Longitudinal and contemporaneous manganese exposure in apartheid-era South Africa: Implications for the past and future

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Abstract:

Manganese is a potent environmental toxin, with significant effects on human health. Manganese exposure is of particular concern in South Africa where in the last decade, lead in gasoline has been replaced with Methylcyclopentadienyl manganese tricarbonyl (MMT). We investigated recent historical levels of manganese exposure in urban Gauteng, South Africa prior to the introduction of MMT in order to generate heretofore nonexistent longitudinal public health data on manganese exposure in urban South Africans. Cortical bone manganese concentration was measured by Inductively Coupled Plasma Mass Spectrometer in 211 deceased adults with skeletal material from a fully identified archived tissue collection at the University of Pretoria, South Africa. All tissues came from individuals who lived and died in urban Gauteng (Transvaal), between 1958-1999. Median Mn concentration within the sampled tissues was 0.3 $\mu g \bullet g^{-1}$, which is within reported range for bone manganese concentration in non-occupationally exposed populations and significantly below that reported in individuals environmentally exposed to MMT . No significant differences were seen in bone Mn between men and women or in individuals of different ethnicity, which further suggests environmental, as opposed to occupational exposure. There were no significant temporal or geographic differences in bone Mn. The results suggest that Mn exposure was low and uniformly distributed across the whole population prior to the introduction of MMT as a gasoline additive. In addition, should manganese exposure follow the same patterns as vehicle-emitted lead, a clear pattern of exposure will emerge with individuals in the urban core facing the greatest manganese exposure.

Keywords: Manganese, human exposure, South Africa, bone concentration

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Abbreviations
MMT Methylcyclopentadienyl manganese tricarbonyl
ICP-MS Inductively Coupled Plasma Mass Spectrometry
PIXE Particle Induced X-Ray Emission
PM Particulate Matter

1. Introduction

Manganese is both an essential trace element and a potent toxin in humans. Exposure to toxic levels of manganese generally occurs in industrial regions as a result of smelting and mining activities. In many parts of the world human exposure to manganese is the result of inhalation of Methylcyclopentadienyl manganese tricarbonyl (MMT), a compound added to gasoline as an anti-knocking agent and released into the air in vehicle exhaust (Walsh, 2007). Manganese affects human health at the acute level (manganism), and the chronic, sub-clinical level (He and Niu, 2004). Acute exposure is generally characterised by severe neurological disturbance and with Parkinson's like pathology (tremors, loss of coordination, motor skill deficits) whereas chronic exposure can result in milder motor skills deficits and mood disturbances (Bouchard et al., 2007; Bouchard et al., 2011; Bowler et al., 1999; Mergler et al., 1999; Roels et al., 2012). Manganese affects neurological development and the central nervous system by interfering with the function of the neurotransmitter dopamine (Aschner and Aschner, 1991; Butterworth et al., 1995; Normandin and Hazell, 2002; Verity, 1999). Manganese accumulates in the central nervous system resulting in increasing damage with long-term exposure (Rivera-Mancia et al., 2011). Both inhaled and ingested manganese have a substantial effect on intellectual function in children, though the level at which manganese exposure becomes dangerous to children's neurological development is under debate (Riojas-Rodríguez et al., 2010; Sharma, 2006). Recent research suggests that manganese levels commonly found in tap water, approximately 34µg/L, are enough to cause a reduction in IQ (Bouchard et al., 2011). Manganese is also known to affect sight and can cause night blindness in exposed children (Afridi et al., 2011). Manganese is associated with neurological and liver pathologies in adults (Butterworth et al., 1995; Laohaudomchok et al., 2011)

The purpose of this research is twofold. Firstly to investigate historical exposure to manganese from a bioarchaeological and anthropological framework and secondly to establish baseline exposure data that may inform future investigations into manganese exposure in urban South Africans. In the first instance, the relative lack of environmental data for the late 20th century encourages a bioarchaeological approach to gathering such data. Human skeletal tissue serves as an excellent repository of many metals and is a useful matrix for investigating environmental exposures in historical populations and to identify historical health issues. The primary aim is to determine whether manganese exposure during this time period followed the same exposure patterns as other toxic elements, such as lead, which vary significantly according to apartheid-designated racial groups. Secondly, from a public health perspective, this research addresses the lack of data regarding manganese exposure in an urban South African population prior to the introduction of MMT and to compare bone manganese concentration in this population with individuals in other industrialized regions both with and without MMT exposure. In addition, the exposure pattern identified here

provides valuable information regarding manganese exposure which can be used to predict future exposure patterns within the urban population of Gauteng, South Africa.

