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Excessive Mercury Exposure During Beethoven's Last Months Revealed in Two Authenticated Hair Strands

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Abstract

Hair can provide longitudinal records of toxic metal exposure, but distinguishing endogenous incorporation from external contamination remains a major limitation. Two authenticated hair strands from Ludwig van Beethoven on his death bed (1827) were analyzed using double-ablation LA-ICP-MS. Mercury and zinc had near perfect reproducibility between hairs consistent with an endogenous, chronological record. Mercury abruptly increased by 300% in October 1826 coinciding with documented health deterioration and potential use of mercuric medicine. A subsequent and steady decline in mercury follows the historically reported discontinuation of conventional medicines that occurred after 11 January 1827. In contrast, highly elevated lead, arsenic, and magnesium followed a distinct offset between strands that did not match the chronological axis. Their elevated detections in the inner cortex layer are consistent with penetrative external contamination from an aquatic source. Only with the analysis of two strands could endogenous exposure be distinguished from spatial contamination.

Introduction

Human hair strands can preserve a record of metal exposure as they become incorporated and locked into the keratin structure during hair formation along a chronological growth axis. Longitudinal analysis has therefore been used in environmental biomonitoring, occupational and forensic toxicology, archaeology, nutrition and historical investigations for toxic metal exposure1–3. Laser ablation inductively coupled with plasma mass spectrometry (LA-ICP-MS) extends this capability by providing sub-millimeter elemental profiles from individual strands4–10. The principal limitation in the use of hair is the challenge of differentiating endogenous and exogenous source attribution to the strand 3,11–13. Hair emerging from the scalp remains exposed to water, sweat, sebum, topical treatments, and dust. Some contaminants remain in or on the outer cuticle layer, whereas dissolved elements can penetrate into the inner cortex layer, particularly after repeated wetting, chemical alteration, prolonged ageing and diagenesis10,14–15. Consequently, detection of elevated metals in the protected inner cortex does not, by itself, establish endogenous incorporation12. Many high-resolution hair studies analyze one strand and assume that the hair length represents the same chronological axis for all elements 16–20. However, external contamination is independent of time and instead will fall along a spatial axis. These axes cannot be differentiated with the analysis of a single hair. Rather, it would take at least two independent strands to achieve this. Specifically, if endogenously incorporated elements record the same exposure history, their profiles should align from root to tip along a “chronological” axis driven by growth rate, but only after accounting for the different distances at which the strands were cut, if no roots are present. Conversely, exogenous contamination sources may instead align according to the spatial relationship of the hairs when a fluid or surface source contacted them – “spatial” axis. This study analyzes two independent hair strands from Ludwig van Beethoven during his final months. Beethoven provides an unusually informative and historically fascinating case study because his final illness is documented through correspondence, conversation books, physician accounts, and autopsy records 21–23 with medical practice 200 years ago being considerably different than today. His health history included progressive hearing loss, chronic gastrointestinal illness, severe wasting, ascites,

jaundice, and advanced liver disease before his death on 26 March 1827 17,21–23. However, many questions remain regarding the direct cause(s) of his illnesses, his deafness, his death, and exact medical treatments used to manage them 21. Two days prior to his death, a lock of Beethoven's hair was cut by his close friend, Anton Schindler, on 24 March 1827, and sent to Ignaz Moscheles – the "Moscheles Lock". This lock was authenticated as belonging to Beethoven 22,23. The focus of the hair analysis is on mercury, lead and arsenic as toxicologically relevant elements, based on previous reports and controversy around their detection at elevated levels 17,21–28. Specifically, longitudinal lead results from the Hiller Lock (formally known as the Guevara Lock) and the Halm Lock showed elevated lead levels associated with possible medical treatments in the final months of Beethoven's life 17,24–25. However, genomic studies later demonstrated that the Hiller Lock was from a female 22,23. Rifia et al. 26 reported elevated lead, mercury and arsenic in both the authenticated Halm-Thayer Lock from April 1826 and the Bermann Lock collected sometime between 1820 and 1827. However, only a single concentration for each element was provided, as opposed to a detailed, longitudinal profile along the strands. Those hairs also pre-date the final months of Beethoven's life, which the Moschele Lock can represent. The objectives of this study were to use duplicate hair strand analysis to: 1) differentiate exogenous and endogenous sources for each element; 2) apply correlation (or lack of) to evaluate possible shared sources; and 3) characterize the endogenous metal chronology with Beethoven's known historical and medical records.

