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Isotopic insights into the early Medieval (600–1100 CE) diet in the Luistari cemetery at Eura, Finland

H. Etu-Sihvola[1] · K. Salo[2] · Y. I. Naito[3,4] · M. Kytökari[1] · N. Ohkouchi[4] · M. Oinonen[1] · V. Heyd[2] · L. Arppe[1]

Abstract

In this article, we present the results of an isotopic study of diet for the early medieval (Merovingian, Viking, Early Christian) humans buried in the unique Luistari cemetery at Eura (ca. 600–1400 CE), southwestern Finland, the largest cemetery of the region. Isotope analysis was conducted on 37 humans for dentine and bone collagen ($\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$), and five of them were also studied using compound-specific nitrogen isotope analysis. Dental enamel and/or bone carbonate $\delta^{13}C$ values were studied from altogether 65 humans, five cattle, and five sheep/goats. The bone and dentine collagen and carbonate data show that throughout the centuries, freshwater fish was a stable part of the diet for the population. Our results do not show systematic dietary differences between estimated males and females, but differences can be large on the individual level. We also discovered a possible temporal change in the enamel carbonate $\delta^{13}C$ values that could be related to the increasing role of carbohydrates (e.g., crops) in the diet. Luistari burials are well comparable to contemporary Swedish Viking trading communities like Birka in their higher protein intake. But contrary to the wider Viking network, they do not show the same marine signal.

Introduction

During the early medieval period, modern southwestern Finland was partaking in the exchange network between the western and eastern Baltic Sea. Based on the archeological records, the region had solid contacts with the major trade hubs such as Birka and its successor Sigtuna in Sweden, the island of Gotland, and the southeastern Baltic coast (Gustin 2017, pp. 230–231; Kivikoski 1940, 1961, pp. 206–208; Lehtosalo-Hilander 1982b, pp. 74, 77), and further to the east with settlements around Lake Ladoga in nowadays Russia (Lehtosalo-Hilander 1982c, p. 77). The by far largest archeologically studied cemetery of that time in the region, and in Finland altogether, is Luistari in Eura comprising of over 1300 graves (Lehtosalo-Hilander 1982c, 2000a; Figs. 1 and 2) of which over 400 contained artifacts.

Luistari is a multi-periodic site; the oldest temporal layer includes a Bronze/Early Iron Age settlement site with several pit-hearths and cremation burial cairns (c. 1300 BCE onwards; (Lehtosalo-Hilander 2000b, pp. 174–175). After an apparent gap in the use of the site lasting the first five centuries of the Common Era, burying continued. The inhumation graves date from the Merovingian period (550/600–800 CE; 107 excavated graves) to the Viking period (800–1050 CE; c. 300 excavated graves) and younger. Among the most lavishly equipped Viking period graves is grave 348, suggested to be a "trader burial" from the end of the tenth century CE (Fig. 3; grave 348). The deceased was buried with a set of weapons, a gilded Borre style ring-pin, ceramic vessels, scythe, and a dog. The finds included microscopic remains of the only identified Viking period silk textile found in Finland, a yellowish fabric decorated with narrow silver passementeries (Lehtosalo-Hilander 1991, 1984, pp. 348–349,

✉ H. Etu-Sihvola
  heli.etu-sihvola@helsinki.fi

1 Laboratory of Chronology, Finnish Museum of Natural History, University of Helsinki, P.O. Box 64, 00014 Helsinki, Finland

2 Archaeology, Department of Cultures, University of Helsinki, University of Helsinki, P.O. Box 59, FI-00014 Helsinki, Finland

3 Nagoya University Museum, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan

4 Department of Biogeochemistry, Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan

Fig. 1 Luistari in Eura and the eastern Baltic Sea network. Asterisks denote important Viking period sites. Numbered circles denote the following reference populations mentioned in this study: (1) Levän-luhta (fourth–ninth century CE), (2) Iin Hamina (fifteenth–seventeenth century CE), (3) Björned (tenth–thirteenth century CE), (4) Bjärby (first–second century CE), (5) Alytus (fourteenth–eighteenth century CE), (6) St. Barbara (fourteenth–eighteenth century CE), (7) Kaberla (thirteenth–seventeenth century CE), and (8) Kukruse (twelfth–thirteenth century CE). Eura Yli-Nuoranne and Osmanmäki sites are located near Luistari

1982c). This grave and some other well-equipped male burials, showing deviations from the usual grave orientations, have been suggested to belong to potential immigrants (Lehtosalo-Hilander 1982c, pp. 55–57). Contrary to these, female burials, often found wearing local jewelry (Fig. 3; grave 56, the "Eura Matron"), have been less discussed from the point of view of their origins.

During the twelfth century CE, the practice of putting artifacts in the graves ceased. Based on the amount of supposedly late, unfurnished graves, burying continued at least until the fourteenth century, and during the last few centuries, the site was still used as a burial place for large domestic animals (Lehtosalo-Hilander 1982a, p. 19, 1982b, pp. 175, 183–184, 1997, p. 398, 2000b, pp. 156–157, 176, 227). Due to this long continuity of the site, temporal development in the material culture and in the burial practices is well visible, and therefore, Luistari can be considered a key site for the studies concerning communities settled around the coasts of the Gulf of Finland (Lehtosalo-Hilander 1982c, p. 63; Mägi 2019, p. 18).

Previous archaeobotanical studies in the area and in the immediate vicinity of Luistari have yielded AMS radiocarbon dated cereal grains of *H. vulgare*, *S. cereale*, and *T.* cf. *aestivum* (Lempiäinen et al. 2020) and possible cereal

phytoliths from the grave 1260 (Juhola et al. 2019). According to pollen studies from the Eura Hyväsuo bog and the Köyliö Lake sediments, the earliest signs of crop cultivation date approximately between the fourth and sixth centuries BCE and the relative proportions of *Secale* and other crops become high during the eleventh to thirteenth centuries CE (Grönlund and Simola 2011, pp. 107–109) implying that crops were cultivated in the Eura area during the early medieval period. The remains of domestic (cattle, sheep/goat, pig, and dog) and wild animals (e.g., cervids, bear, beaver, fox, and lynx) identified in the grave finds (Juhola et al. 2019; Kirkinen 2019; Lehtosalo-Hilander 2000b, pp. 197, 203; Tupala 1999) suggest also that animal husbandry, as well as hunting, were both important parts of subsistence. Today, Luistari is about 40 km away from the Baltic Sea coast but located near abundant freshwater resources, namely the extensive, fish-rich lake Pyhäjärvi, and the river Eurajoki. This suggests fish and possibly also other aquatic organisms were part of the diet. The use of aquatic resources has, however, been an almost invisible livelihood in the so far published archeological record. The Luistari graves did not contain medieval fishing equipment but undated bream scales and pike bones were excavated from the Kauttua village site located near Luistari (Lehtosalo-Hilander 2000a,

p. 204), and a single fishing hook and a fishing spear with ambiguous datings were found during the Luistari excavations (Lehtosalo-Hilander 1982b, p. 61). One of the most effective methods to detect fish consumption in past human populations, and to gain direct evidence of population subsistence in general, is the isotopic analysis of their bones and teeth.

In this article, we aim to study the diet of the Luistari humans using stable isotope analysis. As the Luistari cemetery was used for a period spanning several centuries, it offers unique longer-term perspectives to medieval dietary development at an important easterly node of the Baltic exchange network. Since cremation was the prevalent burial practice in northernmost Europe until the end of the first millennium CE, studies of the Luistari population are important for the general understanding of a rural diet in the region. More specifically, we want to address the following questions: What was the early medieval diet like in Luistari and is there evidence of the use of freshwater foods? Were there any temporal changes in the diet, or dietary differences between the estimated males and females? How do the Luistari people compare to other North European Iron Age and (post-)medieval populations from the perspective of dietary habits? And finally, is there isotopic evidence for mobility?

On dietary isotope research

Isotope methods are used in various types of dietary studies from intra-individual into population level. Sampling different skeletal tissues enables tracking diet from in utero or the earliest years of life (Harvig et al. 2014; Jørkov et al. 2009), for example, from the time of breastfeeding (e.g., Tsutaya and Yoneda 2015; Wright and Schwarcz 1998), to the last years of life (Fahy et al. 2017; Hedges et al. 2007). The time interval recorded is dependent on the formation time and renewal speed of the sampled tissue — these are partly still under debate (Beaumont 2020).

Carbon and nitrogen isotope values ($\delta^{13}C$, $\delta^{15}N$) of bone collagen are the most commonly measured parameters in archeological studies of past peoples' diets and lifeways, these days increasingly supplemented by sulfur isotope values ($\delta^{34}S$). The isotopic values of bulk collagen reflect the average isotopic composition of the diet but weighted towards the isotope values of consumed protein (Ambrose and Norr 1993; Hoefs 1987, p. 156). As a widely available, affordable, and established analytical method, bulk stable isotope values are a great source of information about the average dietary protein sources of past populations and individuals. The $\delta^{13}C$ value of bone collagen increases approximately $+1‰$ while shifting up one trophic step in the food chain, and this relatively small biological fractionation has made carbon a useful

tool for tracing the relative contribution of different dietary sources (DeNiro and Epstein 1978; Post 2002). Bulk collagen $\delta^{13}C$ values are particularly useful for estimating the proportions of C_3-plant (most cool and temperate climate crops and plants) to C_4-plant- (tropical grasses and some crops like sorghum, millet, maize, and sugar cane) based consumption, or dietary input from marine sources (e.g., Eriksson 2004).

The trophic fractionation of nitrogen isotopes is greater, and the primary use of bulk collagen $\delta^{15}N$ levels is related to examining the proportions and source of animal protein in human diets. The consumption of fish and seals especially can raise human bulk collagen $\delta^{15}N$ values prominently (e.g., Schulting et al. 2022) due to the generally longer food chains in aquatic environments. However, the trophic enrichment of ^{15}N has been found to vary between ca. $+2$ and $6‰$ depending on the studied species and its diet, and combined with natural and often poorly defined variability in baseline $\delta^{15}N$ values, interpretations of trophic standing based on bulk $\delta^{15}N$ values are not straightforward (DeNiro and Epstein 1981; Hare et al. 1991; Minagawa and Wada 1984; O'Connell et al. 2012; Schoeninger and DeNiro 1984; Vanderklift and Ponsard 2003). It is relatively common that the isotope values of food sources can overlap, and this may cause challenges for the interpretation of bulk isotope data, for example for the estimation of the relative amounts of terrestrial and freshwater animal protein in the diet.

