



Biting into the truth: Connecting oral pathology and stable isotopes through the paradigmatic example of a hyper-specialized marine diet in Medieval Pontevedra (NW Iberia)

Clara Veiga-Rilo¹ · Antonio Martínez Cortizas^{2,3} · Olalla López-Costas^{1,4}

Received: 13 June 2023 / Accepted: 22 February 2024 / Published online: 7 March 2024
© The Author(s) 2024

Abstract

Human feeding patterns have been reconstructed in Archaeology by analysing either oral pathology or stable isotope ratios in human skeletal remains. However, no clear agreement has been developed between these two methodologies. The main objective of this study is to determine if we can establish a link between them when analysing a population with a hyper-specialized diet, in this case marine resources (and millet/maize). To reach this goal we developed a conjoined multi-isotope analysis using collagen and bioapatite ($\delta^{13}\text{C}_{\text{col}}$, $\delta^{15}\text{N}_{\text{col}}$ and $\delta^{13}\text{C}_{\text{car}}$) and a detailed study of oral health (caries, antemortem loss, periapical lesions, periodontal disease, calculus, and wear). All available skeletons with at least one preserved tooth from two cemeteries of the medieval town of Pontevedra ($n=34$) were studied. The buried individuals belonged to the guild of fishers and artisans, professions which were dominant among the families of medieval Pontevedra. A detailed FTIR-ATR study of extracted bone bioapatite showed a high correlation between bioapatite carbonate content, carbonate typical vibrations, and FTIR-ATR indices related to bone diagenesis, which is in line with previous research. No significant correlations were found with bioapatite yield and isotopic composition ($\delta^{13}\text{C}_{\text{car}}$ and $\Delta^{13}\text{C}$), ruling out possible diagenetic effects. The diet was based on marine fish protein with contributions of millets (e.g., $\delta^{13}\text{C}_{\text{car}} -11.9 \pm 1.8\text{‰}$) that seems to be slightly higher in individuals linked to artisanal guilds. The oral pathology study shows severe dental wear from an early age (Grade 2–4 in permanent dentition for 20% of infants and 60% of juveniles in M1), as well as moderate-high presence of caries in permanent dentition (64%, 22/34) and dental calculus (72%, 24/33). Both the oral pathology and the isotopic signal differ from that observed in other areas of the Iberian Peninsula. This study points to the existence of connections between findings of the two methodologies, and specifically an association between intense dental wear and high consumption of marine resources and millet. At the same time, this analysis implies the necessity of caution in estimation of age by dental wear in populations linked to the sea.

Keywords Dental wear · FTIR-ATR · Bioapatite · Late Middle Ages · Fish diet · C_4 plants

Introduction

Reconstructing diet through the study of human remains has always been a prominent goal for researchers working in Biological Anthropology and Osteoarchaeology. Skeletons can provide direct information about an individual diet or population consumption patterns—in contrast to archaeological materials and animal/plant remains (which provide indirect information). This information can be linked to other features inferred from the burial and skeleton, for example, funerary ritual, health, social status, and biological profile. Traditional methods include oral pathology, which has been used for dietary reconstruction since the advent of paleopathology. There is a link between the type of diet and

✉ Clara Veiga-Rilo
clara.veiga.rilo@usc.es

¹ Group EcoPast (GI-1553), CRETUS, Area of Archaeology, Department of History, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Spain

² CRETUS, EcoPast (GI-1553), Facultade de Biología, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Spain

³ Bolin Centre for Climate Research, Stockholm University, 106 91 Stockholm, Sweden

⁴ Archaeological Research Laboratory, Stockholm University, Wallenberglaboratoriet, 10691 Stockholm, Sweden

the pathological features observed in the teeth and mouth (Hillson 1996; Bonsall and Pickard 2015). Teeth are the only part of the digestive system in direct contact with the external environment and, in consequence, cultural practices can modify oral pathology too (Cheung et al. 2019; Yanko et al. 2021). Individual physiology can also change the development of oral pathology; for example, a given individual can be more/less reactive to oral biofilm and this sensitivity can evolve with age or specific circumstances such as pregnancy (Hillson 2001; Bonsall and Pickard 2015; Kuehl and Temple 2020; Schats et al. 2022). Since the 1970s, geochemical approaches to diet have increased in importance, with stable isotope ratios being the most widely used today. Research on light stable isotope ratios in bone and tooth collagen and bioapatite (e.g., $\delta^{13}\text{C}_{\text{col}}$, $\delta^{15}\text{N}_{\text{col}}$, $\delta^{13}\text{C}_{\text{car}}$) has allowed us to reconstruct the type of food consumed during different periods of life. However, even though the reconstruction of diet through oral pathology and stable isotopes have coexisted for more than forty years and pursue a common goal, specialists are yet to find a clear relationship between them. In recent years, interest in linking stable isotope fingerprints with paleopathological markers has grown. Some agreement has been achieved for fractures (Curto et al. 2020), metabolic markers (Mangas-Carrasco and López-Costas 2021), and infectious diseases (Curto et al. 2019; Katzenberg and Lovell 1999), but the relationship with oral pathology remains elusive (see for example Murphy et al. 2013; Beck et al. 2018; Petersone-Gordina et al. 2018; Jílková et al. 2019; Dlamini et al. 2019). Different authors have found slight and inconsistent relationships of $\delta^{13}\text{C}_{\text{col}}$ with caries and dental wear (Toso et al. 2019; Bonsall and Pickard 2015; Valentin et al. 2006), or no clear pattern (Petersone-Gordina et al. 2018; Lillie et al. 2003). A high frequency of dental caries has often been linked to specific inputs in diet such as consumption of carbohydrates (low $\delta^{13}\text{C}_{\text{col}}$ and $\delta^{15}\text{N}_{\text{col}}$), but the results obtained so far do not show consistency (Toso et al. 2019; Inskip et al. 2019). The disagreement can be explained in part as a reflection of the fact that the two methods reflect different periods of the human diet: oral pathology normally reflects diet throughout life, but it can change quickly to respond to physiological stresses, while stable isotopes in bone reflect an average diet that can go from ten years to multiple decades and can also be modified by stress but in an opposite way than caries (high $\delta^{15}\text{N}_{\text{col}}$). In addition, both isotopic ratios and oral diseases are affected by cultural, social, and physiological aspects that may not necessarily be expressed in similar ways.

Most of the published comparisons between oral pathology and stable isotopes have been made in populations with an ‘average’ diet, which implies a vegetable base with a variable intake of terrestrial animal protein. When comparing average diets, the other confounding factors can be overexpressed easily. Due to this reason, we think that research in

populations with an extreme or hyper-specialized diet can provide a clearer view of the connection between the two methods. In addition, widening the spectra of the recorded oral pathology, rather than caries, and light stable isotopes, instead of $\delta^{13}\text{C}_{\text{col}}$ and $\delta^{15}\text{N}_{\text{col}}$, can also help to unveil associations between the two most widely used methods for diet reconstruction in osteoarchaeology. To pursue that goal, we have selected Pontevedra on the coast of Galicia, Northwest Iberia (Fig. 1), whose medieval and post-medieval skeletal collections have revealed one of the highest consumptions of marine resources in Europe (López-Costas and Müldner 2016, 2019). Textual sources, archaeological materials, and osteological remains all suggest that the medieval diet of the Pontevedra inhabitants was highly specialized in fish and shellfish with important intakes of C_4 plants (millets and later corn) (López-Costas and Müldner 2019; López Costas 2012), that contrast with other contemporary communities in Iberia. This is also one of the few regions in Iberia that remained under Christian domination for almost all the medieval period, a fact that may have helped to homogenise cultural preferences in diet over time. For all these reasons, the Pontevedra skeletal collections offer an excellent opportunity for our aims. Nevertheless, the area also has a disadvantage, as the highly acidic soils and high humidity of Northwest Iberia produce the alteration of the mineral part of the bone, causing intense diagenesis (López-Costas et al. 2016), and limiting the availability of large skeletal data sets.

