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"Hartnell's Time Machine" reprise: further implications of zinc, lead and copper in the thumbnail of a Franklin expedition crewmember

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Abstract

Christensen *et al*. (2016) have described the application of synchrotron micro-X-ray fluorescence mapping, stable isotopic analysis and laser-ablation inductively-coupled plasma mass spectrometry to provide a unique and dynamic time scale of the concentration of metals in the thumbnail of John Hartnell who was a member of the 1845 British Royal Naval “Franklin expedition” which met a fatal end in the Arctic. Their finding of low levels of lead and zinc in Hartnell’s thumbnail has questioned the supposed lead-poisoning of the crew and introduced a new hypothesis that zinc deficiency contributed to the loss of the expedition. It is proposed here that their innovative and intriguing hypothesis might be considered cautiously in light of uncertainty as to the reliability of nail as a biomarker of zinc deficiency and calculations that the Royal Navy’s provisioning of its Arctic ships would have provided adequate dietary zinc. Whilst there may be difficulty in interpreting the *absolute* levels of zinc in the nail, the *change* in the levels over time may provide unique insights. It is agreed that exponential increases in levels of zinc, copper and lead seen in the weeks prior to Hartnell’s death from pulmonary tuberculosis might reflect endogenous release of the metals due to tissue catabolism. It is further proposed that the increase in those metals also reflects the administration by the expedition’s surgeons of lead, zinc and copper-containing medications which were widely used to relieve the distressing symptoms of tubercular disease.

Keywords

Franklin expedition, zinc deficiency, lead poisoning, tuberculosis, medical intervention

1. Introduction

1.1 Investigating the loss of the Franklin expedition

The deaths of all 129 men of the British Royal Naval expedition of 1845 to establish a Northwest Passage under the command of Captain Sir John Franklin remain the greatest single loss of life in Polar exploration (Lambert 2009; Potter 2016; Savours 1999). Significant understanding of the expedition's fate began with autopsies of the permafrost-preserved bodies of John Hartnell, William Braine and John Torrington who died at the first winter quarters at Beechey Island (Beattie and Geiger, 2004). In addition to evidence of tubercular disease, levels of lead in their bone and soft tissue, and in skeletal remains from King William Island, led to the hypothesis that the crew had suffered lead poisoning (Amy *et al*., 1986; Keenleyside *et al*., 1996; Kowal *et al*., 1989; Notman and Beattie, 1995). The supposed role of scurvy (Cyriax, 1939) has not been supported by skeletal analysis (Mays *et al*., 2015).

1.2 Chronology of accumulation of zinc, copper and lead in John Hartnell

Most recently, Christensen *et al*. (2016, Figures 5 and 6) have applied synchrotron micro-X-ray fluorescence mapping, stable isotopic analysis and laser-ablation inductively-coupled plasma mass spectrometry to the thumbnail of John Hartnell to provide a time-line of concentrations of zinc, lead and copper from June 1845 until his death on 4th January 1846. They describe the nail as a "time machine" that relates the chronology of events in Hartnell's life to variation in levels of the metals. The present focus is upon the implications of their innovative analysis for the crew's nutritional state, lead poisoning and medical intervention by the expedition's surgeons.

1.3 The supposition of zinc deficiency

Christensen *et al*. (2016, Figure 5) showed that one month after leaving England in May 1845, the level of zinc in the inner layer of Hartnell's nail was ~30 ppm. The level varied cyclically between ~30 ppm and ~60 ppm to mid-September when the peak level then increased to 65 ppm until mid-November (the later exponential increase prior to Hartnell's death is discussed in Section 4.2 below). Christensen *et al*. compared the levels of zinc in Hartnell's nail with "reference data" showing nail zinc of 80-191 ppm in 96 healthy inhabitants (aged 1-76 years) of northern Sweden (Rodushkin and Axellsson, 2000) and proposed that Hartnell's nails reflected a chronic zinc deficiency that may have affected the whole crew. This proposal must be considered cautiously for several reasons. First, healthy subjects are reported with lower levels of nail zinc than Hartnell (İlhan et *al*., 2004). Secondly, the WHO endorses serum or plasma zinc as a biomarker of the metal (de Benoist *et al*., 2007), a standard that is supported by a systematic review which concludes that there are insufficient studies of several potential biomarkers, including nail, to determine whether they reflect zinc status (Lowe *et al*, 2009). Thirdly, Wieringa *et al*. (2015) observe that there is no specific biomarker related to zinc deficiency *per se*, being consistent with the WHO's observation that whilst serum and plasma zinc are biomarkers of the metal they do not necessarily reflect the individual's zinc status.

