood lead levels in these vulnerable children. Further research is necessary to look at the impact of elevated blood lead levels on long-term health, behaviour and life achievements of children in the Birth to Twenty cohort.

Conflict of interest

The authors declare they have no competing financial interests.

Ethical clearance

Ethics approval has been obtained from the University of the Witwatersrand Human Research Ethics Committee: (Medical). The ethics clearance number is **MO80702**.

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References

Albalak, R., Hart McElroy, R., Noonan, G., Buchanan, S., Jones, R.L., Flanders, D., Gotway-Crawford, C., Kim, D., Dignam, T., Daley, W.R., Jarret, J., Eduardo, E., McGeehin, M.A., 2003. Blood lead levels and risk factors for lead poisoning among children in a Mexican smelting community. Archives of Environmental Health 58 (3), 172.
Bellinger, D.C., 2004. Lead. Pediatrics 113 (4), 1016–1022.
Bellinger, D.C., Needleman, H.L., 2003. Intellectual impairment and blood lead levels. New England Journal of Medicine 349, 500–502.
Bellinger, D., Leviton, A., Allred, E., Rabinowitz, M., 1994. Pre- and postnatal lead exposure and behaviour problems in school-aged children. Environmental Research 66, 12–30.
Bernard, S.M., 2003. Should the Centers for Disease Control and Prevention's childhood lead poisoning intervention level be lowered? American Journal of Public Health 93, 1253–1260
Binns, H.J., Campbell, C., Brown, M.J., Advisory Committee on Childhood Lead Poisoning Prevention, 2007. Interpreting and managing blood lead levels of less than 10 μg/dl in children and reducing childhood exposure to lead: recommendations of the Centers for Disease Control and Prevention Advisory Committee on Childhood Lead Poisoning Prevention. Pediatrics 120, e1285–e1298.
Breysse, P., Farr, N., Galke, W., Lanpear, B., Morley, R., Bergofsky, L., 2004. The relationship between housing and health: children at risk. Environmental Health Perspectives 112, 1583–1588.
Canfield, R.C., Henderson, C.R., Cory-Slechta, D.A., Cox, C., Jusko, T.A., Lanphear, B.P., 2003. Intellectual impairment in children with blood lead concentrations below 10 μg/dl. New England Journal of Medicine 348, 1517–1526.
Centers for Disease Control (CDC), 1991. Preventing Lead Poisoning in Young Children: A Statement by the Centers for Disease Control. US Department of Health and Human Services, Atlanta, GA.
Chetty, N., Jinabhai, C.C., Green-Thompson, R.W., 1993. Lead levels in maternal and umbilical cord blood at King Edward Hospital, Durban. South African Medical Journal 83, 227 Letter.
Ernhart, C.B., Wolf, A.W., Kennard, M.J., Erhard, P., Filipovich, H.F., Sokol, R.J., 1986. Intrauterine exposure to low levels of lead: the status of the neonate. Archives of Environmental Health 41 (5), 287–291.
Falk, H., 2003. International environmental for the pediatrician: case study of lead poisoning. Pediatrics 112, 259–264.
Fewtrell, L.J., Prüss-Üstün, A., Landrigan, P., Ayuso-Meteos, J.L., 2004. Estimating the global burden of disease of mild mental retardation and cardiovascular diseases from environmental lead exposure. Environmental Research 94, 120–133.
Fox, M.K., Cole, N., 2004. Health status, conditions, and risks. Nutrition and health characteristics of low-income populations: Volume III, School age children. pp. 45–55 (Chapter 6) 〈www.ers.usda.gov/publications/efan04014-3/efan04014-3f.pdf〉 [Accessed January 2009].
Gilbert, S.G., Weiss, B., 2006. A rationale for lowering the blood lead action level from 10 to 2 μg/dl. NeuroToxicology 27 (5), 693–701.
Guttinger, R., Pascoe, E., Rossi, E., Kotecha, R., Willis, F., 2008. The Fremantle lead study part 2. Journal of Paediatrics and Child Health 44, 722–726.
Harper, C.C., Mathee, A., von Schirnding, Y., De Rosa, C.T., Falk, H., 2003. The health impact of environmental pollutants: a special focus on lead exposure in South Africa. International Journal of Hygiene and Environmental Health 206, 315–322.
Hernberg, S., 2000. Lead poisoning in a historical perspective. American Journal of Industrial Medicine 38, 244–254.
Kaufman, C.E., de Wet, T., Stadler, J., 2001. Adolescent pregnancy and parenthood in South Africa. Studies in Family Planning 32 (2), 147–160.
Koller, K., Brown, T., Spurgeon, A., Levy, L., 2004. Recent developments in low level lead exposure and intellectual impairment in children. Environmental Health Perspectives 112 (9), 987–994.