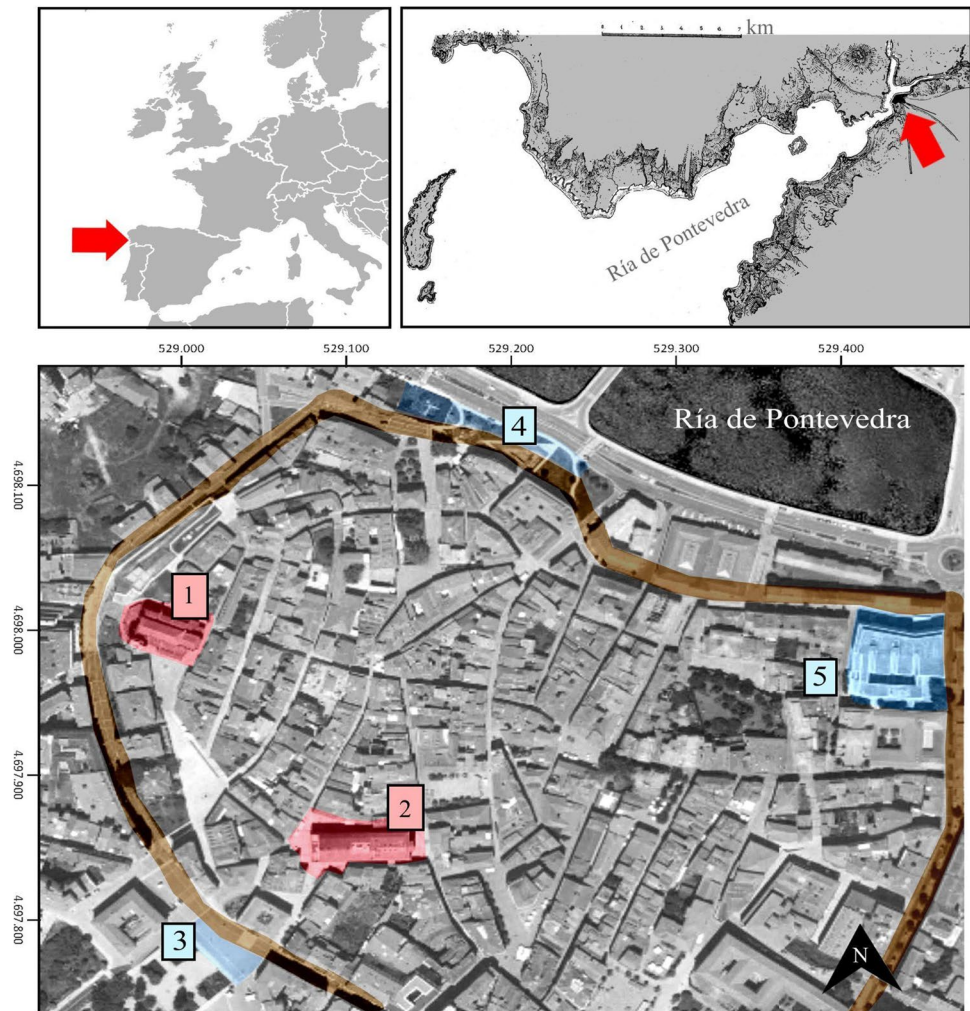
In this work, we analyse all available skeletons from medieval (13th–15th) and post-medieval (16th–17th) times found at the Pontevedra necropoleis of Santa María a Mayor and San Bartolomeu churches. Stable isotopes in bone collagen ($\delta^{13}\text{C}_{\text{col}}$, $\delta^{15}\text{N}_{\text{col}}$) and bioapatite ($\delta^{13}\text{C}_{\text{car}}$) were performed on all skeletons with at least one preserved tooth. Finally, an oral pathological assessment was done, recording not only caries but also antemortem tooth loss (AMTL), periapical lesions, periodontal disease, dental calculus, dental wear, and hypercementosis. Our findings are compared with those of other Iberian collections. Our hypothesis is that a trend between oral pathology and stable isotopes can be found when analysing a hyper-specialized diet, and that once this trend is discovered it can be transferred to other types of diet and skeletal collections.

Material and methods

The archaeological collections of Pontevedra

During the High Middle Ages (eleventh–thirteenth centuries) there was relative economic prosperity in northern Iberia due to the richness of the harvests, derived from the Medieval Climatic Optimum (10th to thirteenth centuries) (Le Roy 1971; Oliva et al. 2018) as well as other social factors

Fig. 1 Map of Pontevedra location including the necropolei of Santa María (n°1) and San Bartolomé (n°2), and the archaeological sites of Plaza España (n°3), Ponte do Burgo (n°4) and Ampliación do Museo de Pontevedra (n°5). The identifiers n°3, n°4 and n°5 correspond to medieval sites from which the animal samples of López-Costas and Müldner (2019) referenced in the isotopic comparison of this study were extracted. Modified from López-Costas and Müldner (2019)



such as the relative economic importance of the Camiño de Santiago. In contrast, during the Late Middle Ages (14th to fifteenth centuries) there is evidence of a gradual worsening of climatic conditions – the Little Ice Age phenomenon-, which, alongside various other factors, significantly affected the modus vivendi and the cereal-based production system of the aforementioned societies (Priegue 1998; Oliva et al. 2018; Silva-Sánchez et al. 2022). The Late Middle Ages were characterised by a decrease in the production of cereals, with direct repercussions on the economy of medieval societies in the form of economic impoverishment. However, in the transition to the Late Middle Ages, a few towns, whose economy was based on hyper-specialised commerce, and with the support of the emerging royal families, became independent of religious power. Among them, Pontevedra stands out for its specialization in the capture, processing and distribution of fish and other marine products. Its economy was primarily based on fishing, processing and commercially-derived products; it constituted, together with Padrón and Noia, one of the three coastal towns that were authorised to trade fish internationally by sea (Armas

Castro 1992; Priegue 1998). Pontevedra's seafaring families acquired different royal privileges as well as commercial advantages such as the commercial monopoly on three fish species (sardine, conger, and hake) and one marine mollusk (octopus) (Armas Castro 1992). Those species were easily preserved by salting or smoking and were in high demand abroad due to the religious precepts regarding fasting. The Ría de Pontevedra (a shallow firth or “fjord”) is one of several of the *Rías Baixas* which are known for their seafood and abundance of fish (Armas Castro 1992; Mangas-Carrasco and López-Costas 2021). The settlement grew around the church of Santa María a Maior *dos pescadores* (that is, the church of ‘the fishermen’), which is visible from the port and which dominates the bridge at the mouth of the navigable Lérez River (López-Costas and Müldner 2019; Armas Castro 1992). This parish comprised sea-connected families and guilds. In the thirteenth century, Pontevedra's urban area increased, and the church and parish of San Bartolomeu appeared at this stage, encompassing the most important artisan guilds. Both churches and their respective cemeteries are located inside the medieval wall

of Pontevedra (Filgueira Valverde 1991 in López-Costas and Müldner 2019) (Fig. 1). The inhumations here comprise a chronological window that spans four hundred years (13th to seventeenth centuries). The chronological ascription was made on the basis of field-work records, stratigraphy and radiocarbon dating (explained in López-Costas and Müldner 2019). Textual sources from this period suggest that the entire community consumed fish; these products formed the main base of the diet (Armas Castro 1992; Puig 2012). However, seafood consumption is associated in historical sources with poorer social classes, showing a cultural bias against the consumption of this type of food among the middle class in Pontevedra (Priegue 1998). Small vegetable gardens for fresh products as well as the introduction of cereals (including millet) from neighbouring farmlands provided the vegetable component of the diet. Terrestrial meat appears to have been scarce, as only two butcher shops were registered (see López-Costas and Müldner 2019), but eggs could be consumed from domestic fowl. Exported fish and octopus were either smoked or salted in the basement of family houses, since the humid and rainy environment of this area of Iberia made this unviable outside.