1.1 Manganese biomonitoring and toxicokinetics

Manganese is generally biomonitored in blood, however hair, nail and bone manganese are indicators of chronic exposure (Smith et al., 2007; Sriram et al., 2012; Zheng et al., 2011). The relationship between blood and urine manganese and airborne manganese is unclear, however blood manganese concentrations in individuals working in areas with high levels of airborne manganese do tend to be significantly higher than those in low-airborne manganese areas (Lucchini et al., 1999). Though the relationship between blood manganese and bone manganese is unknown and it is difficult to make direct comparisons between bone and blood measurements in humans, which limits comparison between studies. Nonetheless, bone manganese studies such as that presented in this paper have clear value in establishing relative environmental exposure to manganese in a given population which may then be used to measure change across time and across a given population. Manganese is a bone-seeking element, with approximately 40 percent of manganese stored in bone, making bone useful as a matrix for studying past exposure (Arnold et al., 2002). To date, studies of bone manganese concentrations are few in number, but the use of bone tissue as an alternative biomonitor of manganese exposure is gaining acceptance (Arnold et al., 2002; Aslam et al., 2008; Pejović-Milić et al., 2009; Zheng et al., 2011). In bone tissue manganese is thought to follow the same kinetic pathway as iron, and whilst it is often included in trace element studies of bone tissue, little is written about manganese-bone interaction and how bone manganese concentration can be interpreted. Moreover, manganese is essential in bone remodelling, with lower bone remodelling rates evident in manganese-deficient animals, and lower serum manganese concentrations evident in osteoporotic, postmenopausal humans (Odabasi et al., 2008; Strause and Saltman, 1987; Strause et al., 1987). Manganese regulates the formation of the osteoid matrix and the process is dependent on glycosyltranspherase, a manganese-dependent enzyme (Gonzalez-Perez et al., 2012).

1.2 Manganese in South African environment

Since the 1990s, MMT has been added to petrol as an anti-knock and octane enhancer as a replacement for tetraethyl lead (Batterman et al., 2011; Forbes et al., 2009; Röllin et al., 2005). South Africa began replacement of lead in gasoline with MMT in 2005 and it is unclear as to the effect of this action on manganese exposure in the South African population. Prior to this, there was no monitoring of manganese exposure in humans in urban South Africa, and there were no published studies of manganese exposure in the population prior to 2006 with one exception, Myers et al. (2003) study of manganese biomarkers in a highly exposed ferroalloy smelters.

The use of MMT as a gasoline additive has been controversial, despite its widespread use. Much like its predecessor lead, MMT is emitted into the atmosphere as particulate matter where it is readily bioavailable to humans (Aschner and Aschner, 1991; Levy and Nassetta, 2003; Lucchini et al., 2009; Spangler, 2012). There is sufficient evidence that inhaled manganese is particularly damaging to human health. Clinical manganese neurotoxicity is evident at airborne manganese concentrations greater than 1.0 mg/m^3, indicating that inhaled manganese affects the body differently than ingested manganese, though the mechanism is still unclear (Santamaria and Sulsky, 2010). It is clear, however, that inhaled manganese adversely affects neurological, pulmonary and reproductive function in exposed adults and children (Boyes, 2010).

Though the data on environmental manganese concentrations in South Africa prior to the mid-1990s is almost non-existent, Formenti et al. (1998) conducted PIXE analysis on urban aerosols in Soweto from 1982-1984. They conclude that atmospheric manganese in Soweto was likely due to manganese smelting activities near Johannesburg. The authors also note that the presence of manganese in the atmosphere was intermittent and dependent on southerly wind, which would not have been often. With regards to the substantial mining activities in the region, aerosol monitoring of a Transvaal goldmine conducted in the late 1980s found negligible manganese concentrations in dust resulting from any mining activities (Annegarn et al., 1987). Prior to the use of MMT then, the most likely source of manganese in urban Gauteng would have been smelting as it used extensively in the production of steel, and ferromanganese alloys. Gauteng has been characterized by substantial ferromanganese processing activities, predominantly iron and manganese smelting and steel and alloy fabrication (DME, 2005; Moja et al., 2013). Lastly, South Africa is home to vast reserves of coal and relies heavily on coal-fired power (CITE). Recent analysis of the trace element constituents of fly ash, soil and plants near coal-fired power plants indicates levels of Mn in soil and plants that exceed the World Health Organisation and the Food and Agricultural Organisation's recommendations regarding maximum manganese concentrations (Ayanda et al., 2012; Okedeyi et al., 2014).