Lane, S.D., Webster, N.J., Levandowski, B.A., Rubinstein, R.A., Keefe, R.H., Wojtowycz, M.A., Cibula, D.A., Kingson, J.E.F., Aubry, R.H., 2008. Environmental Injustice: childhood lead poisoning, teen pregnancy, and tobacco. Journal of Adolescent Health 42, 43–49.
Mathee, A., Röllin, H., Levin, J., Naik, I., 2007. Lead in paint: three decades later and still a hazard for African children. Environmental Health Perspectives 115 (3), 321–322.
Mathee, A., Röllin, H., von Schirnding, Y., Levin, J., Naik, I., 2006. Reductions in blood lead levels among school children following the introduction of unleaded petrol in South Africa. Environmental Research 100, 319–322.
Mathee, A., von Schirnding, Y., Montgomery, M., Röllin, H., 2004. Lead poisoning in South African children: the hazard is at home. Reviews on Environmental Health 19 (3–4), 347–359.
Mathee, A., von Schirnding, Y., Levin, J., Ismail, A., Huntley, R., Cantrell, A., 2002. A survey of blood lead levels among young Johannesburg school children. Environmental Research 90, 181–184.
Melman, S.T., Nimeh, J.W., Anbar, R.D., 1998. Prevalence of elevated blood lead levels in an inner-city pediatric clinic population. Environmental Health Perspectives 106, 655–657.
Needleman, H., 2004. Lead poisoning. Annual Review of Medicine 55, 209–222.
Needleman, H.L., McFarland, C., Ness, R.B., Fienberg, S.E., Tobin, M.J., 2002. Bone lead levels in adjudicated delinquents. A case control study. Neurotoxicology and Teratology 24, 711–717.
Needleman, H., Reiss, A.J., Tobin, M.J., Biesecker, G.E., Greenhouse, J.B., 1996. Bone lead levels and delinquent behaviour. Journal of the American Medical Association 275 (5), 363–369.
Nevin, R., 2000. How lead exposure relates to temporal changes in IQ, violent crime, and unwed pregnancy. Environmental Research 83, 1–22.
Norris, S.A., Richter, L.M., Fleetwood, S.A., 2007. Field report. Panel studies in developing countries: case analysis of sample attrition over the past 16 years within the Birth to Twenty cohort in Johannesburg, South Africa. Journal of International Development 19, 1143–1150.
Nriagu, J.O., Blackson, M.L., Ocran, K., 1996. Childhood lead poisoning in Africa: a growing public health problem. The Science of the Total Environment 181 (2), 93–100.
Nriagu, J., Jinabhai, C.C., Naidoo, R., Coutsoudis, A., 1997. Lead poisoning of children in Africa, 11. Kwazulu/Natal, South Africa. The Science of the Total Environment 197 (1–3), 1–11.
Rahbar, M.H., White, F., Agboatwalla, M., Hozhabri, S., Luby, S., 2002. Factors associated with elevated blood lead concentrations in children in Karachi, Pakistan. Bulletin of the World Health Organization 80 (10), 769–775.
Richter, L., Norris, S., Pettifor, J., Yach, D., Cameron, N., 2007. Cohort Profile: Mandela's children: the 1990 Birth to Twenty study in South Africa. International Journal of Epidemiology. 36, 504–511.
Richter, L.M., Norris, S.A., De Wet, T., 2004. Transition from birth to ten to birth to twenty: the South African Cohort reaches 13 years of age. Paediatric and Perinatal Epidemiology 18, 290–301.
Röllin, H.B., Kilroe-Smith, T.A., Theodorou, P., 1988. Quality control for analysing lead in blood: evaluation and comparison of participating laboratories. South African Journal of Science 84, 233–234.
Strömberg, U., Lundh, T., Schütz, A., Skerfving, S., 2003. Yearly measurements of blood lead in Swedish children since 1978: an update focusing on petrol lead free period 1995–2001. Occupational and Environmental Medicine 60, 370–372.
Thomas, V.M., Socolow, R.H., Fanelli, J.J., Spiro, T.G., 1999. Effects of reducing lead in gasoline: an analysis of the international experience. Environmental Science and Technology 33 (22), 3942–3948.
Tong, S., von Schirnding, Y.E., Prapamontol, T., 2000. Environmental lead exposures: a public health problem of global dimensions. Bulletin of the World Health Organization 78 (9), 1068–1077.
Von Schirnding, Y.E.R., Fuggle, R.F., Bradshaw, D., Stokol, M., 1991a. Blood lead levels in South African inner-city children. Environmental Health Perspective 94, 125–130.
Von Schirnding, Y.E.R., Fuggle, R.F., Bradshaw, D., 1991b. Factors associated with elevated blood lead levels in inner city children. South African Medical Journal. 79, 454–456.
Wright, N.J., Thacher, T.D., Pfitzner, M.A., Pettifor, J.M., 2005. Causes of lead toxicity in a Nigerian City. Archives of Disease in Childhood 90, 262–266.
Yach, D., Padayachee, N., Cameron, N., Wagstaff, L., Richter, L., 1990. Birth to Ten—a study of children of the 1990s living in the Johannesburg-Soweto area. South African Medical Journal 77, 325–326.