The evidence above makes it difficult to determine whether the levels of zinc in Hartnell's nail indicate a deficiency and must question the validity of the conclusion of Christensen *et al*. that "severe zinc deficiency played a greater role than lead in the demise of the Franklin expedition". However, whilst the *absolute* level of zinc may be difficult to interpret, it will be shown in Sections 4.1 and 4.2 that the *relative* changes in the levels of zinc, copper and lead over time do provide a unique and valuable insight to the course of Hartnell's illness and his medical treatment in the weeks leading to his death. Thus, the implications of variation in levels of the metals in the nail over time would still justify the metaphor of the "time machine" applied by Christensen *et al*.

First, however, it is important to examine whether there is objective evidence to support two circumstances proposed by Christensen *et al*. that might have contributed to a crew-wide deficiency in zinc. They proposed that a deficiency might have occurred if the canned meats supplied to the expedition were "not appreciably zinc-rich" and if, in addition, a proportion of those provisions were unfit for consumption thus causing a reduction in the daily meat ration. If both conditions occurred, then zinc deficiency might have affected the whole crew.

These proposals can be examined objectively, first by calculating whether the zinc content of Royal Naval Arctic rations would satisfy present-day recommendations for dietary intake of the metal; secondly by considering the evidence for unfit provisions; thirdly by considering whether the expedition's progress was consistent with a crew-wide deficiency of zinc.

2. Royal Naval Arctic rations

2.1 Calculating the zinc content of meat rations

Rations for Royal Naval ships sent in search of Franklin were described by Armstrong (1858 p14) and allow estimation of a typical crew's dietary zinc. Table 1 shows the weekly rations of preserved (canned) meats, salt beef and salt pork after Armstrong, and the "imaginary" scale of rations composed by Cyriax (1939, p 42) from his assumed consumption of provisions by the expedition. The expedition's preserved meats consisted principally of roasted beef and mutton (ADM 114/17). Estimation of their zinc content must be cautious because they may not be fully comparable with present-day products. Visual inspection of preserved meat from the Franklin expedition conserved in the National Maritime Museum shows it to be predominantly lean meat with moderate fat content (Royal Museums, Greenwich). The "Composition of Foods Integrated Dataset" of Public Health England (2015) provides the zinc content (mg/100g) of 23 samples of roasted "lean and fat" cuts of beef and lamb (as "mutton" is not included the zinc values for "lamb" have been selected instead). Calculation of the median zinc content of those meats estimates the expedition's preserved meats to have contained 4.6mg zinc/100g. Values for salt beef and salt pork are 4.6mg/100g and 0.9mg/100g, respectively, from the nutrient tables of the US Department of Agriculture (2008).

The Royal Navy's weekly ration per man was 1190.7g of preserved meats and 595.3g of salt beef or pork (issued on alternate days), therefore providing a daily total of 12.5mg zinc according to the values estimated above (see Table 1). However, Armstrong (1858, p 14) observed that a serving of preserved or salt meat typically contained 75% meat product, the rest being jelly, sinew or bone. When a 25% reduction is applied to Table 1, the intake of zinc is 9.4mg/day. Cyriax's estimate corresponds to 7.4mg/day when reduced. As the current recommended range of dietary zinc for men in the UK is 5.5 to 9.5 mg/day (www.nhs.uk/conditions/vitamins-minerals/), the Royal Naval rations would have provided adequate zinc.