The compound-specific isotope analysis of amino acids in collagen can be used for a more detailed insight into the protein sources in the human diet (Hare et al. 1991; Ishikawa et al. 2014; Styring et al. 2010). Amino acid $\delta^{15}N$ analysis in particular has been shown to provide additional resolution between terrestrial and freshwater protein use in absence of well-defined baseline $\delta^{15}N$ levels (Drucker et al. 2021; Naito et al. 2016). The approach is based on a clear difference in ^{15}N fractionation between source amino acids (e.g., alanine, leucine, and phenylalanine) and trophic amino acids (e.g., methionine, lysine, and glutamic acid). As a great advantage to paleodietary studies, the method allows the estimation of the consumer's trophic status without knowledge of baseline $\delta^{15}N$ values in coeval plant and animal specimens (Drucker et al. 2021; Naito et al. 2016, 2013a). There is a large diet-to-consumer difference in the $\delta^{15}N$ value of glutamic acid (c. $+6$–$8‰$) but only a small isotopic change (c. $+0.5‰$) for phenylalanine (Ohkouchi et al. 2017). The difference between these two amino acids is used in the estimation of trophic position (TP; Chikaraishi et al. 2009) and together with the bulk isotope data, the amino acid data can be used for the estimation of terrestrial (Naito et al. 2013b) and aquatic resource use (Naito et al. 2010a, 2010b). Using the compound-specific approach together with Bayesian mixing models can also increase the resolution of the studies compared to bulk isotope analyses (Soncin et al. 2021).

◀**Fig. 2** The location of Luistari and a map of the graves excavated between 1969 and 1992 (Lehtosalo-Hilander 1982a, 2000b). Graves sampled in this study have been marked and numbered

Sulfur isotopes have proven to be useful in studies on diet (e.g., Krajcarz et al. 2019; Nehlich et al. 2011) and as tracers of different living environments (Richards et al. 2001). According to controlled feeding studies the $\delta^{34}S$ values of collagen change little compared to diet (Krajcarz et al. 2019; Nehlich 2015). Freshwater sulfate $\delta^{34}S$ values typically range from 0 to +10‰ (Nriagu et al. 1991), reflecting the soil and bedrock values, whereas granitic bedrock values range between −4 and +9‰ in Europe (Hoefs 1997). Collagen $\delta^{34}S$ values within these ranges could be expected for the Luistari individuals because Luistari cemetery is located on top of Laitila rapakivi granite, close to contact with Satakunta sandstone that has its origins in metamorphic rocks (Laitakari 1998, pp. 312, 315 Fig. 11.3). Compared to abovementioned environments, the mean value for the Baltic Sea sulfates is significantly higher, +20.5‰ (Böttcher and Huckriede 1997) making it possible to distinguish individuals relying on marine fauna from those consuming food solely from terrestrial or freshwater environments (Richards et al. 2003). Atmospheric deposition such as anthropogenic sulfur emissions can however alter the natural range of sulfur isotope composition (Nriagu et al. 1991).

More dietary information can be obtained from the carbon isotope composition of the mineral part of the human skeleton, i.e., a form of hydroxyapatite. Skeletal carbonate carbon derives from blood bicarbonate and reflects the average value for all major macronutrient inputs, i.e., carbohydrates, lipids, and protein in the consumed diet (Koch et al. 1997; Krueger and Sullivan 1984; Lee-Thorp et al. 1989) and it is often used to evaluate the $\delta^{13}C$ value of dietary energy (e.g., Zhu and Sealy 2019). Dental enamel, containing mostly hydroxyapatite (Hillson 1999, p. 217), has lower solubility and porosity compared to bone, and therefore, it has been considered an exceptionally robust — and therefore preferred — material for isotopic studies (Koch et al. 1997; Zapanta LeGeros 1981). Bone and dentine are more susceptible to diagenetic alteration in the burial environment, but this depends much on site conditions (e.g., Lee-Thorp and Sponheimer 2003). Generally, archeological bone apatite is a reliable source of carbonate $\delta^{13}C$ data (Zazzo 2014). The carbon isotope compositions of structural carbonate in dental enamel and other skeletal tissues are not fully equivalent due to possible differences in the formation process (Webb et al. 2014). Combined collagen and carbonate $\delta^{13}C$ analysis facilitates a more comprehensive examination of dietary macronutrient sources that is attained by analyzing collagen alone, particularly in cases where the sources of energy differ from the main source of dietary protein (Froehle et al. 2010).

A combined approach also provides additional information on the trophic level of the consumer, and on the used dietary components (Clementz et al. 2009).

Material and methods

Material

The human remains excavated from the Luistari cemetery were partly studied by Salo (2006, 2005). For this project, we conducted a supplementary osteological analysis, focusing on age-at-death, sex, and possible nutrition-related pathological conditions. A detailed description of the used methods and main results of the analysis can be found in ESM 1.

Due to generally acidic soil conditions, the preservation of bone is usually poor in Finland, but the presence of metal objects has likely aided the preservation of organic remains in Luistari. From the excavated > 1300 graves, fragmentary human skeletal remains have been cataloged from approximately 195 individuals. From these, a set of skeletal specimens, visually estimated to be sufficiently preserved, was selected for isotopic analyses. The youngest artifact containing graves had better bone preservation compared to older graves explaining why most of the sampled graves are in the northern parts of the cemetery (Fig. 2). Based on previous radiocarbon datings, artifact types, and the spatial and horizontal locations of the graves, the sampled individuals date approximately between 600 and 1100 CE (Lehtosalo-Hilander 1982a, 2000b). Overview of the sampled individuals is presented in Table 1 and a more detailed information on the selected specimens along with dating is given in ESM 2. Due to the state of preservation of the oldest remains, mainly enamel was deemed fit enough for sampling the Merovingian period individuals (c. 600–800 CE). The remains dating to the Viking period (c. 800–1050 CE) and up to the first half of the twelfth century were partly preserved in a condition that enabled the analysis of collagen from dentine and/or bone. It was unfortunately not possible to sample the youngest-dating burials because skeletal remains had not been preserved in graves lacking burial artifacts.

In addition to the skeletal samples, freeze-dried whole flesh samples of modern fish from lake Pyhäjärvi, including pike (*Esox lucius*; $n = 2$), perch (*Perca fluviatilis*; $n = 2$), and common roach (*Rutilus rutilus*; $n = 2$), were analyzed to gauge the typical isotopic values of carbon, nitrogen, and sulfur in the aquatic environment. Each species included a smaller and a larger specimen, presumed to represent younger and older individuals, respectfully. Please see Table 2 for details.

Fig. 3 Excavation drawings of two prominent Viking period burials found in Luistari. On the left, the "Eura Matron," grave number 56 (eleventh century CE). On the right, proposed immigrant merchant from grave 348; see "Introduction." Modified after Lehtosalo-Hilander (1982a). Skeletal remains have been emphasized with light brown color
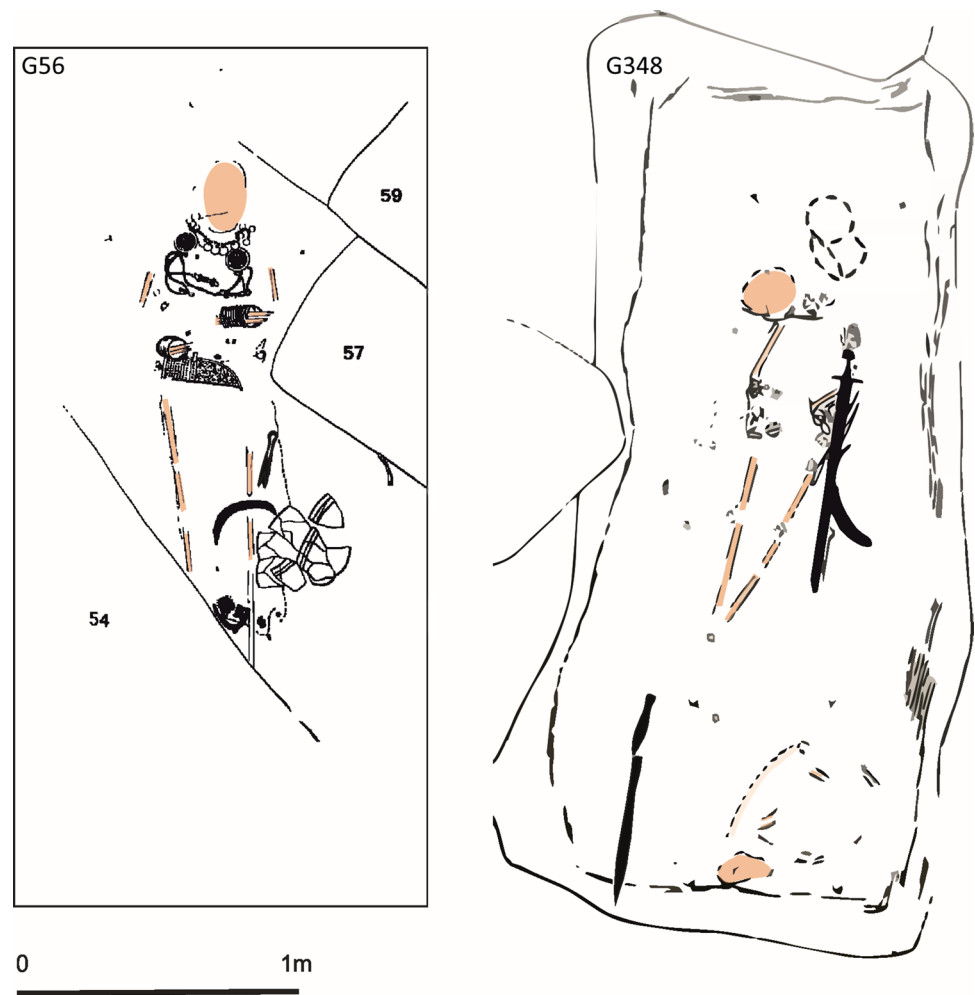

Table 1 Overview for the sampled Luistari humans and the stable isotope analyses conducted in this study. AA refers to compound-specific amino acid analysis

| Period | # of sampled individuals | Collagen | | | | Carbonate |
		$\delta^{13}C$	$\delta^{15}N$	$\delta^{34}S$	$\delta^{15}N_{AA}$	$\delta^{13}C$
Merovingian I (600–750 CE)	7	6	6	1	1	6
Merovingian II–III (750–800 CE)	8	2	2	2	0	7
Viking I (800–880 CE)	15	7	7	3	1	16
Viking II–III (880–1000 CE)	20	26	26	12	3	33
Viking IV (1000–1070 CE)	13	16	16	9	0	18
Final period (1070–1140 CE)	7 (8)	10	10	4	0	7 (8)
Uncertain dating	6 (7)	3	3	1	0	3
No. of analyzed samples	75	70	70	32	5	91

Samples for collagen extraction

Collagen was extracted from altogether 70 skeletal elements (samples) deriving from 37 humans and analyzed for $\delta^{13}C$, $\delta^{15}N$, C%, and N% values. Sulfur content and isotopic composition (S% and $\delta^{34}S$) were measured for 32 of these samples (19 bones and 13 teeth) representing 22 individuals in total. Because of the uneven preservation, it was not possible to sample the same skeletal element from all the individuals. In twelve cases, preservation enabled sampling multiple elements from the same individual. The amount of extracted collagen limited the number of sulfur analyses.

