Skeletal Lead Burden of the British Royal Navy in Colonial Antigua

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ABSTRACT Lead (Pb) has been known to be a cause of human poisoning since ancient times, but despite this, it was a widely used metal in the European colonial period. In this study, the relationship between Pb exposure and the demographic variables ancestry and age was explored by comparing the bone Pb levels of individuals that were of either African or European ancestry, excavated from a British Royal Navy hospital cemetery (1793–1822 CE) at English Harbour in Antigua, West Indies. More direct comparisons of Pb levels between the two ancestral groups were possible in this study because of the unsegregated nature of this cemetery. Inductively coupled plasma mass spectrometry was used to determine bulk Pb levels in cortical bone samples from the fibular diaphyses of 23 male individuals. No significant difference was found between the distributions of the Pb levels of the ancestral groups (p = 0.94). Further, no positive correlations or significant differences were found in relation to the individuals’ ages and their Pb levels (p = 0.24). Levels of Ba, Ca and rare earth elements support a largely biogenic origin of lead. This is bolstered by Pb deposition patterns, generated by synchrotron X-ray fluorescence imaging for another study. The data suggest that naval personnel, regardless of ancestry at English Harbour, had very similar experiences with regard to Pb exposure. Their exposure to the toxic metal was likely not consistent over time as steady exposure would have resulted in accumulation of Pb with age. This study contributes to addressing historical questions regarding the prevalence of Pb poisoning within the British Royal Navy during the colonial period. © 2017 The Authors International Journal of Osteoarchaeology Published by John Wiley & Sons Ltd.

Key words: bone; British Royal Navy; Caribbean; ICP-MS; lead; lead poisoning

Introduction

The toxicity of lead (Pb) has been known for millennia. The first accounts of Pb poisoning can be found in Egyptian papyri (Hernberg, 2000; Nriagu, 1983). Abdominal colic, a symptom consistent with Pb poisoning, was observed in a metalworker and described by Hippocrates ca 370 BCE. Later, in the second century BCE, palsy and abdominal colic were recognised by Nicander as being caused by lead-containing compounds (Hernberg, 2000; Riva et al., 2012; Waldron, 1973). The connections between Pb exposure and its effects were made again in the first century CE by both Dioscorides and Pliny (Hernberg, 2000; Waldron, 1973).

Despite the understanding of the impact of Pb on health, it was widely used throughout history due to its versatility. The prevalence of considerable exposure resulted in several significant epidemics of Pb poisoning over time (Waldron, 1973). Effects of chronic exposure to lower levels of Pb were both less well understood and less studied, in part because they affected individuals of lower socioeconomic classes whose occupations were often a source of exposure, and their working environments were rarely considered by those of higher socioeconomic status (Riva et al., 2012).

The ubiquity of Pb continued into the European colonial period. Pb could be found in many items: water catchment systems, paints, glazes and cosmetics, as well as in medicines and food and drink (Handler et al., 1986; Nicholson, 1993). Medical records from the British Royal Navy during the colonial period...
reveal that Pb intoxication was likely commonplace amongst the personnel (Blane, 1785; Buckley, 1978; Hughes, 1750; Lloyd & Coulter, 1961; Trapham, 1679, Turnbull, 1806). Dry bellyache, a colic now known to be associated with Pb poisoning, was frequently mentioned in medical logs, so often in fact, that it was the third most common health complaint in the Navy at the time (Turnbull, 1806). Dr John Trapham, a physician who worked in the colonial West Indies, connected symptoms he observed in his own patients with those seen in a Pb poisoning epidemic that had occurred in Europe yet did not make the diagnosis of Pb poisoning (Trapham, 1679).

Rum was likely a substantial source of Pb for members of the British Royal Navy in the colonial West Indies (Blane, 1785; Buckley, 1978). Both rum and its primary distillation product, known as 'low-wine', were easily accessible as sugar cane was the chief crop of the islands (Buckley, 1978; Handler et al., 1986; Howard, 2000). Many of the distillation equipment's components were made from Pb, including condenser worms, still heads and troughs. The distillation process itself would also have contributed, as both the high temperatures and the liquid's acidity would have increased the Pb's mobility resulting in even more of the element leaching into the rum (Handler et al., 1986). Daily rations for naval personnel included a half-pint of rum, and even greater consumption was accepted because it was generally believed that rum alleviated the effects of scurvy and tropical fevers (Duffy, 1987; Dyde, 1997; Lloyd, 1969).

The amount of Pb that enters the system is dependent on several factors including age and route of entry. If an adult inhales Pb, their system will absorb about 30–50% of the dose, whereas if the adult ingests the Pb, about 10% of the dose will be absorbed (Bogen et al., 1976; Morrow et al., 1980). In comparison, children absorb significantly more of an equivalent dose. Ingestion of Pb by young individuals will result in systemic absorption of 50% of the Pb (Ziegler et al., 1978). Another factor that can affect absorption is the nutritional status of the individual. Adult absorption of Pb has been seen to increase from 10% to 60% during periods of fasting (Heard & Chamberlain, 1982). Almost all of the Pb that is absorbed into the body (90–95%) becomes deposited in bone tissue, and it can remain there for significant periods of time. The half-life of Pb in bone has been found to range from 2 to 27 years (Schütz et al., 1987). The half-life is influenced by bone type and the individual's metabolism and age (Hyrczuk et al., 1985; O'Flaherty, 1993; Rabinowitz, 1991; Schütz et al., 1987). The lowest remodelling rates are found in cortical bone, and as a result, Pb stays in cortical bone for the longest interval (Gulson & Gillings, 1997).