Methods

Hair samples and provenance

Two hairs, 69 and 83 mm in length, were selected from the Moscheles Lock. Genetic analysis confirmed the association of the Moscheles material with the concordant group of Beethoven hair samples [22,23]. Microscopy indicated intact cuticle structure, no obvious diagenesis, and mean diameters of approximately 87.7 ± 3.2 and 91.9 ± 4.9 µm along the lengths. Growth direction was assigned from cuticle orientation. The hairs were cut rather than plucked; therefore, root bulbs and the most recent below-scalp growth were absent.

Double-ablation LA-ICP-MS

Analysis was performed at TrichAnalytics Inc. (Saanichton, British Columbia, Canada), an ISO/IEC 17025:2017 accredited laboratory. Hairs were handled with clean non-metallic tools and mounted longitudinally on glass slides with double-sided adhesive tape. Minimal cleaning with acetone and deionized water removed loose debris while avoiding aggressive treatment that could compromise inner cortex elemental composition.

The elements were measured using an iCAP RQ ICP-MS connected to an NWR-266 laser ablation system with helium carrier gas at 800 mL/min. Each hair underwent two longitudinal passes, termed "double ablation" [6,10,12]. The first ablation targeted the cuticle and surface-associated material (50-µm spot, 4%

power, 75 µm/s, 10 Hz). The second sampled the remaining inner shaft/cortex (30-µm spot, 4% power, 75 µm/s, 50 Hz). DORM-5 certified reference material was analyzed for calibration and quality control, and sulfur was used as the internal standard at 40,000 mg/kg (4%). Accuracy ranged from 96 to 108%, with precision < 20%. Only inner cortex concentrations are reported here, and all elements were detectable along the length in both hairs (detection limits: S: 200 mg/kg; Mg: 0.1 mg/kg; Zn: 0.65 mg/kg; Hg: 0.083 mg/kg; and Pb: 0.01 mg/kg). Raw concentrations were integrated as the median of 13 consecutive datapoints, representing approximately 0.3 mm of hair length.

Hair strand alignment, regression, and source grouping

As both hairs were cut from the scalp, it was not possible to align the hairs to the root, as the chronological anchor. Therefore, the hairs were aligned using the longitudinal profile of zinc. Zinc was selected because previous work indicated substantially less susceptibility to external contamination of the cuticle and cortex [12] and thereby reflects more reliable endogenous representation along a chronological axis. The preferred alignment of zinc was statistically evaluated and selected using Pearson correlation ($p < 0.05$) of datapoints at various hair offsets, with evaluation of no-intercept R^2, slope ideally near 1.0, and visual agreement in profile shape. The preferred alignment for the other elements was determined independently at various hair offsets and also selected based on a significant Pearson correlation ($p < 0.05$), high no-intercept R^2, slope near 1.0, and visual inspection of profile agreement of major peaks, troughs, and transitions aligned without progressive stretching or compression. Elements sharing a preferred offset were considered to occupy the same positional framework; and correlation among those elements was used to evaluate whether they likely shared a source. All statistics were conducted using RStudio (Version 1.4.1106).