Bone samples ($n = 33$) originate from 25 individuals. Tooth samples ($n = 37$) were taken from 15 individuals.

Table 2 Data for archeological animal samples from the Luistari in Eura and for modern fish from Pyhäjärvi Lake. *Published in Etu-Sihvola et al. (2019). **Standard/total length (Holden and Raitt 1974)

# of individuals	Dating (CE)	Period	Grave no	Taxon	Element for carb./coll	Museum ID	$\delta^{13}C$carb	$\delta^{13}C$coll	$\delta^{15}N$coll	$\delta^{34}S$coll	%Ccoll	%Ncoll	%Scoll	C/N
Animals from Luistari														
1	800–?	After M	494	*Bos taurus*	*Dens M/Cranium*	KM 22346:461	−11.7	−22.5*	4.7*		30.5*	11.2*		3.2*
2	600–800	M	353	*Bos taurus*	Enamel/*Mandibula*	KM 18000:4018	−12.9	−22.9*	4.8*		27.7*	9.9*		3.3*
3	800–1070?	V?	897	*Bos taurus*	Enamel/*Mandibula*	KM 25480:48	−12.9	−22.6*	5.5*		27.2*	9.2*		3.5*
4	800–?	After M	997	*Bos taurus*	–*Mandibula*	KM 25480:148	−11.3	−22.7*	4.3*		29.5*	10.5*		3.3*
5	Late grave	Late grave	1008	*Bos taurus*	Enamel/*Costa*	KM 25480:198								
	Late grave?		632	*Bos taurus*	–*Vertebra caut* fr	KM 23183:430		−21.9*	6.2*	10.0*	37.7*	13.7*	0.17*	
	Late grave?		1203	*Bos taurus*	–*Costa*	KM 26695:138		−22.6*	4.7*	10.0*	40.1*	14.9*	0.19*	
6	880–1000	VII–III	285	*O. aries/C. hircus*	*Mand.I/II/III/Costa*	KM 18000:3267	−13.0							
7	880–1070	V	195	*O. aries/C. hircus*	*Mand.I/II/IIIFemur dx*	KM 18000:2786	−15.4							
8	880–1070	V	344	*O. aries/C. hircus*	*Max. PM/M/Astragalus*	KM 18000:3829	−12.4							
9	800–1070?	V?	739	*O. aries/C. hircus*	Enamel/*Tibia*	KM 23607:469	−12.1	−21.6*	3.2*		32.8*	11.5*		3.3*
10	1070–1130?	FP?	854	*O. aries/C. hircus*	Enamel/*Humerus*	KM 24740:413	−13.3							
						Mean	−12.7							
						St.dev	1.2							
Fish from Lake Pyhäjärvi						*Length***								
1	4/22/2017	Modern		*Esox lucius*	Flesh	36.5/42.0 cm		−23.0	14.5	4.5	48.1	15.3	1.10	3.7
2	4/22/2017	Modern		*Esox lucius*	Flesh	48.0/55.0 cm		−24.0	14.9	4.1	47.7	14.9	1.03	3.6
3	4/22/2017	Modern		*Perca fluviatilis*	Flesh	22.0/25.5 cm		−23.8	14.9	4.6	48.1	14.8	1.30	3.6
4	4/22/2017	Modern		*Perca fluviatilis*	Flesh	33.5/37.5 cm		−24.3	16.1	4.2	48.1	14.5	1.34	3.3
5	4/22/2017	Modern		*Rutilus rutilus*	Flesh	20.0/24.5 cm		−19.2	12.0	4.7	47.1	15.3	1.18	4.5
6	4/22/2017	Modern		*Rutilus rutilus*	Flesh	21.0/25.7 cm		−20.9	12.8	4.8	47.4	15.5	1.20	4.2
						Mean		−22.5	14.2	4.5				
						St.dev		2.0	1.5	0.3				

Depending on the preservation, dentine was sampled either from the crown, the root, or from both combined. Dentine samples were taken from the permanent dentition, except for one deciduous tooth. The sample set included specimens that were used also for aDNA and ^{14}C-AMS analyses (Översti et al. 2019). Collagen samples represent the different time periods as follows: Merovingian period ($n = 8$; sampled individuals $n = 6$), Viking period ($n = 49$; individuals $n = 23$), and post-Viking period (final period; Lehtosalo-Hilander 1982c; $n = 10$; individuals $n = 5$). In addition, there were three samples with seemingly ambiguous datings.

Based on the estimated good sample quality, and interesting find contexts containing dating artifacts and two double or multiple burials, five dentine collagen samples, originating from permanent teeth of three estimated females and two males dating between ca. 600 and 1000 CE, were selected for compound-specific isotope analysis of nitrogen in amino acids. Depending on the sampled tooth (M1, M2, or PM2), they represent dentine forming between ca. 0 and 11 years.

Samples for carbonate analysis

To gain a more comprehensive picture of the bulk diet, bioapatite carbonate $\delta^{13}C$ analysis was conducted on a subset ($n = 43$; 11 bones, 32 enamels) of human specimens used also for collagen extraction. In addition to these, a further 48 samples of enamel from 43 individuals were analyzed from graves where collagen-bearing tissues of sufficient condition were not available. The measured sample set included altogether 91 human samples originating from 65 individuals. In addition to human samples, dental enamel from cattle ($n = 5$) and sheep or goat ($n = 5$) found in the Luistari graves was sampled and analyzed for carbonate $\delta^{13}C$ values (Table 2). Animal samples date predominantly into the Viking period or younger and the human samples cover the time span from the seventh to the twelfth century CE, as follows: Merovingian period I ($n = 6$), II ($n = 7$), Viking period I ($n = 16$), II–III ($n = 33$), IV ($n = 18$), and final period ($n = 7$). Altogether, four samples had ambiguous datings. Human samples originate mostly from people who had reached adulthood. Altogether, 12 of the individuals sampled for carbonate $\delta^{13}C$ analysis had however died already during their childhood or adolescence.

A vertical section of enamel from the whole height of the crown or readily broken enamel pieces, whenever available, was sampled. Thus, the enamel samples represent a dietary average for several years. Enamel samples were taken mainly from permanent teeth (enamel forming between ca. 0 and 13 years), but two deciduous teeth were also analyzed. Seven samples were taken from enamel fragments whose origin from a deciduous or permanent tooth could not be identified.

Methods

$\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ analysis of collagen

Collagen extraction followed Bocherens et al. (1997). Isotopic compositions and weight percentage values were measured at the Laboratory of Chronology, Finnish Museum of Natural History, University of Helsinki, using an NC 2500 elemental analyzer coupled to a Thermo Scientific DeltaPlusAdvantage (C and N analyses) or a Thermo Scientific Flash EA coupled to a DeltaVPlus (C, N, and S analyses) isotope ratio mass spectrometer. Measurement data with applied corrections are listed in ESM 2. All isotopic ratios are expressed using the "δ" (delta) value (e.g., Coplen 1994), as per mille (‰) deviations from the standard scale, relative to the V-PDB standard for $\delta^{13}C$ values, atmospheric nitrogen (AIR) standard for $\delta^{15}N$ values, and CDT for $\delta^{34}S$ values. Measurements for $\delta^{13}C$ and $\delta^{15}N$ values were done in duplicate and were calibrated using the known values of international reference materials USGS-40 ($\delta^{13}C = -26.39‰$, $\delta^{15}N = -4.5‰$) and USGS-41 ($\delta^{13}C = +37.63‰$, $\delta^{15}N = +47.6‰$). Data evaluation and calibration were done with the LIMS for Light Stable Isotopes Software developed by T. B. Coplen at the US Geological Survey. Based on samples analyzed multiple times, as well as repeated extractions and measurements of matrix-matched in-house reference materials (modern camel and elk bone powder), the external reproducibility (1σ) was better than $\pm 0.34‰$ for $\delta^{13}C$, and $\pm 0.25‰$ for $\delta^{15}N$ values. Sulfur measurement data were calibrated to $\delta^{34}S$ values relative to IAEA-S-1 ($\delta^{34}S = -0.30‰$), IAEA S-2 ($\delta^{34}S = +22.7‰$), and USGS-43 ($\delta^{34}S = +10.46‰$). Amount percentage determination was based on the certified value 0.75% S of casein protein (Iva Analysentechnik VA33802155). For sulfur, the external reproducibility, based on the repeatability of in-house matrix-matched bone materials, was $\pm 0.4‰$ for $\delta^{34}S$ measurements. The relative error of the amount percentage measurements was below 7% for C% and N%, and below 3% for S%. The reported data are mean values of all accepted repeats for the sample.

Amino acid $\delta^{15}N$ analysis

Collagen extracts were prepared and the $\delta^{15}N$ values of the individual amino acid derivatives were measured following the established protocol (Naito et al. 2016; Naito et al. 2013b) as follows: The collagen was hydrolyzed by 12 N HCl at 110 °C for 12 h and derivatized with thionyl chloride/2-propanol (1:4, v/v) at 110 °C for 2 h and subsequently pivaloyl chloride/dichloromethane (1:4, v/v) at 110 °C for 2 h. The amino acid derivatives were injected into a gas chromatography/IRMS (GC/IRMS) using an Agilent Technology 6890 N GC coupled to a Thermo Finnigan Deltaplus XP