Pb can be remobilised into the blood from bone. This can occur through normal remodelling, but it can also be brought about by other factors including pregnancy, starvation or bone injury (Gulson et al., 1997; Heard & Chamberlain, 1982; Smith et al., 1996). Once Pb is in the blood, if the levels are high enough, symptoms of Pb poisoning can develop. Pb's presence in bone can therefore be indicative of a chronic disease state, which was likely poorly understood in the past. There might have been a considerable time interval between a known Pb exposure and the occurrence of Pb poisoning symptoms. If the accumulation was gradual, symptom onset might have appeared inexplicable or have been attributed to an incorrect aetiology.

The opportunity to investigate the possible prevalence of Pb poisoning in the colonial British Royal Navy was presented when a cemetery belonging to the Royal Navy Hospital in English Harbour, Antigua, West Indies (ca 1793–1822 CE) was excavated due to disturbance by modern development. According to historical documentation, the individuals interred in this cemetery were likely to have been low-ranking naval personnel and enslaved naval personnel (Varney & Nicholson, 2001). The enslaved were a group of labourers called the 'King's Negroes' that were owned by the British Royal Navy and were given specialised training in trades, such as sail-making (Nicholson, 1991). This cemetery was of special interest, since at the time of excavation it was believed to be one of the only unsegregated colonial era cemeteries (Varney, 2011). The unusual composition of the interred population presented us with the opportunity to explore differential Pb exposure between enslaved and non-enslaved British Royal Navy personnel.

We hypothesised that there would be a significant difference between the bone Pb levels of the two ancestries, as this pattern had been observed in other comparisons of similar ancestral groups (Aufderheide et al., 1981; Hess et al., 2013). Based on previous bioarchaeological and clinical research, we also expected to see higher levels of bone Pb with increasing age at death (Aufderheide et al., 1981; Corruccini et al., 1987; Schütz et al., 2005; Hess et al., 2013).

### Materials and methods

The excavation of the Royal Navy Hospital cemetery spanned five field seasons (1997–2002) and yielded...
the remains of 31 individuals: 24 male adults, two male adolescents and five children under the age of 5 years (Varney, 2011). Ancestry was assessed using craniofacial features following Gill and Gilbert (1990) and Rhine (1990). Because of lack of skull preservation, only 14 of the individuals could be considered for ancestry determination: seven were of European ancestry and seven were of African ancestry. Further evidence supporting the gross assessment of ancestry was obtained via reconstruction of diet based on stable isotopic analysis (Varney, 2011). Based on stable nitrogen values, all individuals in this study had similar protein sources; however, there were differences seen in stable carbon isotope ratios of the two different ancestries, suggesting differing carbohydrate staples (Varney, 2011).

The analysis of these human skeletal remains has been pre-approved by Dr Reginald Murphy of National Parks, Antigua and Barbuda, as well as by the Lakehead University Research Ethics Board [project 042 13-14].

Bone Pb, Ba, Ca and rare earth element (REE) levels were quantified using inductively coupled plasma mass spectrometry (ICP-MS). The ICP-MS data were analysed to allow comparisons between Pb levels of the different ancestries and age groups. REE levels, Ba/Ca, and Pb/Ca ratios were evaluated in order to assess diagenetic contamination.

From the 31 sets of remains, 23 male adult and adolescent individuals with determinable age ranges were selected for ICP-MS analysis. This set of 23 included 13 individuals whose ancestry had been assessed as being of either African or European ancestry (Table 1). One individual whose ancestry had been assessed was excluded in the ICP-MS analysis reported here. The remains of the five children found at the site were also excluded from the study. Metabolic and rapid bone growth rates of very young individuals would potentially complicate interpretation of bone Pb data.

The fibula was chosen for trace element analysis, as it was the best represented and preserved long bone amongst the remains. Cortical bone is preferred over trabecular bone for studies of long-term Pb exposure because its lower turnover rate renders it more reflective of total skeletal burden (Wittmers et al., 1988). In addition, it is also less subject to diagenetic change because of its reduced surface area as compared with trabecular bone (Grupe, 1988, Lambert et al., 1985).

Fibular diaphyses were sampled for analysis. The samples were gently cleaned with a clean toothbrush, using water filtered first by reverse osmosis and then further purified by a Millipore Synergy unit, to remove residual materials resulting from excavation. This mechanical scrub was followed by a 5-min soak in purified water in an ultra-sonicator to dislodge leftover material. Bone samples of approximately 1 inch were cut from the diaphysis using a Ryobi BS903 band saw at Lakehead University in ON, Canada, and then sent to the University of Saskatchewan for further analysis following another 5-min soak in purified water in an ultra-sonicator to dislodge any loose material produced during cutting.

Preceding ICP-MS analysis, bone sections were heated to dryness at 60°C in a slide dryer, dependent on state of preservation (Swanson et al., 2012). The dried bone samples were then ground to powder between two plastic weigh boats before being sent to the ICP-MS (Neptune, Thermo Fisher) in the laboratory of the Geological Sciences Department at the University of Saskatchewan (Saskatoon) for trace element analysis (Swanson et al., 2012). ICP-MS was performed following the methods outlined in Stefanova et al. (2003), Jenner et al. (1990) and Jackson et al. (1990).