Calendar assignment

Calendar dates were assigned after accounting for estimated proximal hair loss from cutting. The estimated chronological assignment was based on a combination of biological and historical information: 1) average follicle depth on the scalp is approximately 4 mm [29]; 2) hair growth rate of ~ 1 cm/month [30]; 3) despite severe illness, Beethoven's hair was still growing based on Ferdinand Hiller's eyewitness account of Beethoven shortly before his death where he describes him as "unshaven, his full, half-gray hair falling disheveled over this temples" [21]; and 4) the sketch of Beethoven on his deathbed by Josef Eduard Teltscher confirming hair length to the temples of ~ 8–10 cm long.

Results

Duplicate Hair Offsets Differentiate Chronological and Spatial Variability

The principal finding is that one chronological and/or spatial alignment did not explain all elements. Rather, the inner cortex elemental profiles separated into two reproducible offset groups. Zinc, the chronological anchor, exhibited a 16.6 mm offset between the two hairs, with a near perfect correlation ($p < 0.0001$), $R^2 = 1.00$, and visual alignment of pattern (Table 1). Hair 2 extended further proximally (i.e., was cut closest to the scalp) and therefore, its proximal end represents the closest in time to Beethoven's death. As such, Hair 2 was estimated to represent 21 July 1826 to 2 March 1827 (224 days) and Hair 1 was estimated to represent 1 July 1826 to 21 January 1827 (204 days). Unfortunately, it is estimated that the last ~ 24 days of Beethoven's life were lost from the hair record due to the cutting of the locks.

Table 1
Between-hair relationships for selected cortex profiles after element-specific alignment.

Element	Preferred offset (mm)	Slope	R^2	p value
As	5.1	0.80	0.88	< 0.0001
Mg	5.1	0.93	0.98	< 0.0001
Pb	5.1	0.89	0.97	< 0.0001
Zn	16.6	1.04	1.00	< 0.0001
Hg	16.6	1.01	0.99	< 0.0001

The preferred alignment for mercury was also at 16.6 mm, and again, with near perfect statistical alignment ($p < 0.0001$; $R^2 = 0.99$; slope = 1.01) and visual alignment of pattern. Therefore, mercury variability is reported with zinc along a chronological axis.

Arsenic, magnesium, and lead did not align at 16.6 mm, but rather all had preferred alignment at 5.1 mm. While all alignments were significant ($p < 0.0001$) these elements had less perfect comparability between hairs, with Hair 2 approximately 10–20% lower in concentration, on average, for all three elements. As these elements do not conform to the chronological axis, they are reported along a spatial axis.

Exogenous variability along the strands (Arsenic, Lead, and Magnesium)

Lead increased from the distal end of the strands from ~ 100 mg/kg to > 250 mg/kg (Fig. 1). Magnesium also increased from the distal end from ~ 100 mg/kg to 200 mg/kg in both strands. Lead and magnesium exhibited closely corresponding longitudinal variation with highly correlated concentrations for both Hair 1 ($p < 0.0001$) and Hair 2 ($p < 0.0001$), with lead 40% higher, on average, than magnesium. Arsenic followed an independent spatial pattern along the strands. Concentrations were 300% higher at the distal end (at ~ 15 mg/kg) relative to the proximal end at ~ 5 mg/kg.

The strong correlation between magnesium and lead spatially on two hair strands supports a common exogenous source. Their detection at elevated levels in the inner cortex layer indicates penetration through the protective outer cuticle layer by a dissolved, aqueous source rather than superficial particulate contamination [10,12,14]. Potential sources include magnesium-rich water that acquired lead from vessels, plumbing, fittings, glazes, or treatment materials; a washing or medicinal fluid; or a body fluid containing physiological magnesium and elevated lead [31]. This latter source is an interesting hypothesis, as Beethoven underwent a total of four paracenteses in the last months for relief of ascites, where between 7.7 and 14 liters of fluid were drained from his abdominal cavity each time [21]. During the operations, and in the days following the procedures, body fluids could easily have contaminated his hair. Davies [21] wrote a section on "The Leaking Wound and the Bedsores", which reports oozing for up to 11 days post-surgery, extra bedding, and a bowl placed under the bed along with hay to collect drippings. If his body fluid was the source of contamination at those extremely high lead levels, it is probable there was previous endogenous lead exposure. Lead exposure was common in the 1800s, and for Beethoven specifically, endogenous exposure sources could have included drinking water, food, adulterated wine, lead utensils and dishes, and even medical treatments for diarrhea and abdominal swelling (e.g., lead acetate) [31]. It is just not possible to quantify those levels due to the confounding external contamination of these hairs.