2.2 The quality of provisions

Christensen *et al*. (2016) observed that concerns were raised in 1850 that the preserved meats supplied by the manufacturer, Goldner, might have been unfit for consumption, potentially leading to starvation if rations had to be reduced (see Cyriax 1939). They propose that zinc deficiency might then have affected the whole crew. Whilst it is correct that Goldner was involved in a later scandal concerning his products, a British Parliamentary investigation found that his supplies to the Franklin expedition had been of satisfactory quality and exonerated him: Lloyd and Coulter (1963, pp 96-102) noted the neglect of this fact by some historians.

2.3 The expedition made good progress over the first two years

If Franklin and his experienced officers had been faced with depleted provisions and a crew debilitated by zinc deficiency within only months of leaving England, it would seem unlikely that they would have continued with the mission. Franklin's sailing orders explicitly required him to protect the health of his men and he had full authority to return home if the ships required resupply rather than commit the crew to hardship (Orders 9 and 10: Ross, 1855). The expedition is known to have over-wintered successfully from 1845 to 1846 at Beechey Island where the men constructed winter quarters, conducted man-hauled sledge operations and built cairns: such strenuous activities would seem incompatible with a crew-wide zinc deficiency. The fact that in May 1847, two years after departure, a senior officer signed off a report stating "*All Well*" (and he underlined it for emphasis) would seem inconsistent with any serious circumstances affecting the crew. Moreover, the Inuit reported that it was not until three years later, in 1850, that they encountered crewmen debilitated by starvation (Woodman, 1991 p26).

3. The health of John Hartnell

3.1 Zinc deficiency

If the provisions were unlikely to cause crew-wide zinc deficiency, and setting aside doubts about nail as a biomarker, it remains possible that Hartnell alone suffered such a deficiency. The question might be answered from the autopsy of John Torrington who died three days before Hartnell and whose nails were sampled with other tissues (Amy *et al*., 1986, p115). Regrettably, it appears that Torrington's nails were not available for examination by Christensen *et al*. (2016).

If it is assumed that dietary zinc was stable and adequate, then variation in nail-zinc content may reflect fluctuation in its absorption by Hartnell. Recurrent dysenteric and diarrhoeal illnesses affected a proportion of Arctic crewmen (Millar *et al*., 2016) and are associated with malabsorption, as are functional and inflammatory disorders of the bowel, and where tubercular disease affects the lymphatic system to cause intestinal lymphangiectasia (of relevance in view of evidence in Section 3.2 below of tubercular disease in Hartnell's mediastinal lymph nodes). Zinc is largely absorbed in the jejunum: the level in Hartnell's nail shows a cyclic rise and fall which might reflect episodes of intestinal malabsorption (and medical intervention: see Section 4.2). Copper is absorbed primarily in the stomach which may explain its stable level compared to that of zinc (Christensen *et al*. Figure 5). If Hartnell had suffered a chronic intestinal disorder it would have been recorded by the expedition's surgeons but their medical journals are lost. However, the surgeons' autopsy of Hartnell may offer further insight.

3.2 The two autopsies of John Hartnell

When Hartnell was exhumed for autopsy in 1986, Notman *et al*. (1987) discovered that he had been subject to a previous autopsy. It is known that his corpse was disturbed in a clandestine exhumation during searches for the expedition in 1852 (Inglefield, 1852) but, as there is no evidence that an autopsy was attempted then, it can be assumed that the previous autopsy was conducted by the expedition's surgeons at the time of Hartnell's death.

In their own autopsy, Notman et al. (1987) and Notman and Beattie (1995) reported evidence of probably tuberculous calcified granulomas in the lungs and mediastinal lymph nodes, and proposed that a final fatal illness might have been pneumonia associated with a reactivation of pulmonary tuberculosis.

Royal Naval surgeons were only required to conduct an autopsy when death was sudden or unexplained (His Majesty's Stationery Office, 1835). If Hartnell's death was caused by so common a 19th-century illness as pulmonary tuberculosis then it might be surprising that it merited an autopsy. Setting aside mere curiosity on the part of the surgeons, the fact that they conducted an autopsy whose unusual execution implied a focus on the lower abdomen might imply that they suspected a secondary intestinal disorder. An autopsy is usually conducted via a Y-shaped incision where incisions at the acromia meet at the xiphisternum at the midline and extend downwards to the symphysis pubis. However, an 'inverted-Y' incision was used for Hartnell where incisions from the iliac crests met at the umbilicus and extended upwards to the sternum (Beattie and Geiger, 2004 p217).

