Journal of Archaeological Science: Reports xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

Hartnell's time machine: 170-year-old nails reveal severe zinc deficiency played a greater role than lead in the demise of the Franklin Expedition

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ARTICLE INFO

Article history:
Received 27 September 2016
Accepted 14 November 2016
Available online xxxx

Keywords:
Franklin Expedition
Lead poisoning
Zinc deficiency
Copper
Diet
Nails
LA-ICP-MS

ABSTRACT

The Franklin Expedition (1845–1848) left in search of the Northwest Passage and ended tragically with the loss of all crew members. Mystery surrounds their ultimate fate, with particular speculation around the role of lead poisoning. Our unique study turns nails from crew member John Hartnell into a time machine to determine what happened to the Franklin Expedition crew members. Using micro-X-ray fluorescence mapping, stable isotopic measurements, and laser ablation inductively coupled plasma mass spectrometry, we navigate through the nails and temporally characterize lead, copper and zinc content in our subject during the early expedition. By circumventing external contamination on exposed nail surfaces, we challenge the theory that crew members were exposed to high levels of lead on the expedition. Our analyses suggest that lead exposure actually decreased over the course of the expedition and Hartnell's levels were within a healthy, normal range. Our study also finds, however, that Hartnell was severely zinc-deficient, possibly leading to immuno-suppression and ultimately, tuberculosis and death. The significant weight loss from his illness resulted in a flush of previously stored lead from his bones into his blood (and nail), but only in the last few weeks of life. These findings provide new insight on the fate of the other crew members, including the role that diet and zinc deficiency played in the lives of stranded crew members before their demise.

1. Introduction

1.1. The Franklin mystery

The Franklin Expedition, commanded by Sir John Franklin, consisted of 24 officers and 110 men. They set sail from England on May 19, 1845 to find the Northwest Passage in the Canadian Arctic. The last written record from the expedition stated that the ships were abandoned on April 22, 1848, after being beset in ice since September 12, 1846; that Sir John Franklin died on June 11, 1847; and that the total loss of lives, at that time, was 9 officers and 15 men (Beattie and Geiger, 2004). Three of those men died during the first overwintering on Beechey Island in 1845/46: lead stoker, John Torrington; able seaman, John Hartnell; and Royal Navy Private, William Braine. Skeletons and bone fragments from some other crew members have been recovered, as well as scattered expedition artifacts (Beattie and Geiger, 2004), records of Inuit accounts (Woodman, 1991), and recently, the sunken ships, *HMS Erebus* (Barr, 2014) and *HMS Terror* (Hinchey, 2016). Despite these discoveries, mystery still surrounds the ultimate fate of Franklin's company.

Dr. Owen Beattie and his research team travelled to Beechey Island in 1984 and 1986 to exhume the bodies of Braine, Hartnell, and Torrington. Autopsies and X-rays of the bodies determined causes of death were likely tuberculosis and pneumonia (Beattie and Geiger, 2004; Amy et al., 1986). Chemical analysis of hair, soft tissue and bone collected from the bodies revealed unexpectedly high lead levels (Keenleyside et al., 1996), particularly for Torrington with 600 ppm in his hair (Beattie and Geiger, 2004). In comparison, Hartnell's head hair ranged from 138 to 315 ppm (Beattie and Geiger, 2004). High lead levels were not limited to those men: bone samples from other crew members who perished later in the expedition, found on King William Island, ranged from 62 ppm to 1740 ppm (Keenleyside et al., 1996). Estimation

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http://dx.doi.org/10.1016/j.jasrep.2016.11.042
2352-409X/

of blood lead levels based on tibia concentrations indicated that the Franklin crew exceeded the recommended upper limit for occupational exposure to prevent neurological changes (Keenleyside et al., 1996), although the estimations were based on the assumption that exposure only happened during the Expedition (i.e., 1845–1848). Additionally, high lead concentrations found in their soft tissues were interpreted to indicate recent exposure i.e., during the Expedition (Beattie and Geiger, 2004; Kowal et al., 1991). These past results led to the conclusion that the crew was likely exposed to toxic lead levels through tinned food consumption (Beattie and Geiger, 2004). During the mid-1800s lead comprised up to 90% of the solder used to seal food tins (Beattie and Geiger, 2004). Thus, lead has generally been linked to the Franklin Expedition crew's declining health, strange behavior recorded in Inuit testimony, and ultimately, their deaths (Beattie and Geiger, 2004; Amy et al., 1986; Keenleyside et al., 1996; Kowal et al., 1991; Martin et al., 2013; Battersby, 2008).

More recently, Battersby (2008) proposed that the lead exposure resulted from the ships' water supply system. Prior to 1845 both the *HMS Terror* and *HMS Erebus* were sailing vessels but in the months preceding the Franklin Expedition both ships were refitted with steam power. This required a one tonne freshwater supply reserve leaving little to no capacity for drinkable freshwater. A water distillation system was installed to generate drinking water and the pipes and storage containers in this system contained lead (Battersby, 2008).

Another possible source of lead exposure, proposed by Martin et al. (2013), was that the men were exposed to lead continuously throughout their lives. This conclusion was based on uniform lead concentrations and isotope distribution among bone layers. The Expedition occurred at the tail end of the Industrial Revolution, when elevated lead exposure and poisoning was common in England (Riva et al., 2012; Hernberg, 2000).