Arsenic followed an independent spatial pattern along the strands. Concentrations were highest at the distal end by 300% relative to the proximal end. As with lead and magnesium, the elevation in the inner cortex layer, particularly at the distal end, supports a fluid-mediated process. Potential sources include contaminated water, medicinal preparations, topical remedies, and washes [32]. The extended and consistent arsenic enrichment observed in both hairs at the distal end could suggest a localized and sustained external source rather than a short-duration contamination event. The combination of spatial localization, reproducibility between hairs, and penetration into the cortex is consistent with prolonged contact with an aqueous arsenic-containing material, potentially a topical preparation, wash, or wetted compress.

Endogenous variability along the strands (Mercury)

From July to October 1826, mercury concentrations are at ~ 2 mg/kg (Fig. 2) considered normal for individuals consuming fish occasionally [12,33,34]. Of note, there are two or three mercury exposure events with increase of 20–50% during this period: 23 July, 6 September and 1 October 1826. At least the latter two of the three mercury excursions were likely diet-related (e.g., fish, methylmercury). Studies show that fish-derived mercury (methylmercury) exposure coincides with increased zinc exposure resulting in a parallel increase in the hair of the two elements [8,9]. Both mercury and zinc share this parallel pattern on 6 September and 1 October, particularly (Fig. 3).

However, two weeks later, on 19 October 1826, during Beethoven's stay with his brother, Johann, at Gneixendorf (Fig. 3), there was an abrupt increase in mercury of 300%, that is not parallelled with

increasing zinc, which argues against a dietary (i.e., fish) source of mercury. Additionally, an increase in methylmercury to that extent over such a short period of time would require implausibly high fish intake [8,9,35].

Figure 3. Chronological and parallelled changes in mercury and zinc concentrations in the inner cortex of Beethoven's Hair 1 strand suggest a dietary (fish) source of methylmercury for these excursions early in the hair record. Mercury and zinc concentrations deviate mid-October.

A mercuric medicinal source is therefore more plausible. Mercurial compounds, including calomel, were historically used as aperients, purgatives, and treatments for gastrointestinal disorders [36]. As is recorded, during the Gneixendorf period, Beethoven experienced poor appetite, diarrhea, abdominal discomfort, swelling, excessive thirst, weight loss, and progressive deterioration [17,21] which may have triggered treatment with a mercuric compound like calomel. Mercuric treatment at early onset of symptoms in October may even have exacerbated the symptoms. As such, excessive levels of inorganic mercury can cause and worsen gastrointestinal illness, anorexia, weight loss, and renal injury [18].

While 6 mg/kg of methylmercury in hair is not considered acutely toxic, inorganic mercury in hair at that concentration has been associated with toxicity and even death. Suzuki [18] reported peak hair mercury of approximately 4 to 8 mg/kg after mercuric chloride ingestion, while Stadlbauer et al. [6] reported 8 to 12 mg/kg in the inner cortex following a fatal HgO poisoning. Wands et al. [37] report hair mercury concentrations at 9.7 mg/kg and 13.5 mg/kg for a patient that died from complications associated with chronic mercuric chloride laxative use. These comparisons suggest that Beethoven may have experienced an excessive, possibly acutely toxic inorganic mercury exposure at a time of health deterioration, and prior to the recorded physician care which did not commence until December 1826 in Vienna. While it is not possible to identify the exact dose, mercuric form, or source, the timing of the exposure suggests plausible access to mercuric compounds at his brother's residence in Gneixendorf. Interesting to note, Johann had once been a prominent and successful apothecary but sold his business in 1819.