IRMS (Thermo Fisher Scientific, Waltham, MA, USA) via combustion and reduction furnaces. The GC was equipped with an Ultra-2 capillary column (50 m × 0.32 mm-i.d. 0.52-μm film thickness; Agilent Technology) and the Gerstel programmable temperature vaporizing (PTV) injector (Gerstel, Mülheim an der Ruhr, Germany) in solvent vent mode. The PTV temperature program was as follows: 50 °C (initial temperature) for 0.2 min, heating from 50 to 250 °C at the rate of 600 °C min^{-1}; isothermal hold at 250 °C for 10 min, heating from 250 to 350 °C at the rate of 600 °C min^{-1}; and isothermal hold at 350 °C for 10 min. Combustion and reduction furnaces were set at 950 °C and 550 °C, respectively. The GC oven temperature was programmed as follows: isothermal hold at 40 °C for 3 min; temperature ramp to 110 °C at the rate of 15 °C min^{-1}; ramp to 150 °C at the rate of 3 °C min^{-1}; ramp to 220 °C at the rate of 6 °C min^{-1}; and subsequent holding isothermally at 220 °C for 18 min. Carrier gas (He) flow rate through the GC column was 1.4 ml min^{-1}. CO_2 generated in the combustion furnace was eliminated by a liquid nitrogen trap. The mean accuracy and precision of the reference mixtures were 0.0‰ and 0.49–0.57‰ (mean of 1σ), respectively. A single injection was measured per sample, and thus, measurement uncertainty can only be evaluated based on the reproducibility of amino acid standards. The amino acid standard SD across the runs were as follows: Ala, 0.5–0.6‰; Gly, 0.3–0.5‰; Val, 0.1–0.7‰; Leu, 0.2–0.5‰; Nle, 0.2–0.6‰; Asp, 0.6–0.7‰; Met, 0.5–1.0, Glu, 0.8–1.0‰; Phe, 0.4–0.6‰; Hyp, 0.3–0.6‰. Nitrogen isotopic composition of the following amino acids was determined: valine (Val), leucine (Leu), isoleucine (Ile), proline (Pro), glutamate (Glx), phenylalanine (Phe), and hydroxyproline (Hyp). All reported $δ^{15}N$ values for glutamate included a contribution from the α-amino group of glutamines, as glutamine is converted to glutamic acid during acid hydrolysis. The trophic positions of the human remains were calculated based on the following equation: TP (C$_3$) = ([$δ^{15}N_{Glx} − δ^{15}N_{Phe} + 8.4$] / 7.6) + 1 for C$_3$-plant-based ecosystems, where $δ^{15}N_{Glx}$ and $δ^{15}N_{Phe}$ are for glutamate, and $δ^{15}N$ is for phenylalanine. TP = 1, 2, and 3 which indicates the primary producers (e.g., plants), primary consumers (i.e., herbivores), and secondary consumers (i.e., carnivores), respectively.

$δ^{13}C$ analysis of structural carbonate

Ca. 1.5 mg of pretreated (see details in ESM 3) sample powder was weighed into 12-ml Exetainer vials; He flushed and reacted with 103% phosphoric acid at 25 °C for 24 h. The isotopic composition of the evolved CO_2 was measured online at the Laboratory of Chronology, Finnish Museum of Natural History, on a Thermo Scientific GasBench II coupled to a DeltaV Advantage isotope ratio mass spectrometer. Ten injections were collected per sample, out of which seven

were used to calculate the mean sample $δ^{13}C$ value. The measured $δ^{13}C$ values were blank corrected and calibrated using the known values of international reference materials NBS19 ($δ^{13}C = +1.95‰$), and LSVEC ($δ^{13}C = −46.6‰$). Precision was estimated based on repeated measurements of in-house quality control materials, calcite ("VIM", $n = 18$) and a milled dentine material from a well-preserved mammoth tusk, which was also subjected to the pretreatment procedure ("P13b", $n = 12$). They indicate an external reproducibility (1σ), including effects of typical sample inhomogeneity, of ± 0.4‰ for bioapatite carbonate $δ^{13}C$ values. Despite reports of a susceptibility to contamination of the $δ^{13}C$ value of LSVEC by atmospheric CO_2 (Assonov 2018), LSVEC was used as the low anchor for normalization of measurement data due to lack of a suitable replacement. The material was stored in a desiccator cabinet with both silica gel and a P_2O_5 drying agent. As a measure of the magnitude of possible error induced by the use of LSVEC as a scale anchor, the NBS18 reference material ($n = 20$) gave a mean value of − 5.0 ± 0.2 (expected − 5.01‰) over the analytical period. Recent tests with IAEA-611, the new low $δ^{13}C$–scale anchor material for carbonates with a certified value of − 30.795‰ (Assonov et al. 2021) also suggests minimal contamination of the LSVEC material; when normalized with LSVEC and NBS19, the IAEA-611 material attained a value of − 30.89‰.

Data analysis

Only enamel samples were considered in the statistical analysis of carbonate $δ^{13}C$ data, as there are indications of a general incomparability of enamel and bone carbonate $δ^{13}C$ values (Webb et al. 2014). A Shapiro–Wilk test was used to verify data normality. However, non-parametric tests were employed in further analyses to yield more conservative estimates of possible differences in view of the still rather limited sample sizes. The Mann–Whitney U test was used to test for differences in sample mean values categorized according to time period or biological sex. Origin 2018b software was used for the statistical analyses and 0.05 was taken as the threshold of statistical significance.

For the temporal analyses, data were grouped using time period designations based on the Luistari burial chronology (Lehtosalo-Hilander 1982c and references therein): Merovingian I (600–750 CE; $n = 6$), Merovingian II (750–800 CE; $n = 7$), Viking I (800–880 CE; $n = 12$), Viking II–III (880–1000; $n = 32$), Viking IV (1000–1070 CE; $n = 14$), and the final period (1070–1140 CE; $n = 4$). Based on the non-parametric Mann–Whitney U test ($p = 0.366$), there was no statistical difference between Merovingian I vs. II, and therefore, in order to increase the sample size, these were

combined as one group, as well as the Viking IV and the final period groups.

It is worth noting that the analysis of differences between biological sexes in the whole dataset spanning ca. 600 years might be affected by temporal interactions, i.e., the uneven temporal distribution of samples assigned to the respective sexes. All but two Merovingian period samples were from females or children and males were overrepresented in the youngest (Viking IV–final period) data. To minimize temporal interaction effects, an additional test was computed on sex-assigned data for the Viking II–III period with the largest number of samples available.

Data numbers for collagen samples were too low for a meaningful statistical analysis of temporal development, and thus, it was not attempted. Indications of dietary differences between females ($n = 13$ individuals) and males ($n = 16$ individuals) were evaluated based on their mean values and standard deviations. Male samples were temporally more focused to the end of the Viking period (IV; $n = 7$) and there were no samples from the M I period. Samples from the graves 13, 135, and 302 (total sample $n = 15$) represent 52% of the male collagen data.

Additionally, the possible impact of the nursing effect, i.e. the tendency of feeding on mother's milk to increase the $\delta^{13}C$ and $\delta^{15}N$ values of dentine collagen (e.g., Bocherens et al. 1994; Fuller et al. 2003) and decrease the $\delta^{13}C$ values of carbonate (Wright and Schwarcz 1998) in early forming teeth, was evaluated. The acceptable data for dental specimens were grouped according to dental formation estimates (ESM 3 Fig. 1) by Haavikko (1970), Harris and Buck (2002), and Moorrees et al. (1963) as "Early childhood" (I/C/M1), "Middle childhood" (PM/M2), and "Late childhood" samples (M3). For dentine collagen data with lower sample numbers, the descriptive statistics (ESM 3 Table 1) between these formation age categories were compared without statistical testing, but for enamel $\delta^{13}C$ values, Mann–Whitney U and Wilcoxon Signed-Rank statistics were computed. See ESM 3 Table 2 for details and results of the tests.

Sample quality

Collagen quality

The quality of collagen samples was monitored using well-established criteria: carbon content 30–45% (Ambrose 1990; Jørkov et al. 2009), nitrogen content 11–17% (Ambrose 1990; van Klinken 1999), sulfur content 0.12–0.35%, C/N ratio between 2.9 and 3.6 (DeNiro 1985; DeNiro and Weiner 1988), C:S ratio of 600 ± 300, and N:S ratio of 200 ± 100 (Bocherens et al. 2011; Nehlich and Richards 2009). We accepted samples within these limits plus an additional $\pm 0.5\%$ because

of the typical precision of the C% and N% percentage measurement and further recognizing that collagen C% and N% values are known to be affected by extraction procedures, which suggests that the strict application of universal cutoff values is not advisable (e.g., Ambrose 1990; Sahlstedt and Arppe 2020; Sealy et al. 2014). Therefore, the lowest accepted elemental concentrations were 28.7% for the amount of carbon and 10.7% for nitrogen. Collagen yields between c. 1 and 25% have been considered acceptable (Ambrose and Norr 1993; Schoeninger et al. 1989; van Klinken 1999). Yields from 0.6 to 26% were obtained, and the low-yield samples were discarded (ESM 2). Additionally, a high-yield sample (G-4169: yield 36.4%) with sufficient amount of carbon and nitrogen was also accepted to the analysis based on the similarity with the other measurement results (G-2323 and G-3851) from the same individual (c.f. van Klinken 1999). Possibly, this collagen extract contained extraneous salts (Ambrose 1990), silicate mineral contamination (e.g., Cersoy et al. 2017), or the yield was high due to a weighing error. Based on C% and N%, there was no indication that the possible extraneous material contained any carbon or nitrogen. Based on too low S%, the sulfur data for sample S-1038 was discarded from further analysis. There was a relatively narrow range in the measured sulfur elemental ratios in the accepted samples (C/S = 420–618; N/S = 124–189).

Carbonate quality

The general preservation level of the bioapatite structural carbonate at the Luistari site was evaluated by attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectroscopy. A subset of 23 samples (21 enamels and 2 bones), originating from 11 individuals excavated from different areas of the cemetery, was measured using ATR-FTIR by Bruker Alpha Platinum-ATR at the Laboratory of Organic Chemistry at the Chemistry Department, University of Helsinki, Finland. The measurement protocol and results are given in ESM 2 and 3.

All the calculated API, BPI, C/C, and C/P indices, including the data for two cranial bones, were within the estimated range of good preservation for chemically pretreated samples (ESM 3, Table 3) and suggest that the structural carbonate of the Luistari skeletal remains, applying common visual and sensory criteria for sample condition, is a reliable reservoir of bioapatite carbonate $\delta^{13}C$ analysis. In three cases, IRSF was, however, just below the recommended range (IRSF = 3.0; samples C-1052, C-1053, and C-1089). Based on the API, BPI, C/C, and C/P indices, these samples were included in the analysis.

Results

Osteology

The main results of the osteological analysis pertinent to the focus of the dietary isotopic studies are summarized here. Intact bones were rarely preserved due to taphonomic reasons. Consequently, it was not possible to estimate the average lifespan or study the frequency of pathological conditions in the whole population. Despite these limitations, certain dental conditions were relatively common findings among the preserved remains. Dental calculus was recognized in 46 individuals and in 24 cases, the condition was present together with small enamel traumas. Dental hypoplasia was found in 25 individuals and caries in 14 individuals of which four also had periapical lesions.