Skeletal collections

All human remains were excavated between the years 2007–2009 during two different archaeological rescue campaigns in the centre of Pontevedra, areas that are today the church of Santa María and the Teatro Principal (built after the demolition of the church of San Bartolomeu). They were found in layers dated to the late Medieval and Early Modern period, 13th to seventeenth centuries (for a detailed explanation about necropolis layers and dating see López-Costas and Müldner 2019 and Chao Álvarez 2008). The churches of Santa María and San Bartolomeu were separated by ~ 100 m and belonged to the same urban complex. Their churchyards can be considered typical of Christian burial spaces, with substantial reuse of the space and W-E oriented primary supine position burials (see Mangas-Carrasco and López-Costas 2021; López Costas 2012; Chao Álvarez 2008). Inhumations were simple fossae excavated directly from the soil, with an absence of coffins or other evidence that suggest the previous presence of coffins (e.g., nails). The individuals belonged to a non-diverse urban middle class, whose activities were related to seafaring and various craft activities. This is consistent with the differences between Pontevedra burials and *ad sanctos* burial type, which were reserved for social elites (Armas Castro 1992; López-Costas and Müldner 2019; MacKinnon et al. 2019) and which were not found here. Many burials had been previously disturbed by construction and infrastructure works. In the Santa María churchyard, remodelling of the water pipes system affected specifically the upper part of many skeletons, and

in consequence most crania were lost. In San Bartolomeu, Survey nº16 produced a high number of skeletons, but high physical alteration due to pressure disturbances caused the collapse and fragmentation of several skulls. A previous study of these collections (López Costas 2012) indicates that unfortunately the cranium was the most altered and missing part of the skeleton in both sites.

Sex and age estimation, and demographic profile

Markers for anthropometry, sex, and age were analysed using international standards suitable for Iberian populations. Sex was estimated for adults and older adolescents (> 16 years old for females and > 18 years old for males). Sex determination followed internationally established markers on the innominate and cranial bones (see Buikstra and Ubelaker 1994), aided by metrical analyses of long bones (Aguilera 1997). Age of non-adults was estimated using international (Scheuer and Black 2004) and Iberian (Lopez-Costas et al. 2012) postcranial developmental standards for growth and maturity, as well as dental development (Schour and Massler 1941; Gustafson and Koch 1974; Van der Linden and Duterloo 1976; Ubelaker and Ripley 1999; Alqahtani et al. 2010). Age for juvenile individuals was also aided by using postcranial fusion of the centres of ossification (Brothwell 1981; Gray et al. 1988; Krogman 1986) and checking them with western European datasets for the sacrum and long bones (Ríos et al. 2008; Cardoso 2008a, 2008b; Rissech 2008). Adult age was assessed using methods developed for the 4th rib, pubic symphysis morphology and auricular surface in the innominate bones, but also considering other features such as cranial suture closure or changes in the clavicle (see Buikstra and Ubelaker 1994). For a better explanation of the selected methods see López-Costas (2012). The sample was divided into five categories according to age estimation: infants/children (1–12 years old), juveniles (13–19 years old), young adult (20–39 years), middle adult (39–60 years), old adult (60+ years). Further information about age methods and categories can be found in López-Costas (2013). The sample comprises no individuals under 1 year old. We are conscious about the problems regarding the artificial group of Infant/Children. We decided to include both categories together in tables due to the small sample size ($n=7$; four individuals up to six years of age; three individuals up to twelve years of age); however, discussion regarding these individuals will be done considering their specific age.

Of the total skeletal assemblage ($n=82$), only 34 skeletons (25 Santa María: 9 San Bartolomeu. 14 females: 9 males; 11 indeterminate) were included in this study since they have part of their maxillae and/or at least one tooth (in situ and in avulsion). The skeletal collections are curated at the Universidade de Santiago de Compostela, in the facilities of the research group EcoPast. The demographic distribution

can be observed in Table 1. The most represented category is young adult, ~44% of the sample; of those ~17% females and ~21% males. The ~35% of the sample were non-adults: ~20% of them were less than 12 years old and ~15% juveniles. Note that the number of females over 40 years old is slightly higher ($n=4$) than the males ($n=2$), and it is the same with juvenile females ($n=4$) compared to males ($n=0$). This means that the female age distribution is wider while most males are young adults (20–39 years old; see Table 1).

Isotopic and FTIR-ATR analyses

The isotopic study was designed to complement a previously published work exclusively focussed on adult paleodietary reconstruction through $\delta^{13}\text{C}_{\text{col}}$ and $\delta^{15}\text{N}_{\text{col}}$ in bone collagen (> 12 years old) from the two collections (López-Costas and Müldner 2019). Here we performed two types of isotopic analyses: 1) to address protein diet with stable isotopes ($\delta^{13}\text{C}_{\text{col}}$ $\delta^{15}\text{N}_{\text{col}}$ $n=34$) by completing the previous bone collagen analyses including those individuals ($n=7$) that were not included previously; 6 infants/children and one juvenile (Table 4). 2) To reconstruct the total diet by knowing the bioapatite isotopic fingerprints ($\delta^{13}\text{C}_{\text{car}}$ $n=30$ up to 34; 4 samples failed during the extraction) with the bioapatite extraction in the same subsample used previously for collagen extraction. All analyses were performed at the EcoPast research group's clean-lab at the Universidade de Santiago de Compostela. Before processing, all bone samples were cleaned for at least 5×5 min ultrasonic cleaning with ultrapure water type-1 at the same facility.

Collagen was extracted in 7 samples following Longin procedure (1971) with modifications recommended by Collins and Galley (1998). The protocol described by Müldner and Jay (2008) and described in López-Costas (2012) explains each step followed in the laboratory. Carbon and nitrogen isotope analysis in collagen was undertaken by

Elemental Analysis—Isotope Ratio Mass Spectrometry (EA-IRMS) at Iso-Analytic Inc. using a Europa Scientific elemental analyser for the samples. Reference materials used for the $\delta^{13}\text{C}_{\text{col}}$ and $\delta^{15}\text{N}_{\text{col}}$ analysis are listed in Table 1 of supporting materials.

Bioapatite was extracted following Garvie-Lok et al. (2004) at the Universidade de Santiago de Compostela in the clean-lab facilities of the research group EcoPast (for more details see López-Costas et al. 2021, where the protocol is explained step by step). Carbon isotope ratios in carbonate from bioapatite were measured using a Europa Scientific 20–20 IRMS by adding phosphoric acid and measuring CO_2 by continuous flow-isotope ratio mass spectrometry (CF-IRMS) at Iso-Analytic Inc. Reference materials used for this analysis are listed in Table 2 and NBS-18, NBS-19 are distributed by the international Atomic Energy Agency (IAEA) as inter-laboratory comparison standard materials as well as internal or external standards. Analytical error was calculated by repeated analyses of internal standards and was $\pm 0.2\%$ or less for all elements.

Finely milled bioapatite samples (27) were analyzed by Fourier-transform infrared spectroscopy in attenuated total reflectance mode (FTIR-ATR), using an Agilent Technologies Cary-630 spectrometer, equipped with a diamond crystal, and hosted at the EcoPast laboratory of Universidade de Santiago de Compostela, Spain. Spectra were acquired in absorbance mode, in the mid-infrared region (4000 to 400 cm^{-1}), using 4 cm^{-1} resolution and averaging 100 scans per sample. The equipment was thoroughly cleaned, and a background was collected before each measurement. The R package {baseline} (Liland et al. 2010) was used for baseline correction of the spectra, to avoid bias in the spectroscopic signal due to scattering, reflection, temperature, concentration, or instrument anomalies; and the R {andurinha} package (Álvarez Fernández and Martínez Cortizas 2020) was applied to determine peak position (i.e., wave numbers of the peaks) based on the second derivative spectra.

Table 1 Age and sex distribution of the analyzed assemblage considering together Santa María and San Bartolomeu churches

	Female		Male		Indeterminate		TOTAL	
	n	%	n	%	n	%	n	%
Infant/Child (1–12 years old)	0	0	0	0	7	21	7	21
Juvenile (13–19 years old)	4	12	0	0	1	3	5	15
Young adult (20–39 years old)	6	18	7	21	2	6	15	44
Middle adult (40–50 years old)	4	12	1	3	0	0	5	15
Old adult (60+ years old)	0	0	1	3	0	0	1	3
Indeterminate	0	0	0	0	1	3	1	3
TOTAL	14	42	9	27	11	30	34	100

Five indices usually applied in bone research to evaluate bone diagenesis and composition were applied, the IR splitting factor (IRSF), B-type and A-type carbonate substitutions in phosphate (BPI, API), the carbonate/phosphate ratio (C/P), and carbonate/carbonate ratio (C/C) (France et al. 2020). Following the minimum standard criteria proposed by Smith et al. (2023), the highest and lowest wavenumbers of peaks and troughs were calculated for each single spectrum. Smith et al. (2023) also reviewed the application of the C/P ratio and found that different authors propose different ratios involving the use of the vibration at peak position of the phosphate stretching (around 1019 cm^{-1}) or at the slope of the peak (at 1035 cm^{-1}), arguing that the second is more stable than the former. Thus, we calculated the C/P ratio in both ways: C/P_1 using the peak absorbance of phosphate and C/P_2 using the absorbance at 1035 cm^{-1} .