1.3 Social and physical geography of the Johannesburg/Pretoria Megacity

The social geography of the South African landscape during apartheid was unique. The Group Areas Act of 1950 brought about strict rules regarding racial segregation within the urban environment. Under the Group Areas Act, black individuals who lived in urban areas were forced into suburban townships. The Group Areas Act ensured no mixing of races in neighbourhoods and complete separation of races in regards to residence, shopping, markets, services, and public amenities such as parks. Black individuals in both Pretoria and Johannesburg were expected to live in townships outside of the city, hostels, if they were men migrating in from a rural homeland. Many black South Africans also lived in informal squatter camps that appeared around the cities towards the end of apartheid, as

more individuals migrated from rural areas in search of work (Christopher, 2005; Richards et al., 2007). It has been estimated that by the 1980s nearly 1.5 million intra-urban commuters moved between townships and urban centres daily (Khosa, 1998). In Pretoria, an estimated 400,000 labourers travelled into the city core each day, with an average commuting distance of 52km (Khosa, 1998). The result was a substantial degree of traffic congestion and accompanying pollution in and around the urban core in these cities (Beavon, 2001). The movement of black South Africans to the urban periphery served to locate them closer to industrial and mining activities (Hattingh and Horn, 1991).

The physical geography of urban Gauteng (formerly Transvaal) is marked by the proximity of the two cities, often referred to as a "megacity" (defined as having > 10 million residents) and is the largest urban area in Africa (Fig. 1) (Lourens et al., 2012). The megacity is located within close proximity to the industrial regions of the Highveld to the Northeast of Pretoria and the Vaal Triangle to the South of Johannesburg, both regions of intense metal and coal mining and industry (McCarthy, 2011; Rogerson, 1990; Terblanche et al., 1992).

Given urban residential patterns and heavy industry as the most likely source of environmental manganese we expected to see higher rates of manganese among black South Africans than among white South Africans. An investigation of bone lead concentration was conducted on the same collection (Hess et al. 2013) and significant differences in bone lead were apparent among individuals of different ancestry. Similarly, analysis of cadmium and arsenic also differ according to ancestry within the same sample population (Hess 2013). The variation in exposure to these elements is ascribed to Apartheid policies, which segregated the South African population along strict racial lines. Thus despite residing in the same cities, and in some cases in relatively close proximity within the urban landscape, individuals classed as either black or white according to the 1950 Population Registration Act experienced very different rates of exposure to inorganic pollutants.