The mean Pb levels and standard deviations for the individuals of European ancestry and individuals of African ancestry were calculated. The distributions were then compared using a nonparametric statistical method, the Wilcoxon rank sum test, due to the small data set ($n < 30$). Box and whisker plots were generated to display the means, distributions and ranges of Pb levels of the two ancestries.

The 23 individuals were separated into different age groups, defined by the decade they were in at their time of death, that is, ≤20, 20–29, 30–39, 40–49, as well as 50 years and over. The mean Pb level and standard deviation of each group was calculated. Box and whisker plots were generated to display the means, distributions and ranges of Pb levels of the age groups in order to visualise any pattern that may be occurring. Finally, because the sample set was small, a Kruskal–Wallis test was performed to query for the presence of significant differences in distribution variance amongst the Pb levels within the age groups.

### Results

The results of the ICP-MS analysis for Pb, Ba, Ca and REE's are shown in Table 1. The graphical depiction of the comparison of Pb/Ca to Ba/Ca ratios can be seen in Figure 1.

Graphical comparison (Figure 2) of the Pb levels of the African and European ancestries suggested a difference between their values, as was expected. The standard deviations, shown in Table 2, and the ranges,
| Burial number | Age (years) | Ancestry* | Pb | Ba | Ca | Sc | Y | La | Ce | Pr | Nd | Sm | Gd | Tb | Dy | Ho | Er | Tm | Yb | Lu |
|---------------|-------------|-----------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| B1            | 45–49       | A         | 41.19 | 181.47 | 313289.51 | ud | 0.11 | 0.04 | 0.07 | 0.02 | 0.08 | 0.01 | 0.03 | 0.00 | 0.02 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 |
| B2            | 25–29       | E         | 22.18 | 70.28 | 348817.46 | ud | 0.28 | 0.10 | 0.15 | 0.03 | 0.18 | 0.04 | 0.06 | 0.01 | 0.04 | 0.01 | 0.03 | 0.00 | 0.02 | 0.00 |
| B3            | 30–34       | E         | 72.25 | 42.26 | 353920.63 | ud | 0.26 | 0.08 | 0.12 | 0.03 | 0.18 | 0.04 | 0.04 | 0.01 | 0.04 | 0.01 | 0.02 | 0.00 | 0.02 | 0.01 |
| B4            | 50–60       | A         | 163.1 | 297.23 | 303833.14 | ud | 0.49 | 0.10 | 0.11 | 0.04 | 0.24 | 0.06 | 0.12 | 0.02 | 0.08 | 0.02 | 0.05 | 0.00 | 0.02 | 0.01 |
| B5            | 16–18       | E         | 90.18 | 73.69 | 291526.64 | ud | 0.70 | 0.17 | 0.16 | 0.07 | 0.37 | 0.09 | 0.14 | 0.02 | 0.11 | 0.02 | 0.04 | 0.01 | 0.03 | 0.01 |
| B6            | 25–29       | E         | 21.03 | 89.44 | 279481.95 | ud | 0.89 | 0.21 | 0.27 | 0.09 | 0.41 | 0.13 | 0.19 | 0.03 | 0.15 | 0.03 | 0.09 | 0.01 | 0.06 | 0.02 |
| B8            | 14–15       | ND        | 214.77 | 77.51 | 347090.87 | ud | 2.47 | 0.52 | 0.51 | 0.22 | 1.25 | 0.37 | 0.54 | 0.08 | 0.40 | 0.07 | 0.20 | 0.02 | 0.11 | 0.02 |
| B9a           | 20–29       | ND        | 36.89 | 70.57 | 268296.55 | ud | 1.97 | 0.30 | 0.18 | 0.15 | 0.89 | 0.28 | 0.43 | 0.06 | 0.33 | 0.07 | 0.18 | 0.02 | 0.12 | 0.03 |
| B9b           | 18–20       | ND        | 149.04 | 120.84 | 311322.15 | ud | 0.53 | 0.14 | 0.22 | 0.06 | 0.37 | 0.10 | 0.11 | 0.02 | 0.11 | 0.02 | 0.06 | 0.01 | 0.03 | 0.01 |
| B12a          | 35–39       | A         | 96.93 | 117.84 | 311132.15 | ud | 0.44 | 0.09 | 0.07 | 0.04 | 0.20 | 0.06 | 0.09 | 0.01 | 0.07 | 0.01 | 0.03 | 0.00 | 0.02 | 0.01 |
| B14           | 35–39       | ND        | 30.9 | 46.13 | 346071.43 | ud | 0.11 | 0.05 | 0.06 | 0.01 | 0.11 | 0.01 | 0.02 | 0.00 | 0.02 | 0.00 | 0.01 | 0.00 | 0.01 | 0.02 |
| B15a          | 35–39       | E         | 251.49 | 34.59 | 328993.54 | ud | 2.26 | 0.59 | 0.54 | 0.24 | 1.24 | 0.32 | 0.52 | 0.07 | 0.33 | 0.07 | 0.16 | 0.02 | 0.09 | 0.02 |
| B16           | 16–18       | ND        | 73.19 | 57.38 | 302159.76 | ud | 0.49 | 0.08 | 0.07 | 0.03 | 0.18 | 0.07 | 0.09 | 0.01 | 0.07 | 0.01 | 0.03 | 0.00 | 0.03 | 0.02 |
| B17           | 35–39       | ND        | 15.99 | 40.47 | 297000.47 | ud | 0.08 | 0.02 | 0.02 | 0.01 | 0.03 | 0.01 | 0.01 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | ud | 0.01 | 0.01 |
| B18           | 30–35       | E         | 54.72 | 98.48 | 338872.00 | ud | 1.19 | 0.16 | 0.09 | 0.08 | 0.48 | 0.14 | 0.23 | 0.03 | 0.18 | 0.03 | 0.10 | 0.01 | 0.04 | 0.02 |
| B19a          | 40–45       | E         | 101.85 | 49.06 | 304251.04 | ud | 0.52 | 0.14 | 0.12 | 0.06 | 0.27 | 0.09 | 0.13 | 0.02 | 0.08 | 0.02 | 0.05 | 0.00 | 0.02 | 0.01 |
| B19b          | 20–24       | ND        | 61.19 | 34.84 | 361215.31 | ud | 1.31 | 0.31 | 0.30 | 0.14 | 0.73 | 0.20 | 0.31 | 0.04 | 0.21 | 0.04 | 0.10 | 0.01 | 0.06 | 0.01 |
| B22           | 20–29       | ND        | 10.08 | 180.94 | 338057.13 | ud | 21.20 | 6.43 | 2.28 | 2.43 | 13.36 | 3.52 | 4.87 | 0.64 | 3.18 | 0.60 | 1.45 | 0.15 | 0.76 | 0.11 |
| B23           | 35–39       | A         | 121.77 | 212.71 | 335581.15 | ud | 4.06 | 1.04 | 0.40 | 0.43 | 2.35 | 0.67 | 0.86 | 0.12 | 0.60 | 0.12 | 0.30 | 0.04 | 0.14 | 0.03 |
| B24           | 25–29       | A         | 42.09 | 131.19 | 333331.72 | ud | 0.38 | 0.09 | 0.11 | 0.03 | 0.20 | 0.06 | 0.08 | 0.01 | 0.06 | 0.01 | 0.03 | 0.00 | 0.02 | 0.01 |
| B25           | 20–25       | A         | 23.08 | 229.14 | 325169.41 | ud | 4.87 | 1.09 | 0.71 | 0.45 | 2.39 | 0.71 | 1.06 | 0.15 | 0.78 | 0.15 | 0.36 | 0.04 | 0.22 | 0.04 |
| B26           | 14–18       | ND        | 21.7 | 102.49 | 343480.39 | ud | 16.14 | 5.03 | 2.11 | 1.77 | 9.30 | 2.43 | 3.45 | 0.46 | 2.28 | 0.44 | 1.01 | 0.11 | 0.59 | 0.10 |