Oral pathology

Oral pathology analysis was performed by different macroscopic studies on 458 teeth (belonging to the 34 individuals analyzed in this study, including both permanent and deciduous teeth), analysing 723 lesions. Dental caries, *antemortem* tooth loss (AMTL), periapical lesions (PL), periodontal disease (PD), dental calculus, dental wear and hypercementosis were recorded. Tooth type, laterality and arch in cases of avulsed teeth were determined according to Hillson (1996). The presence, type and location of carious lesions was identified according to Chimenos (2003). For the severity of periodontal disease, the standards of Ogden (2007) in Nelson (2015) were followed. Periapical lesions were studied based on the recommendation proposed by Chimenos (2003). The presence and severity of calculus was recorded using the standard proposed by Buikstra and Ubelaker (1994). Tooth wear was considered following Smith (1984) for the anterior dentition and premolars and Brothwell (1981) for the posterior dentition (M1, M2). The eight classical categories of dental wear were merged into four to enhance the robustness of the analysis due to the small sample size (premolars and anterior dentition: Grade 0–1, Grade 2–4, Grade 5–7, Grade 8; posterior dentition: Grade 0–1, Grade 2–4, Grade 5–5 + +, Grade 6). The first group Grade 0–1 corresponds to the absence of wear and may present small facets; Grade 2–4 corresponds to moderate wear of the crown including exposure of the dentine on the cusps; Grade 5–7/Grade 5–5 + + (anterior dentition and molars/posterior dentition) corresponds to exposure of large areas of dentine, and Grade 8/Grade 6 (anterior dentition and molars/posterior dentition) corresponds to severe reduction of the crown height and may also include exposure of the roots. An average dental wear score of anterior and posterior dentition was performed for each individual. First and second molars in both maxillae and mandibles were selected to enhance the comparability

with other studies, excluding third molars due to the variable age of its eruption. Anterior dentition was excluded from the dental wear comparison analysis as few Iberian collections address them as well as in the cases that are referenced, methodologies diverge. Hypercementosis was recorded following the descriptions in Tang et al. (2015).

Statistical analysis

Statistical analyses were performed with Rstudio calculating basic descriptive statistics for each group of samples. Shapiro–Wilk tests were used to test normality. We have applied non-parametric (Wilcoxon Mann–Whitney U-test, Kruskal–Wallis tests) and parametric (Student's-t test) tests as necessary to explore comparisons within groups. Correlation between variables was explored through Fisher exact tests due to the small sample size. The p-values were considered significant when $p < 0.05$.

Results

FTIR-ATR evaluation of bioapatite integrity

The FTIR-ATR spectra of the bioapatite samples show the characteristic vibrations of its main mineral constituents, phosphate and carbonate (Fig. 2). The most intense absorbance vibration occurs at 1019 cm^{-1} corresponding to the asymmetric stretching of PO_4^{3-} . It is complemented by PO_4^{3-} symmetric stretching at 958 cm^{-1} , and the doublet of bending vibrations at 602 and 559 cm^{-1} (Figueiredo et al. 2012). The shoulder at 1094 cm^{-1} is attributed to acidic phosphate anion (HPO_4^{2-}). Carbonates are also present, as attested by their stretching vibrations and 1455 and 1415 cm^{-1} , and the bending vibration at 874 cm^{-1} . A minor absorbance band is also observed at 475 cm^{-1} and

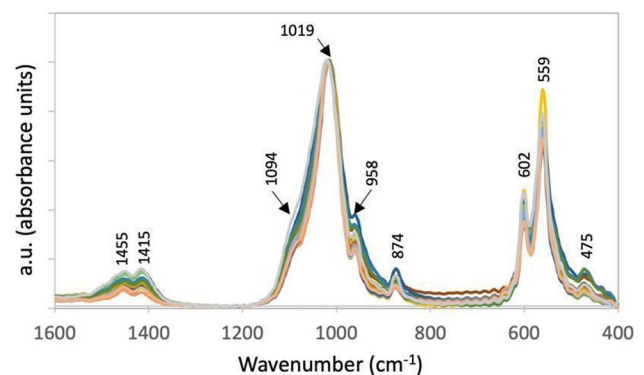


Fig. 2 FTIR-ATR spectra of the bioapatite samples studied in this investigation, with indication of the position (wavenumbers) of the most characteristic vibrations. The region $4000\text{--}1600\text{ cm}^{-1}$ is not represented because it showed background absorbance

attributed to PO_4^{3-} (Jastrzebski et al. 2011). No vibrations of secondary products formed upon diagenesis (as secondary carbonates) were found, as for example the peak at 710 cm^{-1} that is usually related to secondary carbonates formation (Lee-Thorp and Van der Merwe 1987; Smith et al. 2023).

As for the IR indices, we use here the range values suggested by France et al. (2020) for well-preserved archaeological bone as a reference for the values obtained in the samples we analysed (Fig. 3). Nevertheless, the comparison must be considered with care as we calculated the indices on extracted bioapatite and those of France et al. (2020) are based on whole bone measurements. Overall, values for all indices fall in narrow ranges (IRSF 4.34 ± 0.35 avg \pm std; C/P_1 0.10 ± 0.02 ; C/P_2 0.12 ± 0.02 ; C/C 1.00 ± 0.06 ; BPI 0.26 ± 0.05 ; API 0.26 ± 0.03).

The IRSF values are above the range for well-preserved archaeological bone bioapatite for all except three samples; for C/P, both C/P_1 and C/P_2, almost half of the samples fall within the range, but are close to the lower limit; C/C values are well within the range, except for six samples; for BPI all samples are close to the lower limit, but for API all samples fall within the range of well-preserved bioapatite.

In terms of information content, the calculated indices are largely redundant. Very high correlations (> 0.90 or < -0.90) were found between IRSF, C/P indices, and C/C; C/P_1 and C/P_2; BPI and C/P_1 and C/P_2, and API and C/P_2 (Table 2). The lowest correlations were found for API, with the IRSF and C/C (Table 2).

We also calculated the correlation between the indices and the characteristic absorbances of the bioapatite components (i.e., phosphate and carbonate vibrations) to bioapatite

Table 2 Correlation between the IR indices calculated for the samples of this study

	C/P_1	C/P_2	C/C	BPI	API
IRSF	-0.91	-0.90	0.91	-0.89	-0.78
C/P_1		0.98	-0.84	0.91	0.85
C/P_2			-0.85	0.95	0.90
C/C				-0.86	-0.74
BPI					0.97

yield, carbonate content, $\delta^{13}\text{C}_{\text{car}}$ in bioapatite carbonate, and $\Delta^{13}\text{C}$ (Table 3). Strong positive and negative correlations were found between the indices and characteristic vibrations of carbonates with bioapatite carbonate content. C/P_1, C/P_2, API, BPI, and vibrations at 1455 , 1415 cm^{-1} are positively correlated ($r\ 0.77\text{--}0.93$), while the IRSF, and C/C are negatively correlated. Vibrations at 1019 cm^{-1} (maximum absorbance of phosphate) and 874 cm^{-1} (bending vibration of carbonates), show moderate negative and positive correlation, respectively. A strong linear correlation between C/P and carbonate content of the bioapatite has been previously noted (Featherstone et al. 1984; Smith et al. 2023).