Beethoven hastily returned to Vienna on 2 December 1826 due to his failing health and worsening condition. Dr. Wawruch began treating Beethoven on 5 December, with extreme pain and swelling recorded on 10 December, and accounts describing treatment aimed at bowel excavation with "aperients and purgatives" [21]. Calomel, a mercuric compound, was one possible contemporary purgative [36]. The hair record contains two to three small mercury excursions during Dr. Wawruch's treatment regimen between 12 December and 10 January 1827, consistent with the possibility of repeated mercuric exposure during this treatment period. On 11 January 1827, following a physician consultation meeting with other physicians, including Dr. Malfatti, the medical treatment strategy was changed to a cessation of all conventional medicine [21]. The hair record again conformed to this historical account, as no further mercury peaks were observed in the hair; rather, mercury began to decline steadily until the end of the hair record (early March 1827). This convergence of the hair record provides an independent historical

anchor for the proposed chronology of his medical intervention and deteriorating health, while preserving appropriate uncertainty about the exact treatment.

Endogenous variability along the strands (Zinc)

Zinc concentrations were normal and relatively steady from July to early November 1826 at ~ 85–95 mg/kg, with the two fish zinc exposures paralleled with mercury. However, during November to January, zinc steadily increased by 50% to 120–130 mg/kg and remained at that elevated level for the remaining hair record. It is highly implausible that a consistent zinc increase is a result of nutritional improvement; zinc is typically obtained from fish or meat [38,39]. Beethoven had already noted appetite loss and weight loss by October, “excessive weight loss” by late November, was described as “only skin and bone” by February 1827, and by March, the month of his death, Dr. Wawruch wrote “rapidly increasing emaciation” [21]. This historical account does not coincide with a consistent diet heavy in meat and fish after mid-October 1826.

The steady increase in zinc may actually reflect altered homeostasis during advanced liver disease, wasting, and tissue catabolism. Zinc deficiency is common in cirrhosis and may result from poor gastrointestinal uptake, malabsorption, hypoalbuminemia, urinary losses, and sweat losses [40]. Skeletal muscle and other tissues containing substantial zinc, and catabolism during body wasting could alter the pool available for redistribution and incorporation into keratin tissues, such as hair. Direct evidence that muscle-derived zinc enters human hair during terminal wasting is limited, so this mechanism remains a hypothesis. A potentially analogous increase in keratin zinc was observed in nail tissue from John Hartnell during severe physiological deterioration before death during the 1845 Franklin Expedition [41]. Overall, the Beethoven zinc profile is therefore best interpreted as altered zinc homeostasis during terminal illness rather than nutritional recovery.

DISCUSSION

Two authenticated hairs from Beethoven’s Moscheles Lock preserved a complementary and informative chemistry aligned with historical record. Mercury and zinc aligned at 16.6 mm in the duplicate hair strands providing a biological chronology that could be compared to what has been previously recorded in medical and other documents. There is strong evidence of an excessive mercury exposure event in mid-October 1826, consistent with, but not diagnostic of, inorganic mercury exposure that may have exacerbated his worsening condition. There was also evidence of several smaller exposures to mercury in December and January, followed by a sustained decline coinciding with a documented cessation of medicine on 11 January 1827. Conversely, zinc increased slowly during a period of severe wasting, consistent with altered body zinc distribution and homeostasis during terminal illness.

Arsenic, lead and magnesium tell a different story. Their shared duplicate strand offset of 5.1 mm into the inner cortex hair layer demonstrates external fluid-mediated contamination of the hair strands. The

hair clearly shows substantial external exposure to lead- and arsenic-containing material, but it is not possible to discern his endogenous levels or their relationship to his failing health.