*A = African ancestry, E = European ancestry, ND = ancestry not determined.
shown in the bars in Figure 2, demonstrate the wide distribution of values found in both ancestries.

Figure 2 also demonstrates that individuals of European ancestry had a slightly higher mean and a larger standard deviation than those of African ancestry. Statistical analysis using a Wilcoxon rank sum test revealed that the distributions of the Pb levels of the two ancestries were not significantly different (p-value 0.94).

The mean of Pb levels according to age groupings (Table 3) was compared graphically (Figure 3) in order to determine if there was a pattern according to age. An increase according to age was expected, but none was observed. No significant difference was found between the distributions of the age groups when the Kruskal–Wallis test was performed (p-value 0.24). The standard deviations, shown in Table 3, and the ranges, as shown by the bars in Figure 3, demonstrate the broad distribution of Pb levels within each age group.

**Discussion**

Diagenesis is a prevailing concern for studies involving trace element levels in archaeological bone. Soil samples were, unfortunately, not available for trace

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*Figure 1. Relationship between lead/calcium ratios and barium/calcium ratios at the British Royal Navy hospital cemetery at English Harbour, Antigua, West Indies.*

*Figure 2. Lead levels by ancestry of the individuals excavated from the British Royal Navy hospital cemetery at English Harbour, Antigua, West Indies.*
element analysis of the depositional environment. As part of a larger investigation, several bone samples from individuals included in this study were scanned using synchrotron radiation X-ray fluorescence imaging (SR-XFI) in order to map the Pb, along with other trace elements, within the bone structure as reported in Choudhury et al. (2016) and Swanston et al. (2012). This elemental mapping permitted an assessment of the nature of the detected trace elements in terms of whether they were of post mortem (diagenetic) origin or incorporated in life (biogenic). Pb was observed to be unevenly incorporated within the bone microstructure. Some osteones demonstrated Pb enrichment, while others did not. The uneven distribution through the bone microstructure supports the interpretation of biogenic uptake, as diagenetic Pb is likely to appear concentrated on exposed surfaces or more evenly throughout the microstructure (Swanston et al., 2012; Wittmers et al., 2008). These SR-XFI Pb patterns have been observed in remains from multiple disparate sites (Swanston et al., 2012; Choudhury et al., 2016; Swanston et al., 2016). The results of the SR-XFI analyses support the principally biogenic nature of the Pb. The REE levels observed in this study also support biogenic elemental levels. The mean values of the detected REEs were below levels seen in fresh autopsy specimens from a modern non-industrial population, suggesting that the environmental uptake was minimal (Trueman et al., 2004; Zaichick et al., 2011). While we cannot eliminate the possibility of diagenesis entirely, supporting analyses indicate that a significant portion of the Pb detected by ICP-MS was biogenic.