In the highly acidic ($\text{pH} < 5$) environment of the necropoleis studied here, carbonates are expected to be more susceptible to chemical alteration and leaching (i.e., diagenesis) than phosphates. This agrees with our findings, since increases in IRSF (i.e., phosphate crystallinity) and C/C (i.e., increase in B-type over A-type carbonate substitution), which are usually interpreted as evidence of diagenesis, are accompanied by decreases in bioapatite carbonate content

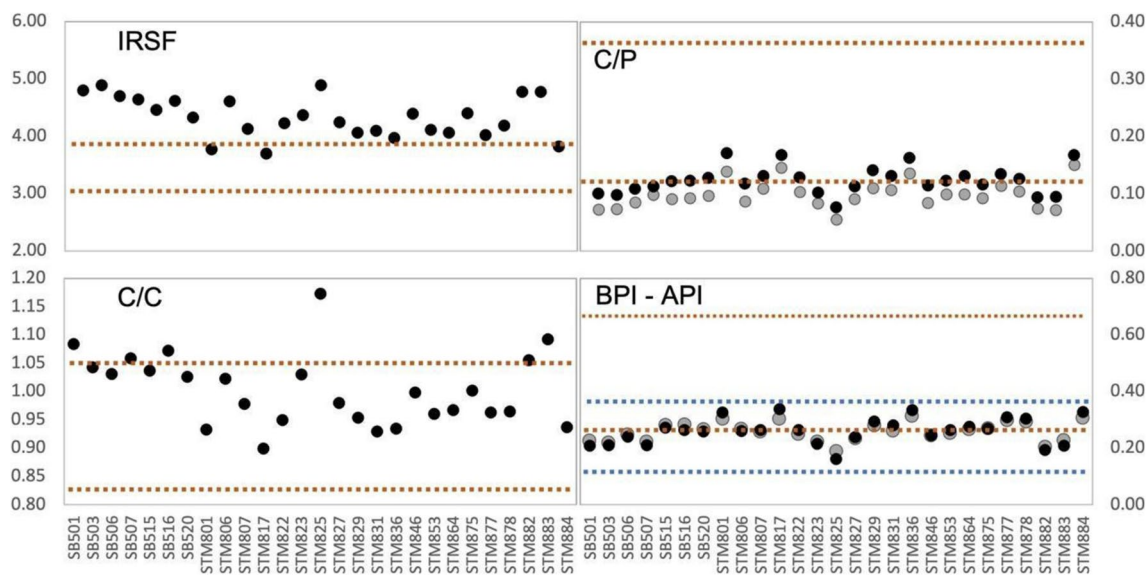


Fig. 3 IR calculated indices. Lines correspond to the lower and upper limits of well-preserved bone bioapatite (after France et al. 2020). Blue lines in the BPI-API panel correspond to API and orange lines

to BPI limits. C/P: black circles C/P_1, gray circles C/P_2; BPI black circles, API gray circles

Table 3 Correlation between the IR indices, characteristic vibrations (in cm^{-1}) of bone phosphate and carbonate, bioapatite yield (%), carbonate content (%) of the bioapatite and the isotopic composition

	yield	Carb	$\delta^{13}\text{C}_{\text{car}}$	$\Delta^{13}\text{C}$
IRSF	0.25	-0.79	0.29	0.19
C/P_1	-0.27	0.86	-0.25	-0.22
C/P_2	-0.31	0.89	-0.25	-0.23
C/C	0.25	-0.77	0.40	0.43
BPI	-0.25	0.83	-0.25	-0.19
API	-0.24	0.79	-0.15	-0.10
1454	-0.40	0.92	-0.14	-0.14
1415	-0.37	0.93	-0.25	-0.23
1094	0.07	0.42	-0.08	-0.06
1019	0.13	-0.65	0.24	0.21
958	0.08	0.18	-0.12	-0.12
874	-.27	0.61	-0.09	-0.24
602	-0.23	0.31	-0.07	-0.23
559	0.01	-0.35	0.27	0.09
475	0.22	0.13	-0.18	-0.05

– reflecting carbonate depletion, possibly by leaching of the weathering products.

Interestingly enough, no index or vibration is even moderately correlated to bioapatite yield or bioapatite isotopic composition. Our data suggest that, for the studied samples, diagenesis may have resulted in mass loss of the carbonates of the bioapatite, and possibly also of the phosphate to a lower extent, but the remaining carbonate preserves the original isotopic composition. This is consistent with the lack of evidence of exogenous carbonates incorporation to bone. As already indicated, the geochemical environment of the studied necropoleis is compatible with strong carbonate leaching but not with the formation of secondary carbonates.

Isotopic analyses

The isotopic study for non-adult and adult bone collagen is summarized in Table 4. The non-adult results are plotted against the total isotopic sample of López-Costas and Müldner (2019) in Fig. 4. The seven samples analyzed fulfilled the established quality criteria for good collagen preservation (see Van Klinken 1999). The C/N ratios of all our samples range from 3.1–3.4, which is considered a sign of no aberrant results and no presence of organic contaminant molecules (following DeNiro 1985; Van Klinken 1999). We calculate the Pontevedra site sample's average (including previous results from López-Costas and Müldner 2019) for $\delta^{13}\text{C}_{\text{col}}$ is $-16.4 \pm 2.1\text{‰}$, $n=68$ (Santa María $-16.1 \pm 2.5\text{‰}$, $n=49$; San Bartolomeu $-16.7 \pm 0.8\text{‰}$, $n=19$) and for $\delta^{15}\text{N}_{\text{col}}$ is $12.6 \pm 0.9\text{‰}$, $n=68$ (Santa María $12.8 \pm 0.9\text{‰}$, $n=49$; San Bartolomeu $12.2 \pm 0.8\text{‰}$, $n=19$).

When considering just the 34 skeletons with well-preserved maxillae and in agreement with previous results from (López-Costas and Müldner 2019), when comparing Santa Marías and San Bartolomeus individuals ($n=34$) no significant difference is found for $\delta^{13}\text{C}_{\text{col}}$ (U-test 538.5, $p=0.40$), while Santa Maria individuals have consistently more elevated $\delta^{15}\text{N}_{\text{col}}$ values than those from San Bartolomeu (U-test 699.5, $p=0.0026$). Regarding $\delta^{13}\text{C}_{\text{col}}$ including previous results from López-Costas and Müldner (2019) of adult individuals two groups were identified, where most of the individuals display values between -18.5‰ and -14.6‰ , while a small group shows values $> -12.5\text{‰}$ (STM824, STM828, STM830, STM833, STM883) (see Fig. 4) (López-Costas and Müldner 2019). This pattern of two separate groups is also observed for the 34 individuals analysed in this study (Fig. 4) presenting three individuals with values $> -12.5\text{‰}$ (STM823, STM824, STM883). Further, one individual (STM825) presents a $\delta^{13}\text{C}_{\text{col}}$ value lower than the rest of the sample reaching -20.3‰ .

Collagen data also suggests that the Infant/Child (1–12 years old) assemblage is distributed in two groups independent of their cemetery – Santa María and San Bartolomeu, provenance, see Fig. 4. Individuals SB519, SB520 and STM875 presented high $\delta^{15}\text{N}_{\text{col}}$ values ($> 13.0\text{‰}$), and a wider distribution in $\delta^{13}\text{C}_{\text{col}}$ (-15.3‰ to -17.3‰); whereas individuals SB518 and STM877 showed lower $\delta^{15}\text{N}_{\text{col}}$ values ($< 12.0\text{‰}$) and a narrower $\delta^{13}\text{C}_{\text{col}}$ distribution (-17.1‰ to -17.4‰). The juvenile STM876 is also included into the low $\delta^{15}\text{N}_{\text{col}}$ non-adult group. Individual STM883 belongs to the aforementioned group due to the high $\delta^{15}\text{N}_{\text{col}}$ (13.6‰) and $\delta^{13}\text{C}_{\text{col}}$ (-11.7‰), but her/his values are among the adult group with high $\delta^{13}\text{C}_{\text{col}}$. When the whole non-adult assemblage was compared to the adult assemblage (Fig. 4) (López-Costas and Müldner 2019) no significant differences were found in $\delta^{13}\text{C}_{\text{col}}$ (U-test 300.5, $p=0.52$) or $\delta^{15}\text{N}_{\text{col}}$ (U-test 311.5, $p=0.63$). Individual STM825 showed $\delta^{13}\text{C}_{\text{col}}$ values reaching -20.3‰ while in terms of $\delta^{15}\text{N}_{\text{col}}$ showed the minimal value of 10.8‰ . When the comparisons between non-adults and adults were done considering each cemetery separately, again no significant differences were found (San Bartolomeu, non-adult SB518, SB519, SB520 to adults; $\delta^{13}\text{C}_{\text{col}}$ U-test 13.00, $p=0.318$; $\delta^{15}\text{N}_{\text{col}}$ U-test 16.00 $p=0.09$), (Santa María, non-adults STM875, STM876, STM877, STM883 to adults; $\delta^{13}\text{C}_{\text{col}}$ U-test 38.0 $p=0.91$; $\delta^{15}\text{N}_{\text{col}}$ U-test 33.0, $p=0.63$). However, Infants/Children belonging to the first group are among the most elevated in $\delta^{15}\text{N}_{\text{col}}$ of San Bartolomeu and Santa María.