Collagen and fish data

There was a relatively large variation in the measured collagen carbon and nitrogen isotope relations ($\delta^{13}C_{mean} = -20.1‰$, SD = 0.5; range from -21.3 to $-18.9‰$; $\delta^{15}N_{mean} = +13.2‰$, SD = 0.9; range from $+11.1$ to $+16.6‰$; $n = 54$). The highest collagen $\delta^{13}C$ and $\delta^{15}N$ values were measured in dentine. The one sampled deciduous tooth (KM 26695:18; grave 1061) produced the highest $\delta^{15}N$ value ($+16.6‰$) in the data set — this was not surprising because the $\delta^{15}N$ values of deciduous teeth are typically 2–3‰ higher in breastfed infants (Tsutaya and Yoneda 2015). The studied individual had died as a child, and there could also be other reasons causing the high $\delta^{15}N$ value, such as poor nutrition or a longer disease period (Beaumont and Montgomery 2016). The mean value for $\delta^{34}S$ was $+8.2‰$ (SD = 1.9; $n = 31$). The overall range for the $\delta^{34}S$ was relatively large ($+4.3$ to $+11.6‰$) and seemed not to be dependent on sample type: low values were in two cases measured from two separate tissues of the same individuals (graves 80 and 294).

Based on the comparisons of mean values of samples grouped according to tooth formation age, there is no compelling evidence of the nursing effect elevating $\delta^{13}C$ values. The mean values were also similar between the sexes and thus, the following text deals with the collagen dataset as a whole, with no distinction as to assigned sex or sample formation age. It is also worth noting that the majority (> 60%) of the collagen data originate from the Viking period.

Modern fish flesh from lake Pyhäjärvi produced a relatively large range in the carbon and nitrogen isotope values ($\delta^{13}C_{mean} = -22.5‰$, SD = 2.0; range from -24.3 to $-19.2‰$; $\delta^{15}N_{mean} = +14.2‰$, SD = 1.5;

range from $+12.0$ to $+16.1‰$; $n = 6$). The results for pike ($\delta^{13}C_{mean} = -23.5‰$, $\delta^{15}N_{mean} = +14.7‰$) and perch ($\delta^{13}C_{mean} = -24.1‰$, $\delta^{15}N_{mean} = +15.5‰$) seem typical considering their carnivorous diet. Roach had distinctively high $\delta^{13}C$ values (mean $-20.1‰$) compared to the analyzed pike and perch, and lower $\delta^{15}N$ values (mean $+12.4‰$) as was expected based on its typical diet containing invertebrates. The sulfur isotope results were quite uniform for the analyzed fish flesh ($\delta^{34}S_{mean} = +4.5‰$, SD = 0.3).

Compound-specific isotope analysis

Of the ten separated amino acid derivatives, $\delta^{15}N$ values for seven amino acids other than alanine, glycine, and methionine were acquired. In addition, the valine value was missing for individual #5 (Table 3.) A comparison of the $\delta^{15}N$ values of glutamate and phenylalanine is presented in Fig. 4. We note that the $\delta^{15}N$ values measured for hydroxyproline and proline do not conform to a 1:1 relationship, previously suggested as a measure of analytical quality (O'Connell and Collins 2018). However, an absence of a one-to-one ratio does not indicate that the remaining amino acid data are invalid (Larsen et al. 2022); the analytical conditions for glutamate and phenylalanine have been demonstrated as robust, and not influencing the resulting TP evaluations (Naito et al. 2018).

Calculated TP values ranged from 2.7 to 3.5 and were > 3.0 for all samples except for the individual #2 with the value of 2.7. TP and the bulk $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values were similar for the studied individuals #1 and #4. Individual #3 had a low $\delta^{15}N$ value compared to others but TP value was still high, 3.1. Compared to others, individual #2 stands out because the sample produced not only the lowest TP suggesting a lower intake of animal protein from a comparable trophic level as for the others, but also the lowest bulk carbon and sulfur isotope values. Furthermore, the $\delta^{15}N_{Phe}$ value was higher ($+14.3‰$) compared to other individuals (range $+9.9$–11.3‰) indicating a possible difference in the source amino acids but at the same time, individual #2 still showed a bulk collagen $\delta^{15}N$ value on par with the others. There were no distinct differences between the studied females and males.

Carbonate results

The mean value for the human carbonate $\delta^{13}C$ values was $-14.5 \pm 0.7‰$ ($-14.6 \pm 0.6‰$ for enamel; range from -16.2 to $-12.7‰$; $n = 79$ and $-13.8 \pm 1.0‰$ for bone; range -15.2 to $-12.3‰$; $n = 11$). For the measured cattle and sheep/goat enamels, the mean carbonate $\delta^{13}C$ value was $-12.7 \pm 1.2‰$ (range from -15.5 to $-11.3‰$; $n = 8$). Animals had on average higher carbonate $\delta^{13}C$ values compared to the measured human enamel samples.

Table 3 Results for the compound-specific nitrogen isotope analysis and corresponding bulk isotope analysis ($\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$) for dentine collagen

Amino acid	$\delta^{15}N$ vs AIR				
	KM 22346:219	KM 18000:3400:3	KM 18000:3190:1	KM 18000:2404:5	KM 27177:29c
	FDI26	FDI37	FDI47	FDI15	FDI47
Individual #	1	2	3	4	5
Sex	F	F	M	M	F
Ala					
Gly					
Val	19.2	17.6	17.4	20.8	
Leu	17.0	17.3	15.7	13.9	18.3
Ile	15.3	15.8	16.8	16.1	16.7
Pro	20.3	19.7	18.4	21.6	19.9
Met					
Glu	19.4	18.6	18.5	20.9	19.0
Phe	9.9	14.3	11.3	10.0	11.2
Hyp	18.9	19.3	16.8	19.4	18.6
TP(Glu&Phe) terrestrial	3.4	2.7	3.1	3.5	3.1
$\delta^{13}C_{COLL}$	-19.8	-20.5	-20.1	-19.6	-19.9
$\delta^{15}N_{COLL}$	13.1	13.1	11.8	13.4	13.2
$\delta^{34}S_{COLL}$	9.2	4.3	9.2	9.4	

For the humans with both dentine (collagen) and enamel analyzed, the mean difference between carbonate and collagen $\delta^{13}C$ values (carbonate-collagen spacing) was $5.7 \pm 0.9‰$ ($n = 37$) while for the sampled cattle and sheep/goat, it was $10.3 \pm 0.7‰$ ($n = 5$). Despite the small number of animal samples in the comparison, the difference in the carbonate-collagen spacing between humans and herbivores is very clear.

Results of the statistical analysis for the enamel $\delta^{13}C$ data are presented in ESM 2. There was no statistically significant difference in enamel $\delta^{13}C$ values between the estimated females and males ($U = 468$, $p = 0.633$) nor in the sex-assigned data within the time period with the largest sample representation, Viking II–III period. In summary, as regards the $\delta^{13}C$ values of total dietary intake, differences related to estimated sex could not be detected, suggesting generally similar base diets through childhood for sexes.

Finally, comparisons between $\delta^{13}C$ values grouped according to period indicate that there was no statistical difference between the Merovingian period and Viking I period samples ($U = 45$, $p = 0.077$). However, the results show that the combined Merovingian–Viking I samples were statistically different from Viking II–III ($U = 147.5$, $p = 0.000$) and combined Viking IV–FP. There was also a statistically significant difference between the Viking II–III and combined Viking IV–FP samples ($U = 393$, $p = 0.034$).

Discussion

On diet and origins

The carbon and nitrogen isotope results for collagen are shown with faunal stable isotope data from Finland and the northern Baltic Sea area in Fig. 5. Based on the faunal comparison data and the commonly applied trophic enrichment factor in the isotope values ($+3–5‰$; e.g., Hedges and Reynard 2007) the Luistari human carbon and nitrogen isotope values on average are higher than would be expected for a diet containing only terrestrial resources suggesting a substantial intake of animal protein of a relatively high trophic status, i.e., high $\delta^{15}N$ values. The Luistari $\delta^{13}C$ values are similar with the Alytus site in Lithuania, interpreted to represent a C_3-based terrestrial diet such as the consumption of different crops and domestic animal products (Whitmore et al. 2019) but the mean $\delta^{15}N$ value at Alytus is lower compared to Luistari. In addition, the Luistari collagen $\delta^{13}C$ values are somewhat higher than expected based on the comparison data from terrestrial fauna and reference populations from the Baltic Sea coast (Figs. 5 and 6). The Luistari $\delta^{13}C$ and $\delta^{15}N$ values are most consistent with a mixed diet of terrestrial and aquatic organisms and considering the inland location of the site and its proximity to Lake Pyhäjärvi most plausibly indicate the use of freshwater fish as a regular component of population diet.
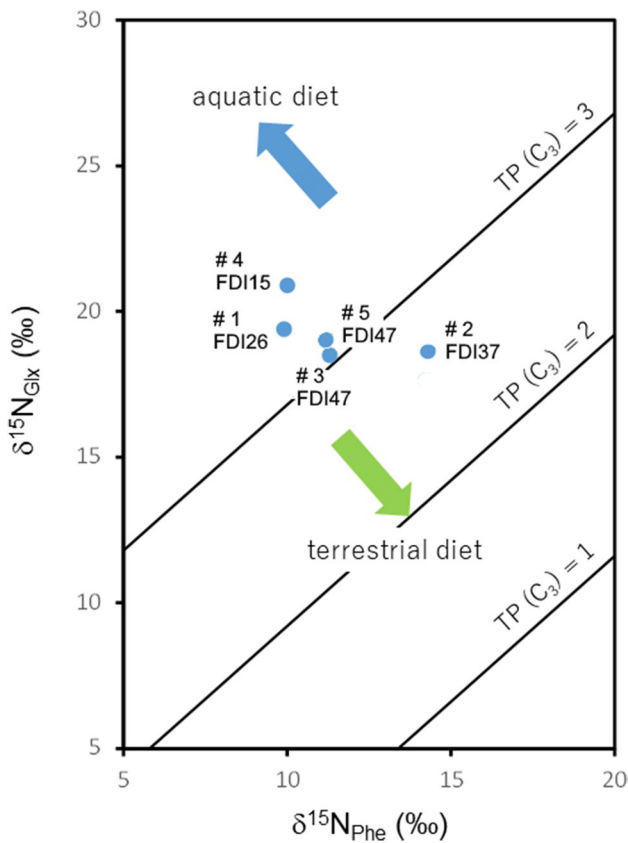
Fig. 4 A scatterplot of $\delta^{15}N$ values of glutamate and phenylalanine for the analyzed dentine samples. The lines represent expected $\delta^{15}N$ values for producers (TP = 1), primary consumers (TP = 2), and secondary consumers (TP = 3). Arrows represent increasing terrestrial and aquatic dietary protein

As severe malnutrition is known to cause elevated $\delta^{15}N$ values in bodily tissues, the on average high $\delta^{15}N$ values could also be manifestation of dietary stress recorded in the dentine. Dental hypoplasia can be caused by various reasons such as nutrition deficiency or a long-lasting disease, or a combination of these (Hillson 2014, pp. 189–191). Its occurrence is highly variable in North European populations (Liebe-Harkort 2012; Limbo 2019; Salo 2016, p. 320). The condition may be underrepresented in the Luistari remains because of the overall preservation but the large frequency (32%) in the studied tenth century CE burials indicates that in the past, famine was possibly not an uncommon guest. However, considering that both the amino acid $\delta^{15}N$ values and the $\delta^{34}S$ data are consistent with extensive freshwater fish consumption, the high $\delta^{15}N$ values are primarily taken as an indicator of a regular intake of high trophic level protein.