Such an execution cannot be found as part of routine practice in pathology at the time (personal communication: Dr. M. Addison, 27th March 2014). It might reflect the idiosyncratic practice of one or both surgeons but might also indicate their focus upon the bowel because the incision would afford better access to the pelvic viscera (personal communication: Dr J. Shaw-Dunn, 6th March 2014). However, the bowel was found not to have been examined (Beattie and Geiger, 2004 p219); rather, dissection was made of the ventricles of the heart, the liver and the roots of the lungs (Notman *et al*., 1987), the latter being consistent with a suspected diagnosis of tuberculosis. The autopsy appeared to have been cursory and completed in haste because Notman *et al*. (1987) observed that the dissected organs were replaced in a disordered mass and the sternum and ribs re-inserted upside-down.

The non-dissection of the bowel would imply that the surgeons did not suspect an intestinal disorder. No examination had been made of Hartnell's brain which might also imply that he had not exhibited the behavioural or mood disturbances sometimes associated with zinc deficiency (and lead poisoning) that the surgeons might have interpreted as evidence of an intra-cranial lesion. It is conceded, however, that the conclusions above must be tentative because the purpose of the surgeons' autopsy remains unknown in the absence of their medical records. It must also be recognised that the surgeons' decision-making drew upon contemporary medical knowledge which might have led to different interpretation of symptoms than today (see Guly, 2012, 2013) and which may then have influenced their focus in an autopsy.

4. Lead in the Franklin crew

4.1 Exogenous and endogenous sources

The bodies of Hartnell and his two shipmates were found to contain relatively high levels of lead in bone, soft tissue and hair (Amy *et al*., 1986; Kowal *et al*., 1989, 1991), leading to the hypothesis that lead-solder which sealed the canned provisions had caused debilitating poisoning (Beattie and Geiger, 2004). The hypothesis has generated much debate and has been questioned on grounds including the low levels of lead in canned provisions supplied to other Arctic crews, the high exposure of the Victorian population to lead, and statistical modelling of the distribution of lead across Franklin's men (Drummond and Lewis 1939; Farrer 1993; Millar *et al*., 2015). Martin *et al.* (2013) have conducted Synchrotron X-RF and Laser ICP/MS analysis of the distribution and concentration of lead in skeletal material to conclude that there was significant exposure to lead prior to joining the expedition but no evidence of a significant increase during the mission. Swanston *et al*. (2016) have applied the same technique to skeletal material from the Franklin expedition and other Royal Naval remains to confirm the ubiquity of exposure to lead.

Uniquely, Christensen *et al*. (2016, Fig. 6) showed that a U-shaped function described the level of lead in Hartnell's thumbnail over time. One month after departure in May 1845, levels were high (206ppm in the inner layer to 750ppm in the underside surface) probably reflecting exogenous contamination of the nail overhang, but declined markedly (inner ~1ppm; underside ~5ppm) and remained low and stable until mid-November. If the nail reliably reflects ingestion of lead then the levels might imply low exposure during the mission, but Barbosa *et al*. (2005) have cautioned that the poor reproducibility of levels of lead within an individual's nails must limit the scope of the biomarker.

Again, however, it is the relative change in the level of lead, rather than its absolute value, that is of potential significance. In the month prior to Hartnell's death on 4th January 1846, levels of lead in his thumbnail rose exponentially and were ascribed by Christensen *et al*. to the release of endogenous lead from the tissues from illness-induced catabolism (Lowe *et al*., 2009): to this can be added the probability of an effect of medication.

4.2 Medical intervention with lead, zinc and copper

Hartnell's pulmonary tuberculosis ("phthisis") would have been readily diagnosed, being the leading cause of death amongst men of his age (Woods and Shelton, 1997). It is assumed that when other sick crewmen were sent home from Greenland in early July 1845, Hartnell was either non-symptomatic, did not disclose his symptoms or, as could happen in early stages of the illness, was misdiagnosed (Durrant, 1842). The progression from vague symptoms including cough and fatigue to haemoptysis, fever, emaciation and death, occurred predominantly within four to nine months of the diagnosis of "phthisis incipiens" (Clark, 1834; Durrant, 1842). On this basis, Hartnell's diagnosis may have been confirmed in late-August 1845.