There are some limitations that should be noted. The hair strands were cut and therefore lacked roots to anchor the date at the proximal end and cut location and estimated growth rate will impact calendar assignments. While the high correlation in concentration and pattern between the two strands for mercury and zinc indicates hair growth rate was the same for those two strands (i.e., no skew in pattern was evident), actual growth rate remains unknown. Analysis of other authenticated hair strands from different locks collected from Beethoven during the same time frame could confirm the interpretation posited here.

The most important lesson from this case study with Beethoven's hair is that duplication of hair strands was integral to interpretation. Had either hair been interpreted alone, the high lead and arsenic profiles in the inner cortex layer could have been mistaken for endogenous exposure, and that their profiles were chronological as opposed to spatial. Element-specific offsets between duplicate strands instead separated biological time from the spatial history of external contamination. Combining replicated hair chemistry with an unusually detailed historical record added evidence about possible mercuric medication and intervention, terminal zinc physiology, and metal-bearing fluids or environments during Beethoven's final months. The duplicate strand analysis provides a framework for improving source attributions in historical, archaeological, forensic, and environmental hair analysis.

Declarations

Conflicts of Interest:

The author, JRC, is majority shareholder of TrichAnalytics Inc.

Declarations

Competing Interests

The author, JRC, is majority shareholder of TrichAnalytics Inc.

Author Contribution

J.R.C. conceived and designed the study, analyzed and interpreted the data, and wrote the manuscript.

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Data Availability

The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request.