Inductively coupled plasma mass spectrometry analysis revealed a wide range of bone Pb level values (Table 1), ranging from 10.08 to 251.49 ppm Pb with a mean of 80.76 ppm Pb. The lowest value belongs to an individual of indeterminate ancestry who was between the ages of 20 and 29 years at his time of death. The highest value belongs to a European individual with an estimated age at death of between 35 and 39 years.

The broad array of lead levels found in this study is not easily interpreted, as individual bone Pb levels are influenced by many contributing factors. The route of absorption has a significant effect, as inhaled Pb doses result in greater absorption than Pb ingestion. Individuals from areas of greater industrialisation would likely have higher bone Pb as a result of environmental contamination (Hess et al., 2013). The metabolic rate and health status of the individual have significant effects on their Pb absorption (Bogen et al., 1976; Heard & Chamberlain, 1982; Ziegler et al., 1978). Periods of fasting or low food intake can result in the Pb absorption rate increasing to 60% of the Pb ingested, when the normal level is 10% (Heard & Chamberlain, 1982). The overall health of the individuals in this study must be considered given the recovery context of their remains, as they were likely of low socioeconomic status and in hospital when they died. The source of exposure will also affect Pb levels. Pb sources can sometimes be determined using isotopic data, but quantitation alone, as we have carried out here, cannot provide adequate evidence of the nature of the source material. The length and timing of exposure will also have an impact on Pb absorption; however, bone remodelling releases Pb back into the blood, which can confound attempts to establish these variables. A small amount of the remobilised Pb will be excreted in urine, but most of it will be reincorporated into the bone (Schütz et al., 2005). The personal habits of the naval personnel would also have played a part in their individual exposure to Pb. It cannot be assumed that all members drank rum excessively. There is historic documentation that indicates some members did not consume their rum ration but rather would pass it on to members that were considered too young to receive a rum ration (Thomas, 1968). This may have

### Table 2. Mean Pb levels by ancestry of individuals excavated from British Royal Navy hospital cemetery at English Harbour, Antigua, West Indies

| Ancestry | Number of individuals | Mean Pb (ppm) | Standard deviation (ppm) | Minimum Pb (ppm) | Median Pb (ppm) | Maximum Pb (ppm) |
|----------|-----------------------|---------------|--------------------------|------------------|----------------|------------------|
| African  | 6                     | 79.69         | 54.56                    | 23.08            | 64.51          | 163.10           |
| European | 7                     | 87.67         | 78.63                    | 21.03            | 72.25          | 251.49           |

### Table 3. Pb levels by age group of the individuals excavated from the British Royal Navy hospital cemetery at English Harbour, Antigua, West Indies

| Age group (years) | Number of individuals | Mean Pb (ppm) | Standard deviation (ppm) | Minimum Pb (ppm) | Median Pb (ppm) | Maximum Pb (ppm) |
|-------------------|-----------------------|---------------|--------------------------|------------------|----------------|------------------|
| 14–20             | 5                     | 91.48         | 74.24                    | 21.70            | 90.18          | 214.77           |
| 20–29             | 8                     | 46.06         | 45.60                    | 10.08            | 29.98          | 151.92           |
| 30–39             | 7                     | 90.58         | 79.19                    | 15.99            | 72.25          | 251.49           |
| 40–49             | 2                     | 71.52         | 42.89                    | 41.19            | 71.52          | 101.85           |
| 50 ≤              | 1                     | 163.1         | N/A                      | 163.1            | 163.1          | 163.1            |
contributed to the high Pb levels observed in some of the younger individuals in this study. The occupational duties and tasks of individuals are another important consideration for those exposed to Pb regularly while working. For example, those who worked with munitions would likely be at greater risk of Pb exposure than personnel whose primary tasks involved sail-making. No documentation regarding the specific individuals in this study has been recovered, and without a greater understanding of their personal histories, it is difficult to draw conclusions regarding the variable bone Pb levels found in this investigation.

The distributions of the Pb levels associated with the two ancestries were not found to be significantly different following statistical analysis. This differs from the results found when the Pb levels of two ancestral groups from a colonial plantation in Virginia were compared. Aufderheide et al. (1981) found significantly higher mean Pb levels in individuals of European ancestry than those of African ancestry. The authors attributed their finding to different practises and behaviours of the two groups (Aufderheide et al., 1981). Notably, Europeans of higher socioeconomic status were known to eat food and drink from pewter dishes, and this may have resulted in their high levels of Pb. Also, the food may have already been contaminated through storage in Pb-glazed vessels, which were commonplace at the time. The enslaved labourers on the plantation were not known to have used the same serving ware for their food (Aufderheide et al., 1981).

The lack of a significant difference between the distributions of the two ancestral groups in the present study suggests that their overall behaviours and practises were more similar than those of the groups studied in Aufderheide et al. (1981). The sources of Pb, including rum and water, were likely equally available to both groups. The drinking water at the naval dockyard was likely contaminated because many of the naval dockyard’s water troughs and cisterns were made from or contained Pb (Handler et al., 1986; Nicholson, 1991; Varney, 2011; Varney et al., 2012). To help remedy the significant problem of rum being regularly passed on to the grounds, the Naval Hospital administration even felt the need to have a cactus hedge constructed as a physical barrier (Nicholson, 1993). Artefacts found in a midden associated with the hospital including lead-glazed pottery and a vessel containing Pb acetate, which was used in medical practice at the time, indicate other possible sources of exposure during hospitalisation (Nicholson, 1983). Food sources for all naval personnel, including the ‘King’s Negroes’, were likely similar as well, given they were all being provisioned by the Navy. An earlier investigation into diet, via stable isotope analysis, indicated that both ancestries shared a common protein source but differed in their carbohydrate staple (Varney, 2011). Because of the ubiquity of Pb in glazes, it is possible that the storage and dining vessels were also contaminated with Pb. Thus, the simultaneous treatment of enslaved and ranking naval personnel in the dockyard hospital, the dietary reconstruction study and, finally, the interment in an unsegregated cemetery together provide evidence of greater similarity in experiences for all Naval personnel of lower rank, regardless of ancestry.