The surgeons would not have passively observed Hartnell's decline but would have intervened to relieve his increasingly distressing symptoms of haemorrhage, profuse night sweats and diarrhoea. The expedition's Royal Naval medicine chests contained acetate of lead (His Majesty's Stationery Office, 1835) which, in various forms and doses, was administered to reduce pulmonary haemorrhage, diarrhoea and sweating (Elliotson, 1839 p762; Pereira, 1839 p517; Thomson 1837 pp 692-696). Evidence for this intervention may be seen in the extremely high levels of lead in the stomach tissue of Hartnell and his two shipmates when compared to present-day lead-exposed groups (Kowal *et al*., 1991) and which might imply acute ingestion shortly prior to death. It might also reflect medical administration of "wine for the sick" which provided comfort rather than treatment but was contaminated with lead when served in pewter vessels and when sweetened with acetate of lead (the expedition received 200 gallons / 909 litres of such wine: ADM 114/17). High levels of lead found in the kidney might also imply acute ingestion (Kowal *et al*., 1991).

Levels of zinc and copper also increased markedly in Hartnell's final weeks (Christensen et al., 2016, Figure 5), again potentially reflecting both catabolism and medical intervention. Zinc sulphate was provided in Royal Naval medicine chests as "*zinci sulphatis*" for use as an emetic and antispasmodic, being administered at short, regular intervals to relieve respiratory difficulty in phthisis (Clark 1834; Dunglison 1845): the cyclic rise and fall in zinc in the nail might reflect such a treatment course. Copper sulphate as "*sulph. cupriatis"* relieved remitting fevers in phthisis and, with opium, controlled the associated diarrhoea (Ryan, 1835). Such treatments would have relieved Hartnell's symptoms, and might have contributed to the increase in the metals in his thumbnail and to the high levels of lead in the soft tissues observed by Kowal *et al*. (1991). However, it is conjecture without evidence from the medical records as to the surgeons' actions.

5. Conclusions

Christensen et al. (2016) have applied an innovative analysis to provide fresh insight to the final months of John Hartnell. The proposal that zinc deficiency affected the whole crew is intriguing but the authors themselves note that their speculation is based on one individual. It must also be questioned in light of uncertainty as to the reliability of nail as a biomarker of deficiency, the estimated adequate zinc content of Royal Naval rations and other considerations including the first-hand report of a senior officer that all was well after two years on mission. Whether Hartnell uniquely suffered zinc deficiency may remain open. However, of greatest significance is the unique evidence of the exponential increase in levels of lead, zinc and copper in the final weeks of Hartnell's life which may reflect both endogenous release of those metals by catabolism and the interventions of the expedition's surgeons to relieve the symptoms of his pulmonary tuberculosis.

Author contributions

KM is the corresponding author who devised the study and collected the data from the sources cited in the text. KM and AWB jointly conducted the analysis and drafted the manuscript.

Conflict of interest

The authors declare that they have no conflict of interest.

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Rations		Preserved meat	Salt beef	Salt pork	Zinc total (mg)	
					Weekly	Daily
Royal Navy	**Weekly ration (g)**	1190.7	595.4	595.4		
	Zinc content (mg)	54.8	27.4	5.4	87.6	12.5
	Zinc -25% (mg)*	41.1	20.5	4.0	65.6	9.4
Cyriax	**Weekly ration (g)**	680.4	680.4	680.4		
	Zinc content (mg)	31.3	31.3	6.1	68.7	9.8
	Zinc -25% (mg)*	23.5	23.5	4.6	51.6	7.4

Table 1. The weekly ration per man of preserved and salt meats (g) and the equivalent daily zinc content (mg) according to the Royal Navy schedule of Arctic victualling (Armstrong, 1858) and Cyriax's (1939) "imaginary" rations consumed by the Franklin expedition. * Denotes the 25% reduction in zinc content to correct for jelly, sinew and bone in preserved and salted meats (see Section 2.1).

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