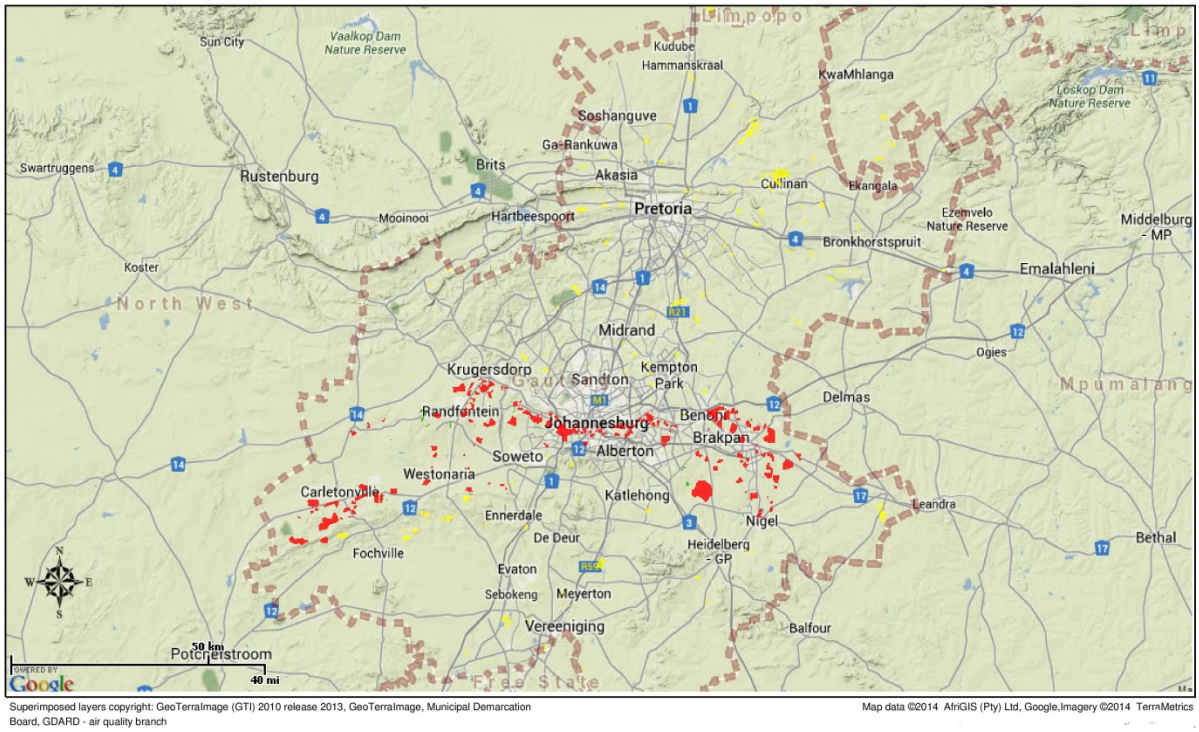

Figure 1. Pretoria and Johannesburg showing major transport routes, known mine residue areas (red) and potential mine residue areas (yellow). Source: Gauteng City Region Observatory.

2. Materials and Methods

Cortical bone samples were taken from the skeletal remains of 211 adult men and women from the Student Bone Collection at the University of Pretoria Department of Anatomy, a sub-collection within the Pretoria Identified Bone Collection on which destructive analysis is permitted. A small number of remains were sampled from the Raymond Dart Bone Collection held at the University of Witwatersrand. Both collections are fully identified, with individual age, ancestry, sex and cause of death accurately recorded. The demographic composition of the Pretoria Student Bone Collection is the same as for the Identified Bone Collection (L'Abbe et al., 2005). Remains in this collection were never subject to burial and as such there are no post-mortem diagenetic complications which may compromise the analytical results. The skeletal remains are those of individuals who died in the Pretoria area between 1943 and 2012 and whose bodies were either unclaimed by relatives or donated. In the former case, unclaimed bodies become the property of the University of Pretoria to be used for teaching and research, subject to the South Africa Human Tissues Act of 1983 (L'Abbe et al., 2005). The collection consists of individuals who range in age from neonates to 95 years of age. The terms "black" and "white" are used here in reference to socioeconomic and cultural group affinity, and follow the racial classification of skeletal remains in the collection (L'Abbe et al., 2005). The predominant demographic within the collection is black males. This is largely to do with both overall demographic patterns within South Africa (Byerlee, 1974; L'Abbe et al., 2005; Smit, 2001). The

Raymond Dart Collection is housed at the University of Witwatersrand, School of Medicine and is similar in demographic composition to the Pretoria Collection. Skeletal remains in the Dart collection date from 1928 (Dayal et al., 2009). Only 12 of the femora included in this study are from the Dart collection. The demographic profile of the sampled skeletal remains are given in Tables 1 and 2.

Table 1. Number of males and females, black and white South Africans and percentage of each in sampled remains.

	N	% of Sample
Males	165	76
Females	49	23
Black	179	82.5
White	35	16.1

Table 2. Demographic breakdown of sampled remains. Includes age and residence by ancestry and sex.

	Mean Age	Median Age	SD	Min. Age	Max. Age
All	53.01	55	16.06	20	95
White Males	66	67	13.1	42	95
Black Females	48.2	46	14.67	25	80
Black Males	51.2	50.5	15.28	20	80

	Pretoria (*n*)	Johannesburg (*n*)	Rural (*n*)	Unk. (*n*)	Total (*n*)
All	153	40	6	18	211
White Males	16	6	2	11	35
Black Females	38	8	1	2	49
Black Males	98	26	3	3	127

It was not possible to include white females in this study due to their scarcity within the fraction of the collections available for destructive analysis. With this exception however, the demography of the subsample is representative of the overall demographic makeup of the collection, with regards to age, sex and ancestry. Black females comprise 23% of the sampled remains and make up 16% of the total collection. The mean age for black females in the collection is 47.4, and is 48.2 in the sampled remains. White males comprise 16% of both the total collection and the sampled remains. The mean age of white males in the whole collection is 66.5 and mean age in the sampled remains is 66. Black males comprise 60% of the complete collection and comprise 60% of the sampled remains. In terms of age, the mean age of black males in the complete collection is 53.9, and is 51.2 in the sampled remains (Table 1).