Isotopic data for bone bioapatite are presented in Table 5. Established quality criteria for well-preserved bioapatite were reached by all samples ($n=29$). There were no significant FTIR-ATR bands that indicate the presence of amide A, B, I, II and III, that is, collagen; or aliphatic compounds (for more information about collagen bands see Martínez

Table 4 Collagen stable isotope ratios and quality indicators for San Bartolomeu and Santa Maria churches. In this table we included the new isotopic values for the 7 non-adults as well as those obtained in López-Costas and Müldner (2019)

Ind Code	Site	$\delta^{13}\text{C}_{\text{col}}$ ‰ (VPDB)	$\delta^{15}\text{N}_{\text{col}}$ ‰ (AIR)	C:N	%C	%N	Yield (%)	Biological Sex	Age (years)	Age category	Sampled bone	Source
SB518	San Bartolomeu	-17.4	12.1	3.1	42.9	16.0	7.8	Indeterminate	04–06	Infant/Child	Fibula	This study
SB519	San Bartolomeu	-16.2	13.2	3.2	42.2	15.3	2.5	Indeterminate	03–06	Infant/Child	Maxilla	This study
SB520	San Bartolomeu	-15.3	13.4	3.1	44.6	16.7	12.4	Indeterminate	04–06	Infant/Child	Rib	This study
STM875	Santa María	-17.3	13.2	3.2	44.8	16.0	6.6	Indeterminate	08–12	Infant/Child	Mandible	This study
STM876	Santa María	-17.1	11.7	3.3	39.2	13.8	1.1	Indeterminate	12–15	Juvenile	Maxilla	This study
STM877	Santa María	-17.9	12.0	3.4	7.9	2.7	0.3	Indeterminate	04–06	Infant/Child	Mandible	This study
STM883	Santa María	-10.0	13.5	3.2	43.5	16.1	6.7	Indeterminate	06–11	Infant/Child	Skull	This study
SB501	San Bartolomeu	-16.1	12.7	3.2	37.2	13.4	-	Indeterminate	20–25	Middle adult	Skull	López-Costas and Müldner (2019)
SB503	San Bartolomeu	-17.2	11.6	3.3	36.5	13.1	-	Female	18–20	Juvenile	Skull	López-Costas and Müldner (2019)
SB506	San Bartolomeu	-16.9	11.8	3.3	29.2	10.3	-	Male	30–39	Young adult	Humerous	López-Costas and Müldner (2019)
SB507	San Bartolomeu	-17.5	12.5	3.3	41.9	15.0	-	Female	40–59	Middle adult	Skull	López-Costas and Müldner (2019)
SB515	San Bartolomeu	-17.4	11.0	3.2	41.6	15.1	-	Female	40–50	Young adult	Tibia	López-Costas and Müldner (2019)
SB516	San Bartolomeu	-16.6	11.4	3.2	35.9	13.0	-	Male	30–39	Young adult	Femur	López-Costas and Müldner (2019)
STM801	Santa María	-16.4	12.4	3.2	42.3	15.4	-	Female	20–30	Young adult	Rib	López-Costas and Müldner (2019)
STM806	Santa María	-17.6	12.7	3.3	36.2	12.8	-	Male	20–39	Young adult	Humerous	López-Costas and Müldner (2019)
STM807	Santa María	-16.5	14.0	3.3	32.6	11.6	-	Female	30–35	Young adult	Fibula	López-Costas and Müldner (2019)
STM817	Santa María	-16.7	12.5	3.6	23.0	7.5	-	Male	35–39	Young adult	Rib	López-Costas and Müldner (2019)
STM822	Santa María	-17.8	12.3	3.3	37.9	13.3	-	Male	+ 60	Old adult	Skull	López-Costas and Müldner (2019)
STM823	Santa María	-15.6	10.9	3.2	42.9	15.6	-	Female	18–20	Juvenile	Femur	López-Costas and Müldner (2019)
STM824	Santa María	-10.7	14.0	3.2	42.9	15.6	-	Female	20–35	Young adult	Radius	López-Costas and Müldner (2019)
STM825	Santa María	-20.3	10.8	3.3	41.5	14.8	-	Female	15–17	Juvenile	Femur	López-Costas and Müldner (2019)
STM827	Santa María	-16.7	12.9	3.3	35.3	12.5	-	Female	30–59	Middle adult	Tibia	López-Costas and Müldner (2019)
STM829	Santa María	-15.8	13.4	3.3	41.4	14.6	-	Female	40–59	Middle adult	Jaw	López-Costas and Müldner (2019)
STM831	Santa María	-17.1	12.9	3.2	40.3	14.5	-	Female	45–50	Middle adult	Rib	López-Costas and Müldner (2019)
STM833	Santa María	-11.7	13.6	3.3	34.8	12.2	-	Male	20–25	Young adult	Rib	López-Costas and Müldner (2019)
STM836	Santa María	-15.7	12.1	3.3	30.6	10.9	-	Female	19–20	Juvenile	Femur	López-Costas and Müldner (2019)
STM846	Santa María	-16.0	14.5	3.3	38.7	13.6	-	Indeterminate	20–30	Young adult	Femur	López-Costas and Müldner (2019)
STM853	Santa María	-18.5	12.5	3.4	36.9	12.6	-	Male	40–59	Middle adult	Long bone	López-Costas and Müldner (2019)
STM864	Santa María	-16.8	12.4	3.2	44.1	16.0	-	Male	39–50	Middle adult	Femur	López-Costas and Müldner (2019)
STM882	Santa María	-14.6	13.6	3.2	42.7	15.5	-	Female	25–35	Young adult	Femur	López-Costas and Müldner (2019)
STM884	Santa María	-17.7	12.7	3.3	42.8	15.3	-	Indeterminate	-	Indeterminate	Rib	López-Costas and Müldner (2019)

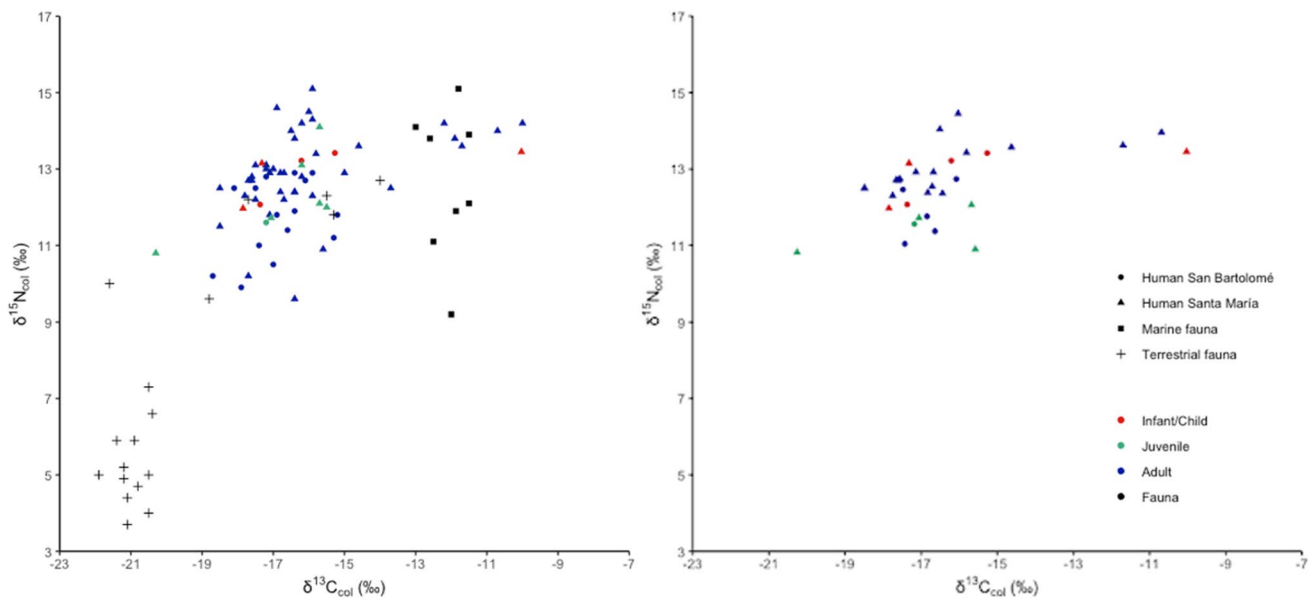


Fig. 4 (Left) Bone collagen $\delta^{13}\text{C}_{\text{col}}$ and $\delta^{15}\text{N}_{\text{col}}$ values of animal and human sample from Santa María and San Bartolomeu of Pontevedra including isotopic values from López-Costas and Müldner (2019). (Right) Bone collagen $\delta^{13}\text{C}_{\text{col}}$ and $\delta^{15}\text{N}_{\text{col}}$ values of the 34 human

samples from skeletons with at least one preserved tooth from Santa María and San Bartolomeu of Pontevedra analyzed in this study. Created with RStudio

Cortizas and López-Costas 2020) – only carbonate and phosphate bands were detected.