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Figures

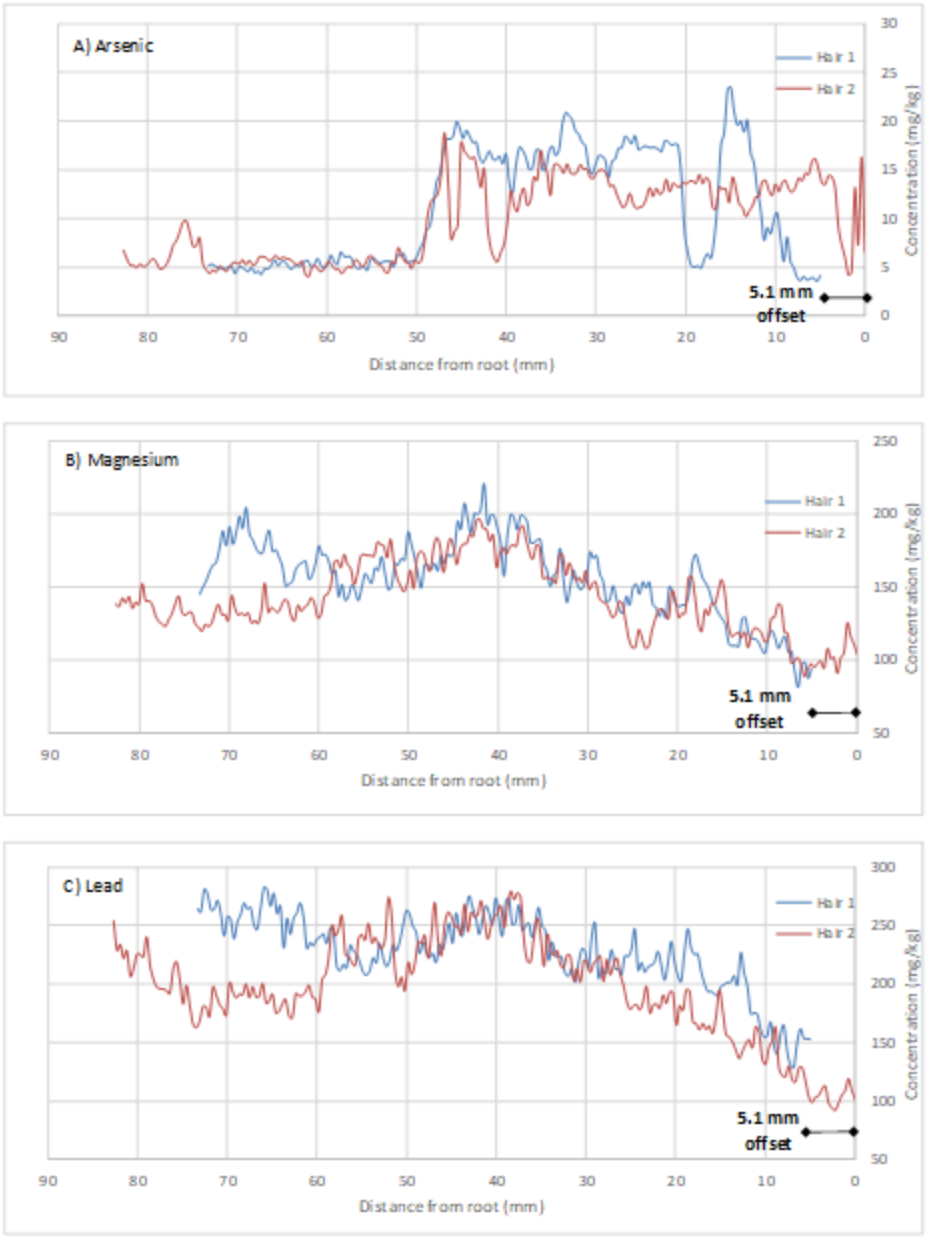


Figure 1

The spatial (distal to proximal) variability in A) arsenic, B) magnesium, and C) lead in the inner cortex layer of Beethoven's two hair strands from the authenticated Moscheles Lock. Note the 5.1 mm offset between the cut ends of each hair strand (right).