Because the study area is located inland, marine animals such as seals were probably a rare dish. There is so far no evidence of seals in the Luistari burials, but a few undated seal bones have been found in the excavations of the Yli-Nuoranne and Osmanmäki sites in Eura (Lehtosalo-Hilander 1984, p. 336, 2000a, p. 204). The seal bones suggest at least occasional hunting campaigns in the past, and therefore, it is possible that some of the people buried in Luistari also participated in sealing. Regular consumption of marine protein should be recorded into bone collagen as high $\delta^{13}C$ and $\delta^{34}S$ values. For example, Baltic Sea fish and seals display typically $\delta^{34}S$ values between + 10 and + 20‰, and human populations relying on the Baltic Sea catch should show similar values depending on proportions of seals and fish from various trophic levels included in the diet (Craig et al. 2006; Linderholm et al. 2014). In Luistari, the measured

Fig. 5 Mean values and standard deviations for the Luistari human collagen and selected reference fauna from Finland and the Northern Baltic Sea area (Bläuer et al. 2016; Etu-Sihvola et al. 2019). Modern fish flesh samples from the Pyhäjärvi lake have been corrected for the Suess effect by + 1.5‰ (Keeling 1979)
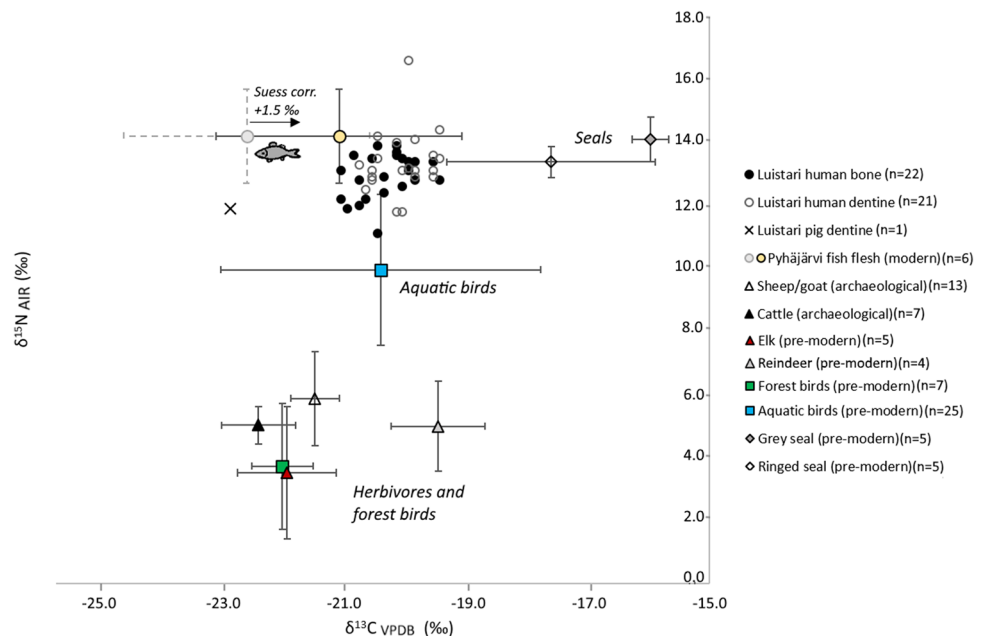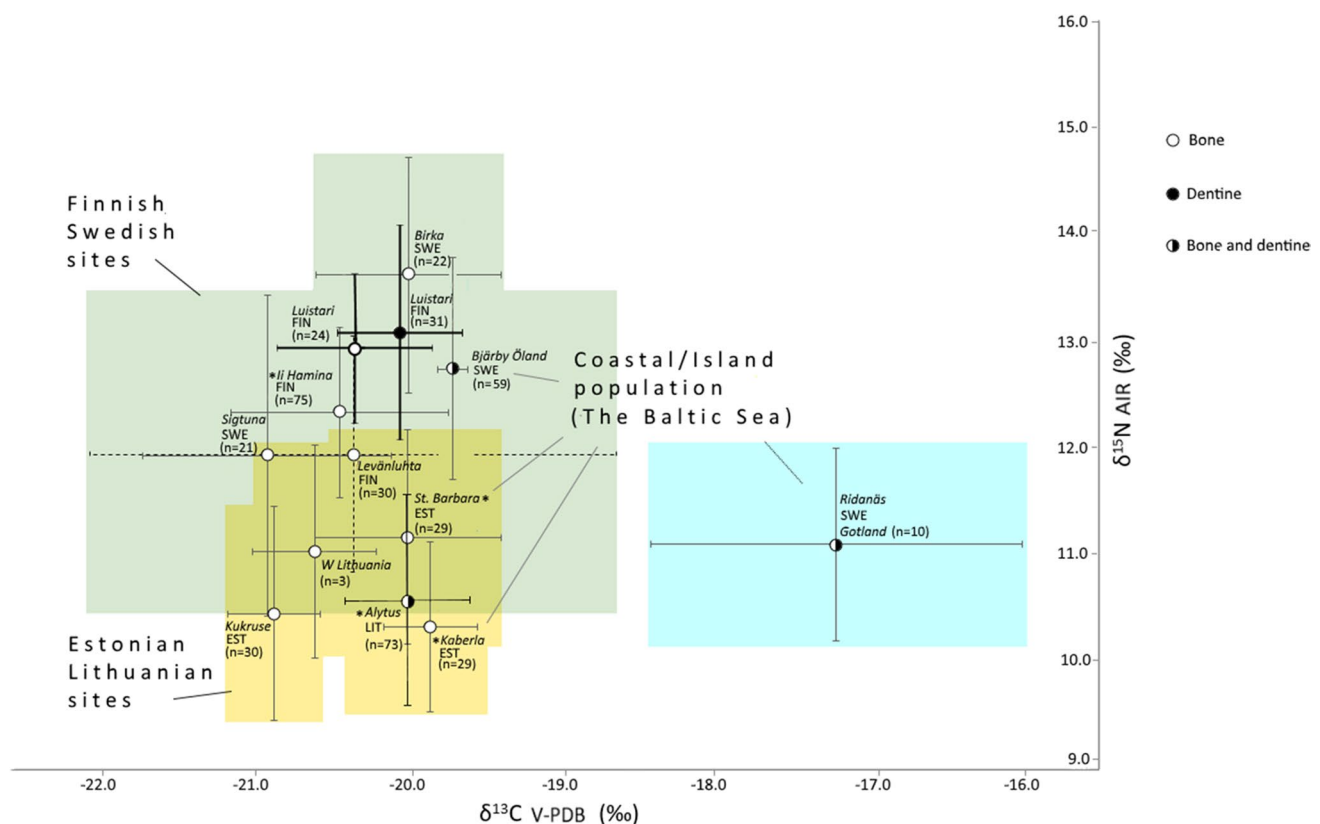
Fig. 6 The Luistari human collagen $\delta^{13}C$ and $\delta^{15}N$ results (mean and SD) compared to north European Iron Age and medieval populations (Aguraiuja-Lätti and Lõugas 2019; Bliujienė et al. 2020; Eriksson et al. 2008; Kjellström et al. 2009; Kosiba et al. 2007; Lahtinen and Salmi 2019; Linderholm et al. 2008; Oinonen et al. 2020; Oras et al. 2018; Whitmore et al. 2019). Sites dating considerably older and younger than Luistari have been marked with *. For better legibility, a dashed line is used to depict the standard deviation of the Levänluhta population. Site coordinates are listed in ESM 3

human $\delta^{13}C$ values do not indicate a consistent and significant marine contribution in the diet of any of the studied individuals. An example of a highly marine (brackish) dietary intake is the Neolithic Västerbjers site on Gotland, Sweden, where the collagen carbon isotope values of humans interpreted as mostly depending on Baltic Sea seals were on average as high as $-14.8 \pm 0.6‰$ and the mean for $\delta^{15}N$ was $+15.7 \pm 0.7‰$ (Eriksson 2004). Later Viking Age and Early Christian period, humans from the site of Ridanäs on the island of Gotland with an estimated marine dietary contribution of ~50% display $\delta^{13}C$ values at $-17.3 \pm 1.2‰$ (Fig. 6; Kosiba et al. 2007). Compared to these Baltic Sea reliant populations and typical isotope values of Baltic Sea seal collagen, the Luistari humans had lower $\delta^{13}C$ values (Figs. 5 and 6), suggesting that Baltic Sea resources did not feature significantly in their diets. Furthermore, the fact that the human $\delta^{15}N$ values are on par with those of seals precludes the possibility of seals making up a significant part of their regular diet. If there was marine influence, it would slightly increase the $\delta^{13}C$ values such as in the Finnish sites Levänluhta (c. 300–800 CE; Oinonen et al. 2020) and

Iin Hamina (c. fifteenth–seventeenth century CE; Lahtinen 2017; Lahtinen and Salmi 2019) that were located near the Baltic Sea coast. At both sites, the Baltic Sea catch has been interpreted to feature in population diets.

Furthermore, the carbon isotope values in Luistari also overlap with those measured from Estonian and Swedish coastal/island populations of St. Barbara, Kaberla, and Bjärby (Aguraiuja-Lätti and Lõugas 2019; Eriksson et al. 2008). However, considering the location of the site, we find the Pyhäjärvi catch a more likely dietary source. We argue that the somewhat elevated $\delta^{13}C$ level of the Luistari people could be related to the unusual $\delta^{13}C$ values for the Pyhäjärvi fish (see also Tarvainen et al. 2008; Vuorio et al. 2007) which are high compared to values measured for fish in southern and central Finnish lakes Kernaalanjärvi, Jyväsjärvi, and Päijänne (mean $\delta^{13}C$ value between $-25.6‰$ and $-34.3‰$; Figueiredo et al. 2014; Syväranta et al. 2006). The carbon isotope values for the Pyhäjärvi fish suggest an influence of a carbon source with a distinctively high $\delta^{13}C$ value on the lake. Lake Pyhäjärvi sits on top of the Mesoproterozoic Satakunta Formation which, uncharacteristically for

the old crystalline rocks of Finland in general, contains calcite, present also in the dispersed glacigenic sediments of the region, having a $\delta^{13}C$ value of ca. -6 to $-4\%o$ (Kortelainen et al. 2007). Also, the relatively large size of the Pyhäjärvi lake, c. 155 km², could be one cause for the on average high fish isotope values because in larger lakes the role of atmospheric CO_2 and weathered carbonates seems to be large in the in situ production of the dissolved inorganic carbonates (Post 2002). These local conditions underline the importance of regional fauna and other environmental references in the study of human diets.