Demographic information such as age, sex and ancestry were taken directly from cadaver records associated with each individual. Individual ancestry was presented in racial groups and individuals were classified as either black or white. These records are based on information provided by the admitting hospital at the time of death and based on the Population Registration Act, which classified South African individuals by race (Christopher, 1990). Hospital in Table 1 refers to the city in which the admitting hospital is located and is used as a proxy for residential history.

Analytical methods follow the procedure described previously by Hess at al. (Hess et al., 2013). Cortical bone samples (description) of approximately 0.250g were removed from the popliteal surface of the femur or the distal end of the fibula, radius or ulna with a 10mm diamond-tipped core drill attached to a drill press, cleaned and subject to nitric acid digestion. In order to compare different long bones effectively, six long bones were taken from each of 15 individuals and bone element concentrations measured. No significant differences in intra-individual in bone Mn concentration were found (Hess, 2013). Analysis was conducted at the University of Southampton Geochemistry Class 100 Clean laboratory at the National Oceanography Centre Southampton. Samples were analyzed by ICP-MS (Thermo Scientific XSeries 2). Certified reference material, NIST SRM 1486 Bone Meal was used for method validation. Ten 0.1g samples of reference bone meal were analyzed alongside analytical samples. Mean Mn recovery was within acceptable range. Repeatability and precision for reference material was calculated as % relative standard deviation and was between 1 and 3%.

Bone Mn is not normally distributed and in all cases, non-parametric statistical tests are used. In the case of multiple comparisons, Bonferron's Correction is applied (α/n).

This research was approved by the Bournemouth University Ethical Review Committee and the University of Pretoria, Department of Anatomy. In addition, the project met all requirements set by the UK Human Tissues Act (1994) governing the use of human tissues for research and bone samples were imported into the UK and analyzed in accordance with the Act.

3. Results

Descriptive statistics for bone Mn concentration in the sampled remains are given in Tables 3and 4. Bone Mn concentration is not normally distributed. There is no significant difference in bone manganese between any of the demographic groups among these remains . Black females, white males and black males have median bone manganese concentrations of 0.31 (SD=0.31), 0.25 (SD=0.07) and 0.32 (SD=0.56) $\mu g \cdot g^{-1}$ respectively. There is no significant difference in bone Mn concentration between black and white individuals (Mann Whitney $U = 3263$, $p > 0.05$). Among males only, there is no difference in bone Mn between black and white males ($U = 2156$, $p > 0.05$). Between black males and females, there is also no difference in bone Mn ($U = 3114.5$, $p > 0.05$).

Between black females and white males, there is no significant difference in bone Mn ($U = 1317$, $p > 0.05$). Table 3. Descriptive statistics for bone Mn concentration in $\mu g \cdot g^{-1}$ within the sampled remains.

Group		N	Median Mn	SD	Minimum	Maximum
Black Males		129	.32	0.558	0.05	4.38
White Males	Mn $\mu g \cdot g^{-1}$	35	.25	0.068	0.09	1.68
Black Females		44	.31	0.308	0.11	1.49

Figure 2. Bone Mn concentration ($\mu g \cdot g^{-1}$) by decade of death in white males, black males and black females.

Table 3. Bone Mn concentration in $\mu g \cdot g^{-1}$ and decade of death by ancestry and sex.

Decade	1960-1969			1970-1979			1980-1989			1990-1999		
	N	**Median *(SD)***	**Range**	**N**	**Median *(SD)***	**Range**	**N**	**Median *(SD)***	**Range**	**N**	**Median *(SD)***	**Range**
Black males	41	0.25 *(0.24)*	0.11-1.0	48	0.31 *(0.32)*	0.05-1.55	36	0.38 *(0.67)*	0.13-3.05	3	0.42 *(0.38)*	0.34-1.04
White males	2	0.24 *(0.10)*	0.17-0.307	14	0.25 *(0.29)*	0.12-1.02	12	0.24 *(0.26)*	0.09-0.97	8	0.45 *(0.64)*	0.15-1.68
Black Females	23	0.29 (0.15)	0.13-0.64	20	0.42 (0.38)	0.17-1.49	5	0.16 (0.17)	0.11-0.53	1	1.24	