Given Pb’s tendency to accrue in cortical bone with age, along with similar bioarchaeological research, it was anticipated that a positive correlation pattern would be observed in the individuals examined in the

Figure 3. Lead levels by age group of the individuals excavated from the British Royal Navy hospital cemetery at English Harbour, Antigua, West Indies. The bars indicate standard error (*the 40-49 group has no quartile positions as there were only 2 individuals in this group, †the 50≤ group has only one individual and therefore only one data point).
present study (Aufderheide et al., 1981; Corruccini et al., 1987). Our results were unexpected in that no distinct pattern of accumulation with respect to ancestry or age was observed in the population from the British Royal Navy hospital cemetery at English Harbour.

The generally high accrual of Pb in the fibula of the youngest group, those between the ages of 14 and 20 years at death, was in line with expectations. The prevalence of Pb in the colonial period coinciding with the greater degree of Pb dose absorption and higher rate of bone deposition in younger individuals all support this outcome (Ziegler et al., 1978). It should be noted that diagenesis may have contributed to the subadult Pb levels, as their bones are more porous and thus more subject to environmental alteration (Wittmers et al., 2008). However, the range of Pb values within the young individuals’ age group, 21.70 to 214.77 ppm Pb, supports biogenic incorporation, as not all have high Pb levels.

The absence of the expected positive correlation pattern between bone Pb levels and age implies that the Pb exposure may not have been at a consistent rate. This is supported by our comparison of Ba/Ca ratios to Pb/Ca ratios (Figure 1) that found a lack of correlation between these two ratios, suggesting exposures that varied in intensity and duration (Patterson et al., 1991). Even if the exposure within the navy was constant, we lack information regarding at what age each of these individuals became involved with the navy. During the European colonial period, a significant percentage of naval personnel was acquired through press-ganging, and this tactic was known to be rather indiscriminate (Lloyd, 1969). Substantial variability within each of the age groups indicates considerable variation amongst individuals’ habits and behaviours, for example, in their alcohol consumption levels. Some members consumed amounts beyond their daily rations, some abstained and there were likely moderate consumers as well (Lloyd, 1969; Thomas, 1968). Pb exposure may have occurred at any point in their lifetime, and their ages, individual habits and health at the time of exposure would have significant effect on the Pb levels detected in their bones. At this time, there is no method of bone tissue analysis that allows researchers to determine at which points in an individual’s life the exposure to Pb occurred.

An estimation of the prevalence of lead poisoning in the British Royal Navy as a whole cannot be directly answered with the results of this study. The elevated bone Pb levels of several of the individuals do, however, indicate a probability that at some point they would have suffered some effects of Pb poisoning. Parts per million levels of Pb found in bone roughly correspond with microgram/decilitre concentrations found in blood (Glenn et al., 2006). This suggests that as many as 17 of the 23 individuals analysed here might have experienced symptoms of Pb poisoning, ranging from mild to very severe (Handler et al., 1986; Schroeder et al., 2013). This is a rough evaluation, as diagenetic deposition could alter interpretation. Even if the biogenic Pb levels were certain, there are other variables that govern a given individual’s vulnerability to the effects of Pb poisoning, such as stress levels and genetic factors (Millar et al., 2015).

This study determined the bone Pb levels of 23 individuals from a colonial era British Royal Navy hospital cemetery at English Harbour, Antigua. As discussed earlier, there are some limitations that must also be considered. Diagenesis cannot be completely excluded, limiting the accuracy of our deductions. The fact that these individuals had been hospitalised at the time of their death may have biased the results because of their presumed poor health status which may have increased Pb absorption. Their hospitalisation itself may have directly resulted from Pb poisoning and, ultimately, may have resulted in death. Thus, the prevalence of higher Pb levels may be positively skewed in this sample set. If the individuals’ health status was negatively affected by elevated Pb levels, they may have been more susceptible to the many pathogens that prevailed at this point in history. The small sample set also limits the conclusions that can be drawn from the data.

This investigation does still provide insight into the lives of those in service to the colonial British Royal Navy. There are few historical accounts of the lives of Navy personnel in colonial Antigua, especially those regarding the lives of those in the lower ranks, and as such, there has been a gap in the knowledge base regarding the European expansion into the West Indies.