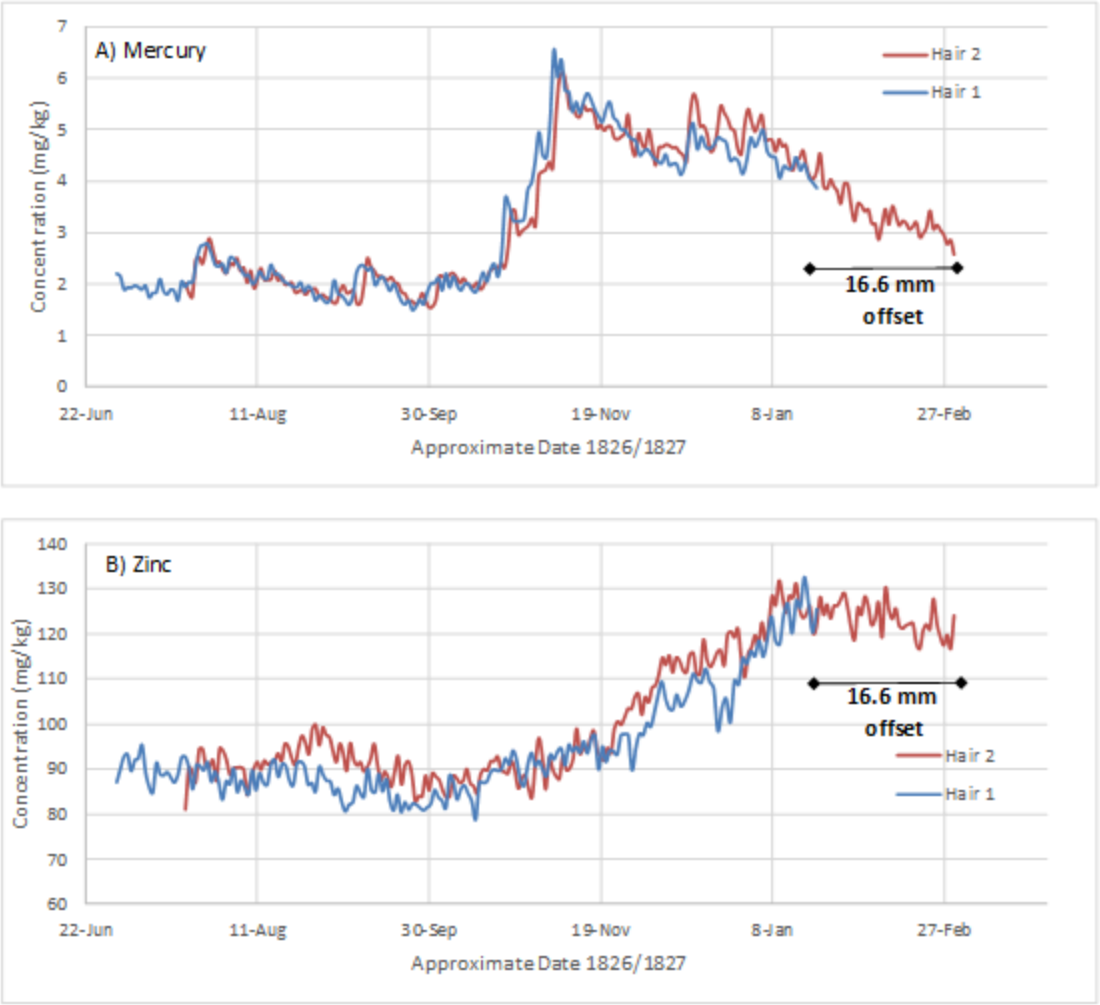


Figure 2

The estimated chronological changes in A) mercury and B) zinc in the inner cortex of Beethoven's two hair strands from the authenticated Moscheles Lock. Note the 16.6 mm offset between the cut ends of each hair strand (right).

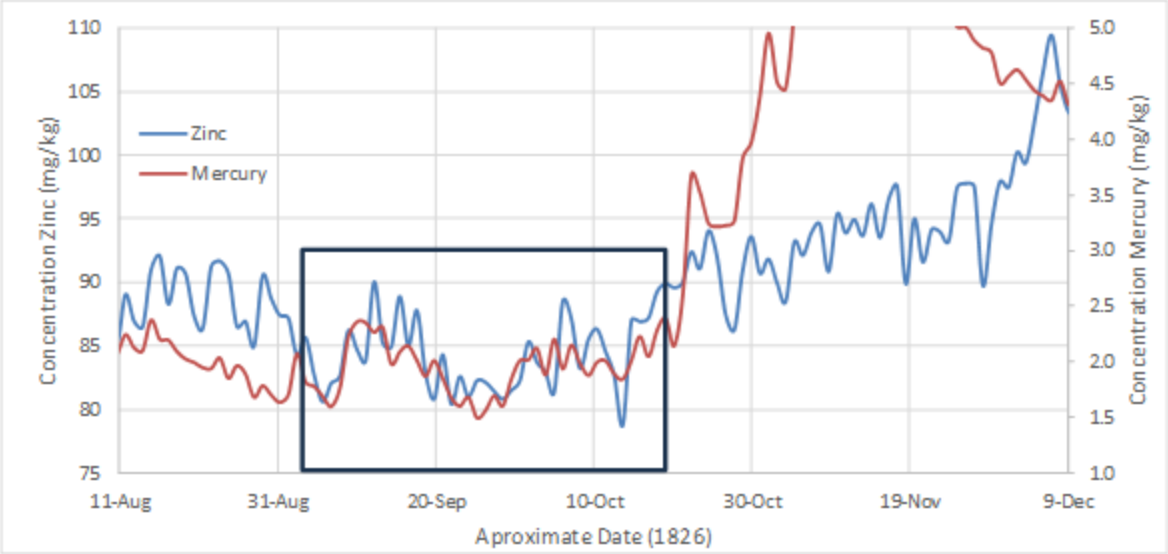


Figure 3

Chronological and parallelled changes in mercury and zinc concentrations in the inner cortex of Beethoven's Hair 1 strand suggest a dietary (fish) source of methylmercury for these excursions early in the hair record. Mercury and zinc concentrations deviate mid-October.