Additionally, other contributors towards elevated $\delta^{13}C$ values measured in humans could be the consumption of (wild forest) reindeer (*Rangifer tarandus* sp.) or the use of C_4 crops. Because of their diet, reindeer typically have high $\delta^{13}C$ compared to other C_3 herbivores (Drucker et al. 2001). Reindeer fur has been identified in the grave 56 finds (Kirkinen et al. 2020) and it seems possible that this species also contributed to the Luistari diet. The role of high $\delta^{13}C$ crops such as millet remains however uncertain. Until the Middle Ages, millet was a common crop in central Europe (Gyulai 2014). Archaeobotanical evidence on millet use has been reported also in the Baltic Sea countries, and there are sporadic finds from southernmost Sweden, dating from the Bronze Age to the Roman Iron Age (e.g., Grabowski 2011; Pollmann 2014). Despite these finds, there is so far no archaeobotanical evidence on the consumption of millet nor other C_4 plants in Finland during the medieval period, and the collagen isotopic data for domestic animals also implicates a reliance on C_3 crops (Bläuer et al. 2016; see also Kosiba et al. 2007). Therefore, we assume that millet was not a frequent dietary resource for the Luistari population.

Aquatic diets shown by $\delta^{15}N$ values of amino acids

The compound-specific isotope data analyzed from five individuals show that there were individual differences in terrestrial and aquatic protein use during childhood. The highest TP (trophic position) values were calculated for the first molar of individual #1, a Merovingian period (eighth century) child (9–11 years) who had dental calculus and was buried with a small equal-armed brooch and a knife (grave 461; Lehtosalo-Hilander 2000a, pp. 24, 26). The TP value was high also for the individual #4, a Viking period (tenth century) male who had several dental pathologies: alveolar resorption, calculus, dental trauma, and dental hypoplasia. The individual was buried with a Petersen E-type spearhead, a Borre style animal head ring pin, a fire steel, bronze spiral ornaments, a scythe, and other grave goods (grave 135; Lehtosalo-Hilander 1982c, pp. 129, 131, 1982a, p. 111). The bulk $\delta^{13}C$ and $\delta^{15}N$ isotope values were very similar for these individuals and the $\delta^{34}S$ values were among the "base population" (see "Sulfur"). The high TP values ($>> 3.0$) can

be interpreted as indications of significant use of freshwater fish but could also be explained by the consumption of pork that had fed with high trophic–level food such as fish (Müldner and Richards 2005; Naito et al. 2013a) or other human waste (Lahtinen and Salmi, 2019). The stable isotope values for a Merovingian period pig analyzed from Luistari indicate that it had a high trophic level diet ($\delta^{13}C = -22.8\%o$; $\delta^{15}N = +11.9\%o$; Etu-Sihvola et al. 2019).

Two Viking period (ninth/tenth century) individuals had TP values at 3.1 possibly indicating that fish or other high trophic–level animals were possibly included as a part of their diet. Individual #3 was a male who had dental calculus and was buried under a sword in a double grave together with another possible male, a dog, three spears, and other artifacts (grave 281; Lehtosalo-Hilander 1982c, pp. 187–188, 1982a, p. 186). Individual #5 was a female who had calculus, caries, dental hypoplasia, a minor dental trauma, and a periapical lesion in the mandible. The individual was buried wearing abundant amount of bronze jewelry, including two round Finnish shoulder brooches with a bronze chain, a large neck-ring, and a wide bead set similar to those found in Gotland and Courland (grave 1260; Bliujienė 2006; Lehtosalo-Hilander 2000a, pp. 147–149). These individuals had similar collagen $\delta^{13}C$ values to those of individuals #1 and #4 but individual #3 had a distinctively low $\delta^{15}N$ value ($+11.8\%o$) compared to the other four individuals, and the mean for the Luistari humans.

An exception for the high TP values was individual #2, a female buried in a multiple grave with another female and two or three children at the beginning of the Viking period. The deceased was buried wearing Finnish round brooches and a finger-ring (grave 294; Lehtosalo-Hilander 1982c, pp. 200–201) and based on the amino acid data (TP = 2.7), this individual had consumed omnivorous diet with a lower amount of aquatic foods compared to the other Luistari humans studied using amino acid analysis. The difference observed in the source amino acid phenylalanine $\delta^{15}N_{Phe}$ value compared to the other individuals indicates a different source of nitrogen for the foods consumed by this individual even though the source could not be further specified. Terrestrial animals can have large range in collagen $\delta^{15}N_{Phe}$ values (Ohkouchi et al. 2017). The bulk $\delta^{13}C$ and $\delta^{15}N$ values were high which could mean that also this individual consumed protein-rich aquatic products. The low sulfur isotope value ($\delta^{34}S = +4.3\%o$) could mean that the individual had lived in a family relying on the Pyhäjärvi catch. Another possible explanation is that the individual had originated elsewhere.

Sulfur

The Luistari sulfur isotope results can be grouped into two or three different clusters. The largest group, interpreted to

represent values typical for "the base population" ($n = 24$), with $\delta^{34}S$ values between ca. $+ 7.4$ and $9.5‰$, was present throughout the whole studied time interval and based on this likely represents the most typical variation in the local values. This range is similar to the $\delta^{34}S$ values measured for pre-modern, terrestrial mammals from Finland (Etu-Sihvola et al. 2019), and it is somewhat lower than the values measured for the Luistari cattle remains that likely date younger than the human burials (Lehtosalo-Hilander 2000b, pp. 56, 146). If the Luistari cattle $\delta^{34}S$ values ($+ 10.0‰$; $n = 2$; Etu-Sihvola et al. 2019) represent an average for the local terrestrial sources, this suggests that the diet of the base population included a dietary component with lower $\delta^{34}S$ values. The $\delta^{34}S$ values obtained from the various modern lake Pyhäjärvi fish species were highly consistent at $+ 4.5‰$ (± 0.3, $n = 6$), suggesting a relatively low $\delta^{34}S$ value for the hypothesized main freshwater component of the diet. The Pyhäjärvi fish $\delta^{34}S$ values thus support the idea that the average human $\delta^{34}S$ value (c. $+ 8‰$) would be a mixture of terrestrial and the lake Pyhäjärvi signals. However, we note that while the fish may accurately reflect the present-day $\delta^{34}S$ levels of Pyhäjärvi aquatic organisms, we cannot be certain whether these values apply to conditions that prevailed over 1000 years ago. Despite this uncertainty, the $\delta^{34}S$ values of the Luistari humans support the conclusion that the relatively high $\delta^{15}N$ levels are related to regular freshwater fish consumption.

Five individuals presented $\delta^{34}S$ values above $+ 10‰$. It is an interesting observation that the individuals with the highest measured sulfur isotope values (range $+ 10.3–11.6‰$; males in graves 13, 404, and 407 and females in graves 319 and 404), all date to the tenth–twelfth centuries CE. There is a weak positive correlation between the Luistari $\delta^{13}C$ and $\delta^{34}S$ values which suggests that the somewhat higher $\delta^{34}S$ values could indicate that some individuals consumed marine (Baltic Sea) foods, or, assuming that the range of local terrestrial $\delta^{34}S$ values is higher than that indicated by the cattle samples, they could be included within the range of the interpreted base population. Interpretation of the data is complicated by the lack of clear indications of marine input in the $\delta^{13}C$ measurement data.

Distinctively low sulfur isotope values below $+ 6‰$ (range $+ 4.3–5.8‰$; $n = 6$), resembling those of the Lake Pyhäjärvi fish, were measured for four Viking period individuals: two estimated males (graves 80 and 480), and two females (grave 294: individual #2 in and grave 765). It is however not obvious that the low values would reflect a more aquatic diet, i.e., the consumption of greater amounts of Pyhäjärvi fish, because there was a relatively large range in the corresponding $\delta^{15}N$ values ($+ 12.7 \pm 1.0‰$) for these individuals, resulting from varying amounts of terrestrial resources with typically lower $\delta^{15}N$ values compared to the aquatic environment. Here, it is worth noting that fish

muscle contains higher concentrations of sulfur compared to e.g., cattle meat (Nehlich 2015), suggesting that even a small regular intake of Lake Pyhäjärvi fish, especially in situations with a lower general intake of animal protein, could dominate the dietary $\delta^{34}S$ signal and decrease consumer´s $\delta^{34}S$ values from the assumed terrestrial levels indicated by the cattle samples. For example, the male buried in grave 480 with a dog, a large spearhead, straight-backed bearded axe, a dirham fragment, and a piece of an amber bead in a purse, with clothes decorated with bronze spirals (Lehtosalo-Hilander 1982a, pp. 32–34) had low $\delta^{34}S$ value ($+ 4.8‰$) and one of the lowest $\delta^{15}N$ values ($+ 11.1‰$). This individual also had one of the largest values of carbonate-collagen spacing (8.0) consistent with a diet of relatively limited animal meat intake (see "Dietary insights from carbonate $\delta^{13}C$ values" below) compared to the individuals with higher $\delta^{15}N$ values and a smaller spacing.

Based on the isotope data, it is also possible that some of the individuals with the lowest and highest measured sulfur isotope values originated elsewhere, however, from a similar dietary culture with generally high $\delta^{15}N$ values, but it seems difficult to distinguish possible immigration based on the burial artifacts because distinctive graves with only foreign types of objects and dress-details are lacking. Two individuals had low $\delta^{34}S$ values measured both for dentine and bone. The dentine and petrous bone results for the male (grave 80) may represent at least the childhood spent somewhere else. If the female (grave 294) had a nonlocal origin, then the change of residence had to have happened within the last years before death.

Earlier research conducted on the high-status boat graves of Tuna in Alsike in central Sweden has shown reliance on fish (Lidén et al. 1997; Lidén and Nelson 1994) but the research in Viking town Birka has also revealed that high status does not always equal a high trophic level diet (Linderholm et al. 2008). The variation visible in the Luistari isotope results suggests that besides the Pyhäjärvi fish which appears to have been widely available everyday food, some individuals with seemingly high status (female in grave 56, and male buried under a sword in grave 281) used mainly terrestrial protein sources such as cattle or game or perhaps had a personal preference for certain types of food during their childhood.

Dietary insights from carbonate $\delta^{13}C$ values

Fewer published data are available for comparisons, but the Luistari human carbonate $\delta^{13}C$ values ($- 14.5 \pm 0.7‰$) were overall similar with previously reported Swedish archeological human data (Frälsegården $- 14.4 \pm 0.6‰$ and Birka $- 15.0 \pm 1.3‰$; Price et al. 2018; Sjögren and Price 2013).