A wide range of Pb levels was found in the bone samples analysed in this study. This variation can be attributed to many influencing factors, including metabolism, habits, labour duties and health. No bone Pb accumulation patterns in regard to ancestry or age were detected. While we cannot definitively determine the prevalence of Pb poisoning within the colonial British Royal Navy with the results from this study, it is likely that several individuals from this group experienced symptoms of Pb poisoning at some point in their lifetimes, particularly those whom had bone Pb levels exceeding 200 ppm. It is important to note that there is no accepted safe amount of Pb for humans, particularly for those who are still undergoing physical development (Centres for Disease Control and Prevention, 2016; National Institute of Environmental...
Health Sciences, 2016; World Health Organization, 2016). Data from this study indicate that Pb exposure was likely commonplace during the colonial era, as all the individuals’ bones analysed in this study contained Pb. These results also demonstrate that it should not be presumed that all individuals from the Colonial period were consistently exposed to very high levels of Pb. Farrer (1993) believed that 19th century British adults would have had a very high background level of Pb and our study reveals that would not have always been the case. Methodological improvements that allow investigators to determine more precise information regarding timing and severity of an individual’s exposure will likely allow researchers to draw even more information from the bone Pb results found in this study, as well as greater understandings of the health status of other past populations.

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References

Aufderheide AC, Neiman FD, Wittmers LE, Jr, Rapp G. 1981. Lead in bone II: skeletal-lead content as an indicator of lifetime lead ingestion and the social correlates in an archaeological population. American Journal of Physical Anthropology 55: 285–291. https://doi.org/10.1002/ajpa.130550304.

Blane G. 1785. Observations on the Diseases Incident to Seamen. London: J. Cooper.

Bogen DC, Welford GA, Morse RS. 1976. General population exposure of stable lead and 210Pb to residents of New York City. Health Physics 30: 359–362.

Buckley RN. 1978. The destruction of the British Army in the West Indies 1793–1815: a medical history. Journal of the Society for Army Historical Research 56: 79–92.

Centres for Disease Control and Prevention. 2016. Pb. http://www.cdc.gov/nceh/Pb/acclpp/blood_Pb_levels.htm, accessed April 22, 2016.

Choudhury S, Swanston T, Varney TL, Cooper DML, Gordon RA, George GN, Pickering IJ, Coulthard I. 2016. Confocal X-ray fluorescence imaging facilitates high resolution mapping in friable archaeological bone. Archaeometry 58: 207–217. https://doi.org/10.1111/arcm.12232.

Corruccini RS, Aufderheide AC, Handler JS, Wittmers LE, Jr. 1987. Patterning of skeletal lead content in Barbados slaves. Archaeometry 29: 233–239. https://doi.org/10.1111/j.1475-4754.1987.tb00416.x.

Duffy M. 1987. Soldiers, Sugar and Seapower: The British Expeditions to the West Indies and the War against Revolutionary France. Clarendon Press: Oxford.

Dyde B. 1997. The Empty Sleeve. St. John’s: Hansib Caribbean.

Farrer KTH. 1993. Lead and the last Franklin Expedition. Journal of Archaeological Science 20: 399–409. https://doi.org/10.1006/jasc.1993.1024.

Gill GW, Gilbert BM. 1990. Race identification from the midfacial skeleton: American blacks and whites. Skeletal Attribution of Race. Methods for Forensic Anthropology. Maxwell Museum of Anthropology, Anthropological Papers #4, G, GW Gill, S Rhine (eds.). University of New Mexico: Albuquerque, NM; 329–339.

Glenn BS, Bandeen-Roche K, Lee B-K, Weaver VM, Todd AC, Schwartz BS. 2006. Changes in systolic blood pressure associated with lead in blood and bone. Epidemiology 17: 538–544. https://doi.org/10.1097/01.ede.0000213284.19078.4b.

Grupe G. 1988. Impact of the choice of bone samples on trace element data in excavated human skeletons. Journal of Archaeological Science 15: 123–129. https://doi.org/10.1016/0305-4403(88)90002-7.

Guilson BL, Gillings BR. 1997. Lead exchange in teeth and bone: a pilot study using stable lead isotopes. Environmental Health Perspectives 105: 820–824. https://doi.org/10.2307/3433699.

Guilson BL, Jameson CW, Mahaffey KR, Mizon KJ, Korsch MJ, Vimpani G. 1997. Pregnancy increases mobilization of lead from maternal skeleton. Journal of Laboratory and Clinical Medicine 130: 51–62. https://doi.org/10.1016/S0022-2143(97)90058-5.

Handler JS, Aufderheide AC, Corruccini RS, Brandon EM, Wittmers LE. 1986. Lead contact and poisoning in Barbados slaves: historical, chemical and biological evidence. Social Science History 10: 399–425. https://doi.org/10.2307/1171025.

Heard MJ, Chamberlain AC. 1982. Effect of minerals and food on uptake of lead from the gastrointestinal tract in humans. Human Toxicology 1: 411–415. https://doi.org/10.1177/096032718200100407.

Hernberg S. 2000. Lead poisoning in a historical perspective. American Journal of Industrial Medicine 38: 244–254. https://doi.org/10.1002/1097-0274(200009)38:3<244::AID-AJIM3>3.0.CO;2-F.

Hess CA, Cooper MJ, Smith MJ, Trueman CN, Schutkowski H. 2013. Lead exposure in adult males in urban Transvaal Province, South Africa during the Apartheid Era. PloS One 8. https://doi.org/10.1371/journal.pone.0058146.

Howard MR. 2000. Red jackets and red noses: alcohol and the British Napoleonic soldier. Journal of the Royal Society of Medicine 93: 38–41. https://doi.org/10.1177/014107689108400519.

Hughes G. 1750. The Natural History of Barbados. London.
Hyrhorczuk DO, Rabinowitz MB, Hessl SM, Hoffman D, Hogan MM, Mallin K, Finch H, Orris P, Berman E. 1985. Elimination kinetics of bone lead in workers with chronic lead intoxication. American Journal of Industrial Medicine 8: 33–42. https://doi.org/10.1002/ajim.4700081015.