There are two other theories on health issues that may have led to the loss of the crewmen. Analysis of human skeletal remains found on King William Island suggested that scurvy may have occurred in some crewmen, particularly after they had abandoned the ships (Beattie, 1983). Scurvy is caused by a deficiency in vitamin C, and was common in sailors on long voyages until the late 18th century. However, during the time on the ships (May 19, 1845 to May 24, 1847) the crew had regimented doses of lemon juice for the prevention of scurvy. Accordingly, Mays et al. (2015) confirmed that analysis of available bones showed little to no evidence of the presence of scurvy on the Franklin Expedition; they concluded that prior to leaving the ships, other factors likely caused the deaths of 24 of the 129 crewmen. Horowitz (2003) proposed that botulism may have been responsible for the expedition's demise. Spores from an unspecified *Clostridium* species (responsible for botulism) were detected in the intestine of one of the exhumed sailors. Rushed and inadequate sealing of the expedition's tinned foods was thus theorized as to have caused widespread botulism, and ultimately, many deaths within the crew (Horowitz, 2003).

1.2. Going back in time

In this study, we have examined lead, zinc and copper exposure and carbon and nitrogen stable isotopes chronologically in one of the Franklin's crewmen, John Hartnell. We have identified the source of lead, and characterized the nutritional health (e.g., zinc deficiency) of Hartnell during the early expedition. We analyzed his nails using synchrotron micro-X-ray fluorescence (microXRF) mapping combined with stable isotope analysis and laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Our assessment was based on the principle that metals circulating in blood readily bind to living and growing keratinous tissues such as nails. As nails grow, metals are recorded along the length of the nail. Therefore, like bone (Keenleyside et al., 1996), nails can provide information on average body intake over an extended period of time. However, nails can also reflect changes in metal exposure over shorter periods of time (i.e., daily/weekly). These analytical methods have been successfully used for monitoring metal exposure in human nails (Rodushkin and Axelsson, 2000, 2003; Sakamoto et al., 2015; Grashow et al., 2014; Ponomarenko et al., 2014; Mehra and Juneja, 2005; Nowak and Chmielnicka, 2000) and human and wildlife hair where metal accumulation was linked to diet (Legrand et al., 2007; Noël et al., 2015, 2014), drinking water quality (Sela et al., 2007), and occupational exposure (Rodushkin and Axelsson, 2000, 2003; Nowak and Chmielnicka, 2000; Kempson et al., 2006, 2007; Niculescu et al., 1983). Here we present data from analyses of Hartnell's big toenail and thumbnail. These samples presented a unique opportunity to examine metal exposure and health in a Franklin Expedition crew member through time (Fig. 1).

2. Material and methods

2.1. Sample collection and preparation

John Hartnell's big toenail and thumbnail, originally collected by R. Amy and O. Beattie on June 18, 1986 (Beattie and Geiger, 2004; Amy et al., 1986), were obtained from a freezer housed at the Canadian Museum of History (Ottawa, Ontario), following approval of sample use by the Inuit Heritage Trust. Unfortunately, nail samples were not available from other crewmen. We also collected reference toenails (lost through trauma) from a living, healthy, male adult who consumes red meat regularly. Ethics permits were obtained from the University of Ottawa (permit #H01-15-09) and the University of Saskatchewan (permit #15-203).

The samples from John Hartnell are unique and thus we aimed to minimize our use of the samples to preserve them for future analyses. We cut a longitudinal section through the center of the nail approximately 3 mm wide that provided the longest section through time, and returned the unused portions of the nails to the museum. The thumbnail sample section (19.5 mm long) was divided into two pieces, lengthwise, for the following analyses: 1) micro-X-ray fluorescence (micro-XRF) mapping; and 2) laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). The toenail (22.5 mm long) was divided into three lengthwise segments for the following analyses: 1) micro-XRF mapping; 2) LA-ICP-MS; and, 3) stable isotope analysis. The reference toenail was sectioned for microXRF mapping analysis.

To remove as much external contamination as possible, nail sections were first wiped gently with a Kimwipe, followed by application of the standard washing procedure developed by the International Atomic Energy Agency (IAEA) (Ryabukin, 1978). Briefly, the samples were rinsed with acetone for 5 min, stirring constantly. The liquid was then decanted and the procedure was repeated twice with deionized water. The washing process was repeated again, and then nails were left to dry at room temperature for an hour.

2.2. Timeline assumptions

Growth rates for nails were based on de Berker et al. (2007) who recommended a “reasonable guide of 3 mm/month”. This value was used to calculate from the date of death (root of the nail; January 4, 1846) the various timeframes along the remaining length of the nail. Based on these assumptions, we estimated that the thumbnail represented the time period June 22, 1845 to January 4, 1846, and the big toenail represented the time period May 23, 1845 to January 4, 1846.

2.3. Nail embedding

Nail segments were embedded prior to microXRF imaging. Methods for nail embedding were modified from Korbas et al. (2008). Briefly, the nail segments were fixed in 4% paraformaldehyde (5 min), rinsed in water, washed in acetone (5 min), and rinsed with water. The nail segments were then cut into 2 or 3 pieces 6.5–10 mm in length so they would fit in the resin mold, embedded in 2% low melting point agarose

Please cite this article as: Christensen, J.R., et al., Hartnell's time machine: 170-year-old nails reveal severe zinc deficiency played a greater role than lead in the demise of the Fra..., Journal of Archaeological Science: Reports (2016), http://dx.doi.org/10.1016/j.jasrep.2016.11.042