There is significant difference in median bone Mn across time in all individuals ($H(3) = 9.50$, $p < 0.05$). Initial analysis reveals that individuals who died between 1990 and 1999 had significantly higher bone Mn concentrations than individuals who died in who died between 1960 and 1969 (Fig 2). Subsequent pairwise comparisons with Bonferroni's Correction (.05/4) confirm that individuals living in the 1990s had significantly higher bone Mn concentrations than in the 1960s, however no other decades differed. When individual demographic groups are separated however, this trend is not significant. In black females, bone Mn appears to be greatest in individuals who died between 1970 to 1979, however a Mann Whitney test with Bonferroni Correction (.05/4) indicates none of the decades differs significantly in terms of bone Mn in black females. The overall trend towards higher bone Mn in the 1990s could be due to the small sample size relative to other decades. The presence of a single female with high bone Mn was not found to affect significance. Outliers in each demographic group do not affect results.

No significant differences were seen between individuals admitted to Pretoria, Johannesburg or rural hospitals. Nor were there any significant differences in bone Mn concentration by age at death.

Bone Mn was compared to other bone element concentrations. No correlation was found between bone Mn and bone Pb, nor with As, Ni, Zn, or Mg. Bone Mn was significantly correlated with V (Spearman's $r = 0.632$, $p < .0001$) as well as with Cd (Spearman's $r = 0.589$, $p < .0001$) and Cu (Spearman's $r = 0.553$, $p < .0001$). Bone Mn was also correlated with bone Fe (Spearman's $r = 0.613$, $p < .0001$) but only in white South African males.

DiscussionThe lack of significant difference in mean bone manganese, as well as the low concentration relative to other countries suggests a common environmental source of manganese exposure affecting all individuals. In these remains, in which all individuals lived and died prior to the use of MMT, bone manganese concentration does not differ significantly across the population nor does it differ across time or place. Moreover, bone manganese concentration in the sampled remains is comparable to manganese concentrations measured in non-occupationally exposed populations in Spain, New Zealand or Korea which range from .006 to 0.36$\mu g \cdot g^{-1}$ (Benes et al., 2000; Casey et al., 1982; Llobet et al., 1998; Yoo et al., 2002). Pejović-Milić et al. (2009) have examined bone manganese as an indicator of occupational exposure in Canada. In that study bone manganese in occupationally exposed individuals ranged from 3.8 to 9.1$\mu g \cdot g^{-1}$ and in non-exposed individuals the range was 0.2 to 3.0$\mu g \cdot g^{-1}$. Only one individual in the sampled remains has a bone manganese concentration above 4$\mu g \cdot g^{-1}$, a black male. Outside of that individual, no other group has any one individual with a bone manganese concentration above 2$\mu g \cdot g^{-1}$. The median bone manganese concentration of approximately 0.3 $\mu g \cdot g^{-1}$ lies just at the higher end of the values for these countries and could be considered low to moderate exposure, given that it is above what is expected for non-occupationally exposed individuals and far below what is expected for occupationally exposed individuals. Moreover, the distribution is skewed left, and the median is substantially lower than the mean at 0.302$\mu g \cdot g^{-1}$, below bone manganese concentrations reported for Russia or New Zealand (Casey et al., 1982; Pejović-Milić et al., 2009; Zaichick et al., 2009). Notably, Canada, New Zealand and Russia all permit the use of MMT in gasoline, though Canada largely discontinued the practice in 2006 (Joly et al., 2011; Zayed, 2001).

These results are commensurate with the environmental data, which indicates that during the period from 1960 to 1998, manganese, although present in the atmosphere, was low relative to values measured elsewhere, particularly in light of the ferromanganese and alloy activities in the region (Steenkamp and Basson, 2013). The lack of significant difference in mean bone manganese, suggests a common environmental source of manganese exposure across the population. This is further supported by the relative stability of manganese across time and space in the sampled remains.. It remains unclear however, why bone manganese in white males who died between 1990-1999 varies substantially compared to other decades. Within the limited environmental monitoring data, there does not appear to be a trend towards increasing manganese in the urban environment, and the period precedes the introduction of MMT in the petrol supply. It could be that this variability is simply a