For bone bioapatite isotope analysis, average and standard deviation for $\delta^{13}\text{C}_{\text{car}}$ is $-11.9 \pm 1.8\text{‰}$, $n = 29$ (Santa María $-11.9 \pm 2.1\text{‰}$, $n = 22$; San Bartolomeu $-11.6 \pm 0.8\text{‰}$, $n = 8$) with values ranging from -14.2‰ to -4.7‰ . For $\delta^{13}\text{C}_{\text{car}}$, no significant difference was found between San Bartolomeu and Santa María for $\delta^{13}\text{C}_{\text{car}}$ (U-test 50, $p = 0.08$), but Santa María's $\delta^{13}\text{C}_{\text{car}}$ values tend to be higher than those from San Bartolomeu. There are no significant differences between non-adults and adults from Santa María ($\delta^{13}\text{C}_{\text{car}}$ U-test 73, $p = 0.16$) or for the San Bartolomeu site ($\delta^{13}\text{C}_{\text{car}}$ U-test 26, $p = 0.12$). The total assemblage shows a smooth distribution, but the non-adult individual SB520 separates from the group due to his/her high $\delta^{13}\text{C}_{\text{car}}$ value (-10.6‰). There are also no significant differences between males and females (San Bartolomeu $\delta^{13}\text{C}_{\text{car}}$ U-test 5, $p = 0.64$; Santa María $\delta^{13}\text{C}_{\text{car}}$ U-test 13, $p = 0.18$).

For $\Delta^{13}\text{C}_{\text{car-col}}$, the average of the total sample is 4.71 ± 1.12 , ranging from 1.95 (STM882) to 7.87 (STM825); Santa María 4.46 ± 1.24 ; San Bartolomeu 5.32 ± 0.71 . Although no significant differences were found between both sites when considering the whole sample; Santa María adult samples ($n = 20$) are significantly lower in $\Delta^{13}\text{C}_{\text{car-col}}$ than San Bartolomeu adult ($n = 9$) samples (U-test 75; $p = 0.047$), a trend that despite the small sample size can be seen in Fig. 4. Individual STM825 showed the maximum value of $\Delta^{13}\text{C}_{\text{car-col}}$ (7.87) and the minimum value of $\delta^{15}\text{N}_{\text{col}}$ (10.8‰) with respect to the total set. Individual STM882 showed the

minimum value of $\Delta^{13}\text{C}_{\text{car-col}}$ (1.95) while its $\delta^{15}\text{N}_{\text{col}}$ is over the average (13.6‰). No significant differences were found among age groups or sex.

Oral pathology

Dental caries With regard to the study of caries, 64% (22/34) of the individuals showed some type of lesion. Carious lesions were displayed in seventeen individuals from Santa María's churchyard ($n = 17/25$; 68%) and five from San Bartolomeu ($n = 5/9$; 59%), showing similar prevalence and with no significant differences between them. Within the non-adult sample, 33% (4/12; Santa María, $n = 2$; San Bartolomeu, $n = 2$) of the individuals showed carious lesions in the deciduous dentition, and 33% (4/12; Santa María, $n = 3$; San Bartolomeu, $n = 1$) in the permanent dentition. At least one carious lesion is observed in 60% (12/21) of the adult sample ($n = 6$ males, $n = 6$ females). Regarding age, 53% ($n = 8/15$) of the young adults displayed some type of carious lesion (1:1 male:female individuals), middle adults showed 60% ($n = 3/5$; 40% female individuals, 20% male individuals) and the only old adult showed carious lesions. No differences were found between churchyards (U-test 79, $p = 0.47$) or sexes (Kruskal–Wallis chi-squared = 4.9, $p = 0.08$), adult/non-adult, and age groups. Note that four individuals presented a greater number of carious lesions (STM876, STM824, STM825, STM833), three of them being female. As expected, there are significant differences between adult and non-adult groups (U-test = 28.5, $p = 0.003$) for

Table 5 Carbon stable isotope ratios in bioapatite and quality indicators for Santa María and San Bartolomeu churchyards

Code	Churchyard	$\delta^{13}\text{C}_{\text{carb}}$ (‰) V-PDB	$\Delta^{13}\text{C}_{\text{carb-col}}$ V-PDB	% Calcium carbonate content	Biological Sex	Age categories	Age (years)
SB501	San Bartolomé	-10.9	5.2	5.3	Indeterminate	Middle adult	20–25
SB503	San Bartolomé	-12.1	5.1	5.9	Female	Juvenile	18–20
SB506	San Bartolomé	-12.7	4.2	6.7	Male	Young adult	30–39
SB507	San Bartolomé	-12.7	4.8	7.2	Female	Middle adult	40–59
SB515	San Bartolomé	-11.4	6.1	7.6	Female	Young adult	40–50
SB516	San Bartolomé	-11.7	4.9	7.3	Male	Young adult	30–39
SB518	San Bartolomé	-11.3	6.1	5.7	Indeterminate	Infant/Child	04–06
SB520	San Bartolomé	-10.6	4.7	7.0	Indeterminate	Infant/Child	04–06
STM801	Santa María	-12.5	4.0	9.0	Female	Young adult	20–30
STM806	Santa María	-13.2	4.4	7.6	Male	Young adult	20–39
STM807	Santa María	-11.7	4.8	7.2	Female	Young adult	30–35
STM817	Santa María	-13.5	3.2	8.1	Male	Young adult	35–39
STM822	Santa María	-14.2	3.6	7.1	Male	Old adult	+ 60
STM823	Santa María	-10.9	4.7	6.6	Female	Juvenile	18–20
STM825	Santa María	-12.4	7.9	4.5	Female	Juvenile	15–17
STM827	Santa María	-12.1	4.6	7.3	Female	Middle adult	30–59
STM829	Santa María	-11.8	4.0	7.6	Female	Middle adult	40–59
STM831	Santa María	-13.3	4.0	7.8	Female	Middle adult	45–50
STM833	Santa María	-8.0	3.7	5.7	Male	Young adult	20–25
STM836	Santa María	-11.1	4.6	8.4	Female	Juvenile	19–20
STM846	Santa María	-13.0	3.1	7.0	Indeterminate	Young adult	20–30
STM853	Santa María	-12.9	5.6	7.4	Male	Middle adult	40–59
STM864	Santa María	-12.9	5.6	7.1	Male	Middle adult	39–50
STM875	Santa María	-12.3	4.6	6.7	Indeterminate	Infant/Child	08–12
STM877	Santa María	-11.6	5.7	6.4	Indeterminate	Infant/Child	04–06
STM878	Santa María	-13.3	-	6.9	Indeterminate	Infant/Child	03–05
STM882	Santa María	-12.7	2.0	5.2	Female	Young adult	25–35
STM883	Santa María	-4.7	5.3	5.8	Indeterminate	Infant/Child	06–11
STM884	Santa María	-12.1	5.6	9.4	Indeterminate	Indeterminate	-

permanent teeth. There are no differences between adult age groups (U-test = 36, $p=0.83$), nor between juveniles and adult age groups (U-test = 28, $p=0.69$); there are differences between the Infant/Child age group and the Juveniles (U-test = 0, $p=0.003$) as the Infant/Child group did not show any carious lesions in the permanent dentition (0/82). Therefore, a significant pattern of increased lesions with age is not observed, except among the Infant/child group and the rest of the sample.