Jackson SE, Fryer BJ, Gosse W, Healey DC, Longerich HP, Strong DF. 1990. Determination of the precious metals in geological materials by inductively-coupled plasma-mass spectrometry (ICP-MS) with nickel sulphide fire-assay collection and tellurium coprecipitation. Chemical Geology 83: 119–132. https://doi.org/10.1016/0009-2541(90)90144-V.

Jenner GA, Longerich HP, Jackson SE, Fryer BJ. 1990. ICP-MS – a powerful tool for high-precision trace-element analysis in Earth sciences: evidence from analysis of selected USGS reference samples. Chemical Geology 83: 133–148. https://doi.org/10.1016/0009-2541(90)90145-W.

Lambert JB, Vlasak Simpson S, Gorell Weiner S, Buikstra JE. 1985. Induced metal ion exchange in excavated human bone. Journal of Archaeological Science 12: 85–92. https://doi.org/10.1016/0305-4403(85)90053-6.

Lloyd C. 1969. Life at sea in Nelson's day-recruitment-victuals-punishment-pay-disease and hygiene-women in the Fleet—The Great Mutinies of 1797. History of the Royal Navy, P Kemp (ed.). Arthur Barker Ltd.: London; 101–108.

Lloyd C, Coulter JLS. 1961. Medicine and the Navy 1200–1900. E. & S. Livingstone Ltd.: London.

Millar K, Bowman AW, Battersby W. 2015. A re-analysis of the supposed role of lead poisoning in Sir John Franklin’s last expedition, 1845–1848. Polar Record 51: 224–238. https://doi.org/10.1017/S0032247413000867.

Morrow PE, Beiter H, Amato F, Gibb FR. 1980. Pulmonary retention of lead: an experimental study in man. Environmental Research 21: 373–384. https://doi.org/10.1016/0013-9351(80)90040-7.

National Institute of Environmental Health Sciences. 2016. Pb. http://www.niehs.nih.gov/health/topics/agents/Pb/, accessed April 22, 2016.

Nicholson DV. 1991. The Story of English Harbour, Antigua, West Indies. St. John’s, Antigua: Historical and Archaeological Society.

Nicholson DV. 1993. Mud and Blood. Artifacts from Dredging and the Naval Hospital Site. English Harbour. Museum of Antigua and Barbuda.

Nriagu JO. 1983. Lead and Lead Poisoning in Antiquity. John Wiley & Sons: New York.

O’Flaherty EJ. 1993. Physiologically based models for bone-seeking elements. IV. Kinetics of lead disposition in humans. Toxicology and Applied Pharmacology 118: 16–29. https://doi.org/10.1006/taap.1993.1004.

Patterson C, Ericson J, Manea-Krichten M, Shirahata H. 1991. Natural skeletal levels of lead in Homo sapiens sapiens uncontaminated by technological lead. The Science of the Total Environment 107: 205–236. https://doi.org/10.1016/0048-9697(91)90260-L.

Rabinowitz MB. 1991. Toxicokinetics of bone lead. Environmental Health Perspectives 91: 33–37.
Varney TL. 2011. The Royal Naval Hospital cemetery at English Harbour, Antigua: not just the "Grave of the Englishman". Proceedings of the XXIII International Congress for Caribbean Archaeology, Antigua. 2009. Antigua, 291–300.

Varney TL, Nicholson DV. 2001. Digging "The Grave of the Englishman": a preliminary report on excavations at a former British Navy hospital cemetery, English Harbour, Antigua, W.I. Proceedings of the XVIII International Congress for Caribbean Archaeology. Grenada, 329–335.

Varney TL, Swanston T, Coulthard I, Cooper DML, George GN, Pickering IJ, Murphy AR. 2012. A preliminary investigation of lead contamination in a Napoleonic era naval cemetery in Antigua, W.I. Caribbean Connections 2. Accessed June 2, 2015 at http://fieldresearchcentre.weebly.com/uploads/1/8/0/7/18079819/varney_et_al.pdf

Waldron HA. 1973. Lead poisoning in the ancient world. Medical History 17: 391–399. https://doi.org/10.1017/S0025727300019013.

Wittmers LE, Jr, Walgren J, Alich A, Aufderheide AC, Rapp G, Jr. 1988. Lead in bone IV. Distribution of lead in the human skeleton. Archives of Environmental Health 43: 381–391. https://doi.org/10.1080/00039896.1988.9935855.

Wittmers LE, Jr, Aufderheide AC, Pounds IG, Jones KW, Angel JL. 2008. Problems in determination of skeletal lead burden in archaeological samples: an example from the first African Baptist Church Population. American Journal of Physical Anthropology 136: 379–386. https://doi.org/10.1002/ajpa.20819.

World Health Organization. 2016. Pb poisoning and health. http://www.who.int/mediacentre/factsheets/fs379/en/, accessed April 22, 2016

Zaichick S, Zaichick V, Karandashev V, Nosenko S. 2011. Accumulation of rare earth elements in human bone within the lifespan. Metallomics 3: 186–194. https://doi.org/10.1039/c0mt00069h.

Ziegler EE, Edwards BB, Jensen RL, Mahaffey KR, Fomon SJ. 1978. Absorption and retention of lead by infants. Pediatric Research 12: 29–34. https://doi.org/10.1203/00006450-197801000-00008.