result of the small sample size for individuals who died during this decade. However four of the eight white males who died in the 1990s have bone manganese concentrations above 1.1 $\mu g \cdot g^{-1}$ whilst the remaining four had bone manganese concentrations below 0.5 $\mu g \cdot g^{-1}$ which suggests a clear trend. Without knowing the occupational history of these individuals it is difficult to speculate as to why this dichotomy occurs in individuals who died during this decade. No other significant trends were apparent in this sub-group with regards to bone manganese and city of residence or age at death. We surmise that the most likely explanation for this trend is sampling bias, a limitation of bioarchaeological investigations and the use of skeletal collections in epidemiological studies.

Overall, we found no significant differences in bone Mn by age or sex. The relationship between bone Mn, age and sex differs in the literature. Zaichicket al. (2011) did report decreasing bone Mn with age and higher bone Mn in women. Recent measurements of bone Mn in the femoral head of hip-replacement patients in Poland found no significant variation in bone Mn by age or sex (Budis et al., 2014). Both Zaichick et al. (2011) and Budis et al. (2014) report positive correlations between bone Mn and Fe and given the metabolic pathways of each element we would have expected to find a similar relationship. Furthermore, given a ferromanganese as a potential environmental source, it is unexpected that bone Fe and bone Mn do not correlate in all individuals. Notably, in the sampled remains, white South African males showed significantly lower bone Fe than black South Africans regardless of sex, which may likely be affecting these results. The reasons behind this are unclear. Both Zaichick et al. (2011) and Budis et al. (2014) report positive correlations between bone Mn and Fe and given the metabolic pathways of each element we would have expected to find a similar relationship.

The significant correlations between bone Mn, Cd and V are interesting. The three elements are constituents of South African coal and fly ash from coal-fired power plants (Ayanda et al., 2012; Kalenga et al., 2011). It is logical that they may be correlated if the source of Mn exposure in our sampled remains is coal, which can release particulate matter into the atmosphere via combustion or contaminate water via acid mine (AMD) drainage near coal mines (McCarthy, 2011; Moyo et al., 2011). Highveld coal in particular is highly enriched in Mn compared to other South African coals and compared to the global average for Mn in coal (Wagner and Hlatshwayo, 2005). In addition, low income urban households, particularly those located within the townships and in informal settlements also burn coal for cooking and heating. Approximately 20 percent of households in Soweto and in Alexandria Townships burn coal in this way (Kimemia and Annegarn, 2011).

4.1 Manganese exposure in the future

Due to the paucity of manganese exposure data in urban South Africans, these results become valuable, particularly in light of the replacement of lead with MMT in gasoline. Studies of lead exposure on adult males in the same skeletal population yielded a ancestry-specific dichotomy in bone

lead concentration that is linked to residential segregation and exposure to traffic (Hess et al., 2013). In this study white males showed significantly higher bone lead concentration than did black males, owing largely to the fact that the latter lived in residential areas outside of the highly congested central business district. In the present study of manganese, no such dichotomy exists between either black and white individuals, or urban versus suburban residents indicating that exposure to automotive pollution is likely not the main route of exposure for manganese prior to 2000. In addition, there is no significant correlation between bone manganese and bone lead in the sampled remains, which would be expected if there was a common source for both elements. However, with little change in urban residential patterns in Gauteng in the post-apartheid era (Christopher, 2001), this is likely to change as exposure to traffic-related manganese affects the population. In addition to an increase in manganese exposure, we hypothesize that the pattern of exposure will mirror that of lead exposure, namely that white South Africans living living in the urban core will bear a greater burden of exposure to manganese through more significant exposure to traffic pollution. Although highly decentralized, mass transportation in urban Gauteng, particularly Johannesburg, is still centered around the congested central business district, resulting in greater exposure to vehicular pollution in this area (Czegledy, 2004).