Further dietary information is provided by the relative offset of carbonate $\delta^{13}C$ values compared to the $\delta^{13}C$ value of collagen for the same sample, i.e., the carbonate-collagen spacing. The systematic differences in the carbonate-collagen spacing between different trophic level consumers stem from the relative proportions of the main macronutrients in the diet (Krueger and Sullivan 1984). The composition of the diet, body size, and physiology differences reflect in the carbon isotope values for both carbonate and collagen and influence the carbonate-collagen spacing for $\delta^{13}C$ (O'Connell and Hedges 2017; Tejada-Lara et al. 2018). Carnivores get protein from meat and energy from lipids and proteins. Because lipids have less ^{13}C compared to proteins and carbohydrates, abundant intake of lipids lowers $\delta^{13}C$ value for carbonates and thus also decreases the carbonate-collagen spacing (Lee-Thorp et al. 1989). Herbivores get their energy from plant carbohydrates and their diet is very low in lipid content, and the collagen $\delta^{13}C$ values are typically lower compared to carnivores because the protein content in plants is relatively low and the body must synthesize it from available plant carbohydrates. In addition to the above dietary differences, the production of methane in the digestive process of ruminant herbivores leads to an increased carbonate-collagen spacing (e.g., Passey et al. 2005). As a result, herbivores typically have large spacing (c. $7.8 \pm 1.1‰$) in comparison to carnivores (c. $3.4 \pm 0.9‰$), and omnivores show values in between c. $6.4 \pm 1.1‰$, depending on the consumed diet (Krueger and Sullivan 1984; Lee-Thorp et al. 1989).

In the Luistari results, the difference in the spacing between cattle and sheep or goat ($10.3 \pm 0.7‰$; $n = 5$) and humans ($5.7 \pm 0.9‰$; $n = 37$) is evident even though the animal carbonate samples were taken from different skeletal elements (enamel) than the analyzed collagen (bone). Although the formation and maturation of dental enamel and dentine are not contemporaneous processes, and thus the human carbonate and collagen $\delta^{13}C$ values examined have not formed from the exactly same dietary carbon input, the relatively small carbonate-collagen spacing in the Luistari humans compared to that of cattle and sheep can be interpreted as reflecting their omnivorous diet containing a significant amount of animal products rich in protein and lipids (Crowley et al. 2010; Lee-Thorp et al. 1989). There is a weak but significant negative correlation (Pearson's $r(35) = -0.44$, $p < 0.01$) between the human carbonate-collagen $\delta^{13}C$ spacing and collagen $\delta^{15}N$ values that reflect the association of the carbonate-collagen spacing to dietary protein and lipid intake. The carbonate-collagen spacing value measured for Luistari is slightly smaller compared to the value 6.5‰ observed at the Neolithic Frälsegården (Sjögren and Price 2013). Based on the difference, the Luistari diet could include more meat which is consistent also for the individuals having the lowest measured $\delta^{15}N$ values.

The establishment of the Luistari cemetery coincides with improving yet unstable climatic conditions recorded in the Northern Hemisphere during the first millennium. During the Merovingian period and at the beginning of the Viking period, climatic instability (reviewed by Helama et al. 2017) may have limited the success in farming and possibly also influenced negatively in population growth. Based on the paleo records, climate stabilized and the mean summer temperatures became more favorable during the tenth century CE (Medieval Warm Period; Lamb 1982, 1977; Mann et al. 2009) concurrently with increasing precipitation amounts (Büntgen et al. 2011, 2016; Helama et al. 2009; McDermott et al. 2001).

Our enamel carbonate $\delta^{13}C$ results (Fig. 7) show a possible temporal trend in the diet of Luistari humans. The mean $\delta^{13}C$ value increased from $-15.3‰$ during the Merovingian-Viking I period to $-14.3‰$ over the Viking II–III and was $-14.5‰$ in the Viking IV and final period samples. Mann–Whitney test indicated that the Merovingian period and Viking I period are not different from each other but combined are different from the ensuing VII–VIII period. The observed increase in the mean carbonate $\delta^{13}C$ values could tentatively be linked to a change in the energy component of diet, e.g., increasing intensity of farming, but this possibility should be studied more. Innovations such as crop rotation agriculture, introduced in southern Sweden at the latest during the Viking age (Grabowski 2011) and in Finland possibly at the same time (Vanhanen 2012) or at the beginning of the second millennia CE (Lempiäinen-Avci 2019, p. 26), may have also contributed to the observed change. Because the collagen isotope values show a general heterogeneity of dietary protein sources, it is also possible that population increase — reflected in the increasing number of burials during the Viking period (Lehtosalo-Hilander 2000b, p. 164) — included immigrated or otherwise mobile individuals with distinctively different diets. As mentioned earlier, females were overrepresented in the Merovingian and Viking period I group (77% of samples with sex identification), suggesting the possibility that the lower $\delta^{13}C$ values observed for this earlier part of the chronology of the site are not an actual temporal dietary trend, but related to a sex difference in dietary habits. However, the similarity of isotope values assigned to both sexes in the Viking II–III era samples suggests that the childhood diet was similar between sexes at least during the tenth century CE. This observation would support an earlier conclusion that the Luistari community was relatively egalitarian (Lehtosalo-Hilander, 1982c, p. 46); this view was based on the relatively even distribution of similar types of status artifacts in both female and male graves especially during the latter half of the Viking period (Lehtosalo-Hilander 1982c, p. 63, 2000a, p. 306).
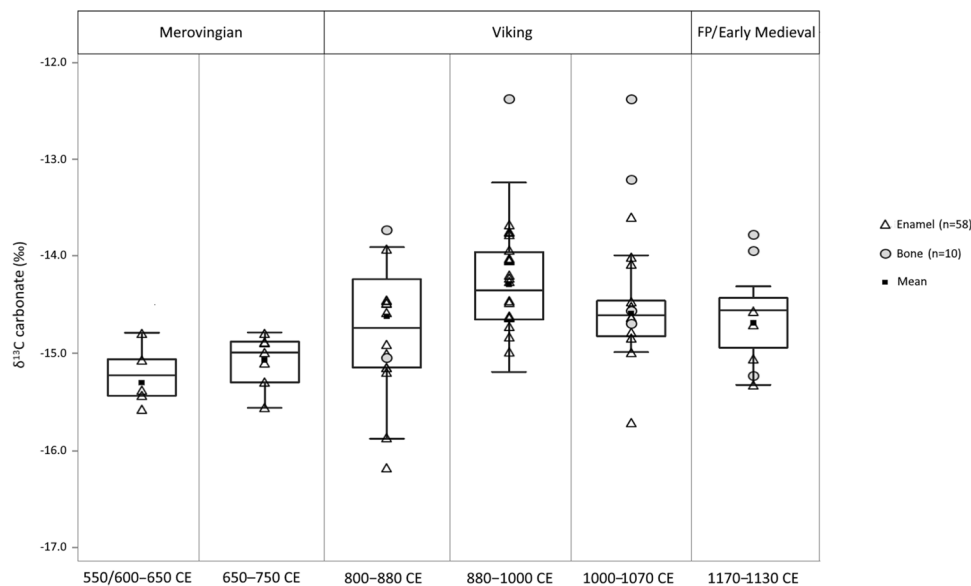
Fig. 7 Temporal distribution of the Luistari human carbonate $\delta^{13}C$ values for enamel. Whiskers denote range within 1.5 IQR. Horizontal line denotes median value. Boxplot area is the mean for 25%~75% percentiles. Data have been averaged for the individuals with multiple enamel samples so that each data point equals one individual. Bone sample C–1080 with ambiguous dating has not been included in the data. Year CE refers to the grave periodization by Lehtosalo-Hilander (2000a, 1982c). Mann–Whitney test indicated that the Merovingian period and Viking I period are not different from each other but combined are different from the ensuing VII–VIII periods

Conclusions

In this study, we presented the first results on the isotopic research focusing on the Merovingian, Viking, and Early Christian period human diet in the Luistari site of southwest Finland. The collagen $\delta^{13}C$ values were somewhat elevated for an inland population but are consistent with the $\delta^{13}C$ values for Lake Pyhäjärvi fish. Together with the high bulk $\delta^{15}N$ values and compound-specific $\delta^{15}N$ data for amino acids, they indicate regular use of freshwater fish (or other high trophic level animals) in the diet. The $\delta^{34}S$ results are also consistent with a mixed diet of freshwater fish and terrestrial resources.

Collagen carbon and nitrogen isotopic data did not yield clear indications of significant marine dietary intake that could explain the highest $\delta^{34}S$ values. Therefore, terrestrial and freshwater dietary resources seemed to form the essential part of the subsistence. However, versatility in the local livelihood strategies may not be the only explanation for the observed wide range in the measured isotopic values. Alternatively, the observed dietary variation may be related to population increase. Such mobile individuals (both males and females) could explain also the outliers we see in the sulfur isotope data.

Additional dietary information was acquired from carbonate $\delta^{13}C$ values, with a carbonate-collagen spacing consistent with generally high consumption of animal foods. We observed a possible temporal trend, an increase in the carbonate $\delta^{13}C$ values during the tenth–eleventh centuries

CE. This phenomenon could tentatively be associated with a change in diet linked with the intensification of farming during the late Viking period or a possible increase in population having different food habits. The Luistari individuals come from a small but apparently high-status community and compare well with the Swedish Roman Iron Age and Viking communities of Bjärby, Birka, and Sigtuna in their basic diet components. All these people had a relatively high protein intake through the consumption of fish and domestic and wild animals. However, contrary to members of the Birka trader community (Linderholm et al. 2008) and some other Scandinavian Vikings (Jarman et al. 2018; Kosiba et al. 2007), Luistari people do not show a distinct marine signal. Luistari individuals do not show a C_4 plant signal either which excludes any millet consumption. This also makes them distinct from contemporary Slavic communities south of the Baltic Sea (Błaszczyk et al. 2021; Reitsema et al. 2010) whose stable food consisted of a good deal of millet. Overall, early Medieval Luistari took part in the Viking Age exchange and trade network of the Baltic Sea despite their more easterly and inland location.

In summary, our isotopic investigation of the Luistari people indicates a population consuming plentiful animal proteins, with aquatic foodstuffs featuring prominently. While there was no evidence of dietary differences between biological sexes, a temporal trend in carbonate $\delta^{13}C$ values, suggesting some changes in typical diet towards the end of the study period, was noted. The observed change may be related to a change in the dietary culture or possibly

signal-increased mobility. The outliers among the measured sulfur isotope values could indicate mobility and the highest values possibly the use of marine products but interpreting the data is not straightforward.

Declarations

Conflict of interest The authors declare no competing interests.

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