It is unclear to what extent this expected spatial pattern in manganese exposure is actually realized in the current population, as little research into adult exposure to manganese has been carried out in Johannesburg or Pretoria. What research has been carried out has focused on blood manganese monitoring which can only be compared to bone manganese data insofar as it highlights broad regional trends in exposure. Röllin et al. (2009) found that blood manganese and cord blood manganese levels in women and infants from urban Gauteng were substantially lower than those in women and infants from any other region, including mining and industrial areas. Notably, this does not follow the same trend as lead which shows a clear urban/rural, high/low dichotomy in regards to blood lead concentration, though this may change over time with cumulative exposure (Grobler et al., 1986; Monna et al., 2006).What the results of this research demonstrate is that should manganese exposure shift towards a similar exposure route to that of lead in the period prior to 2006 some predictable patterns may emerge. Most notably perhaps may be the appearance of manganese hotspots across the urban landscape. These are likely to emerge along transportation corridors in and around the urban core and affect road users and residential areas adjacent to major roadways more substantially than suburban residents. Demographically these residents are more likely to be white residents of the urban core, or black South Africans working in domestic settings within the urban core or within the central business district. Most critically, manganese emitted from crustal (soil) sources such as ferromanganese smelting and mining tend to be found in more coarse particulate matter (PM_{10}) and found in the environment as inorganic manganese or manganese oxides (Post, 1999) and may not be as widely as manganese found in fine particulate matter ($PM_{2.5}$). Manganese

from tail pipe emisssions and other combustion activities is generally found in fine PM and as manganese phosphate or sulfate which which may result in greater neurotoxicity in humans than inorganic manganese or manganese oxide exposure from ferromanganese smelting (Davis et al., 1988; Dorman et al., 2006; Normandin et al., 2004).

Our data demonstrate that the urban population of Gauteng were already exposed to levels of manganese commensurate with those in MMT-exposed populations such as Canada, though the form of manganese was likely different (Pejović-Milić et al., 2009). Should manganese exposure patterns follow the same traffic-related pattern as lead (and there is little reason to believe it will not), it is possible that white South Africans and those who live or work near the urban core will face increased exposure to manganese phosphate and manganese sulfate. This means for at least part of the population, the degree of manganese exposure and the potential neurotoxic effects of such may increase with increasing use of MMT in South Africa. .

4. Conclusion

This research highlights the historical distribution of manganese exposure within an urban South African population. The results show no demographic variation in exposure to manganese and that overall exposure to manganese in the sampled remains was low to moderate. There are however, limitations to the data presented here. Firstly, bone is only beginning to be used as a matrix for biomonitoring manganese in humans, despite recent research demonstrating the utility of in vivo neutron activation analysis as a non-invasive measurement of manganese in bone (Aslam et al., 2008; Pejović-Milić et al., 2009). As yet, there is limited bone manganese data from other regions with which to compare the bone manganese results presented here. In addition, there is no established bone manganese threshold by which clinical or subclinical effects of manganese is expected to appear, making it difficult to speculate as to the health consequences that may have occurred as a result of manganese exposure in this population. Nonetheless, these results do yield critical information regarding trends in manganese exposure in the sampled remains. Despite strict residential segregation, manganese exposure may have remained relatively uniform across the population, a trend which is likely to change in the future.

Secondly, it is impossible, as with most skeletal collections, to determine the complete residential history of the individuals from these collections. Admitting hospital is used here as a proxy for determining geographic residence. This may result in imperfect geographic, but not necessarily demographic (e.g. race and sex) results. It is possible that some of the black South Africans were circular migrants – individuals whose legal residence was located in one of the apartheid homelands. These individuals often worked in the urban areas in mining and industry for predetermined periods of time and were then expected to return to their homeland (Byerlee, 1974). However there is also

evidence that rural to urban circular migrants tended to return to their homeland upon becoming ill and were more likely to die in their homeland (Clark et al., 2007).

The widespread use of MMT as a lead replacement however, is troubling. The neurotoxic effects of manganese are clear, particularly as they relate to neurological disability. Whereas the individuals studied in this project had uniform and relatively low (compared to other countries) exposure to manganese, this will most certainly change. Increased manganese exposure is already being reported in urban South African school children (Batterman et al., 2011; Rollin et al., 2005). Certainly, the heavy traffic areas of urban Gauteng include many historically white-only residential areas, and exposure to manganese in this population will rise. The end of apartheid has meant the unrestricted movement of the black African population, who are now free to live in neighborhoods once strictly off limits to them, yet there is evidence that apartheid residential patterns persist and are changing very slowly. Living conditions among new urban settlers have not changed significantly and hundreds of thousands of informal urban households have arisen, often near transport networks and potential employment opportunities. These individuals are may be exposed to similar levels of manganese as their affluent white compatriots. Whilst the effects of manganese exposure are not as acute as those of lead, the potential for disability among the affected may be greater.

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