Table 6 displays the prevalence of carious lesions in the teeth. For the total tooth sample, 10% of the teeth presented some type of carious lesions. Among the adult age group, 18% of permanent teeth were affected by at least one carious lesion, 11% of the permanent juvenile teeth also presented lesions. In contrast, the infant/child group (< 12 years) showed 0% in the permanent teeth, while 24% of the deciduous teeth were affected. They did show significant

differences between non-adults and adults (U-test 51.5, $p=0.007$), and with the adult group (U-test 0, $p=0.001$) without observing significant differences between juveniles and adults (U-test 13, $p=0.51$), or adult groups (U-test 42, $p=0.83$). No significant differences between biological sexes for the number of teeth affected were found (U-test 80, $p=0.87$). Analysing by type of teeth (deciduous/permanent dentition) a high prevalence of caries was found in all dentitions. The prevalence for permanent teeth is 22.1% for incisors, 28.3% in canines, and 24.5% in premolars, while first, second, and third molars showed 32.7%; 27.3%, and 54.3% respectively.

Analysis of the total number of lesions for permanent teeth ($n=130$) by position in the tooth, coronal lesions are the most prevalent in the anterior dentition as well as in premolars and first molars (M1); while occlusal lesions are the most common in the second molars and the third molars. In the anterior dentition after coronal lesions (62%),

Table 6 Oral pathology prevalence in deciduous and permanent teeth in the Pontevedra (together Santa María and San Bartolomeu) sample for carious lesions (CL), antemortem tooth loss (AMTL), dental calculus, and hypercementosis

Age group	N. Individuals	N. teeth CL		N. deciduous teeth CL		N. AMTL		N. Periapical lesions		N. teeth calculus		N. deciduous teeth calculus		N. teeth hypercementosis	
		n/n _{total}	%	n/n _{total}	%	n/n _{total}	%	n	%	n/n _{total}	%	n/n _{total}	%	n/n _{total}	%
Infant/Child	7	0/82	0	11/46	24	0/25	0	1	2	1/82	1	5/46	11	0/82	0
Juvenile	5	14/125	11	-	-	3/85	4	1	2	62/125	50	-	-	0/125	0
Adults	21	35/195	18	-	-	49/315	16	4	11	64/195	33	-	-	14/195	7
Indeterminate	1	2/11	18	-	-	-	-	0	0	3/11	27	0/0	0	0/11	0
TOTAL	34	42/413	10	11/46	2	52/397	13	6	15	112/413	27	5/46	11	14/413	3
Female	14	19/180	11	-	-	20/225	9	2	14	76/180	42	-	-	5/180	3
Male	9	22/106	21	-	-	30/139	22	1	11	28/106	26	-	-	9/106	9
Young adult	15	26/121	22	-	-	28/183	15	1	7	30/121	25	-	-	7/127	6
Middle adult	5	3/53	6	-	-	16/103	15	1	20	25/53	47	-	-	5/53	3
Old adult	1	3/21	14	-	-	5/29	22	1	100	9/21	43	-	-	3/21	2
Juvenile ♀	4	9/96	9	-	-	1/57	2	0	0	44/96	46	-	-	0/96	0
Indt. Juvenile	1	5/29	17	-	-	2/28	7	1	100	18/29	62	-	-	0/29	0
Young adult ♀	6	3/21	14	-	-	6/58	10	1	17	9/21	43	-	-	2/21	1
Young adult ♂	7	18/78	23	-	-	20/89	23	0	0	15/78	19	-	-	5/78	5
Indt. Young adult	2	0/5	0	-	-	0/8	0	0	0	4/5	80	-	-	0/5	0
Middle adult ♀	4	2/46	4	-	-	11/82	13	1	25	21/46	46	-	-	5/46	3
Middle adult ♂	1	1/7	14	-	-	5/21	24	0	0	4/7	57	-	-	0/7	0

cementoamel junction caries reach 38%. Prevalence on premolars and first molars is distributed among coronal caries (46%, 45%), lesions in the cementoamel junction (21%, 35%), root caries (18%, 5%), and occlusal lesions (1%, 5%). The main difference between M1 and premolars is that in the former 10% of the lesions correspond to total destruction of the crown (severe caries), where the origin of the lesion could not be determined. In the second and third molars, after lesions in the occlusal area (48%, 41%), the most common are the lesions in the cementoamel line (38%, 22%) and coronal area (10%, 30%); in both cases, we found that 5% were severe caries with indeterminate origin.

Antemortem tooth loss (AMTL), periapical lesions (PL) and periodontal disease (PD) Since presence of alveolar bone from upper or lower maxilla is necessary to evaluate AMTL and periapical lesions, only 21 individuals could be studied (see Table 6). From them, a total of 14 (67%) individuals showed AMTL: 62% adults (n = 13; Santa María, n = 11/19; San Bartolomeu, n = 2/2; no significant differences between sub-samples) and 9% non-adults (n = 1) (Table 6). Within individuals with AMTL, 52% showed also at least one carious lesion (48% adults, 4% non-adults). By number of preserved alveoli, 13% were reabsorbed (alveoli completely closed). When age groups are taken into account, 0% of the Infant/Child alveoli (0/25), 4% of Juvenile non-adult alveoli (3/85) and 16% of adult alveoli were reabsorbed; of

them 9% (20/225) belonged to females and 22% (30/139) to males. No significant differences could be found regarding sex (U-test 84, p = 0.7), although males tend to be more affected, despite their age distribution being narrower than females. Significant differences exist between non-adults/adults (U-test 55, p = 0.003) as older individuals are more affected. Although no differences can be determined between adult age groups (U-test 52.5, p = 0.12), significant differences are shown between < 12 years and adult groups (U-test 3, p = 0.006) as well as juvenile and adult groups (U-test 2.5, p = 0.011). Regarding periapical lesions 23% (5/21; Santa María, n = 4/19; San Bartolomeu, n = 1/2) of the individuals showed at least one. Results are displayed in Table 6. Among individuals in which PD was recognizable (n = 25) significant differences were observed between non-adults and adults (U-test 125, p = 0.0001) with regard to severity as older individuals presented more intense PD. Non-adults did not show significant differences among age groups (U-test 1.5, p = 0.19) nor did the adult groups display differences between them (Kruskal–Wallis chi-squared = 3.0, df = 1, p = 0.08).

Dental calculus Individuals with dental calculus on permanent dentition constitutes 72% (24/33; Santa María, n = 20/24; San Bartolomeu, n = 4/9; no significant differences between sub-samples) of the sample. For those individuals who presented deciduous dentition, 40% (2/8) of

the sample exhibited dental calculus. In Table 6, data about prevalence per tooth are displayed. Among the total sample 27% (112/413) of permanent teeth showed dental calculus. For the non-adult sample Infant/Child (1–12 years old), infants and children, 1% (1/82) of the permanent teeth and 11% (5/46) of the deciduous teeth had dental calculus (see Table 6). For non-adults > 12 years old, juveniles, dental calculus was observed in 50% (62/125) (see Table 6), and 33% (64/195) of adults. There is a significant difference (U-test 170, $p=0.05$) between adults and non-adults, indicating that adults had more calculus. Infants have significantly less calculus than juveniles (U-test 0, $p=0.004$), young adults (U-test 3, $p=0.001$) and middle adults (U-test 3, $p=0.009$). Differences between sexes were obtained (U-test 95.5, $p=0.04$), with female individuals more affected than males. Since the adult sample includes more middle age females than males ($n=5$; females = 4; males = 1) (Table 1), we repeated the analyses only considering young adults ($n=13$; females = 6; males = 7), and found no significant differences in this age category (U-test 98, $p=1$).

Dental wear and hypercementosis Dental wear results for posterior permanent dentition are described in Table 7, as Table 8 lists anterior permanent dentition and premolar results. The San Bartolomeu and Santa Maria sub-samples were analysed together since no significant differences in their values were detected. The majority of teeth display dental wear of Grade 2–4 and Grade 5–7, including anterior

permanent dentition. As expected, there is a relationship between dental wear and age. Infant/children have none or very little dental wear in anterior and posterior teeth (Grades 0–1), while in juveniles most of teeth show a moderate intense wear (Grade 2–4). However, we found cases where M1 dental wear is moderately severe (Grade 2–4) in non-adult individuals (20% of infants/children, and 60% of juveniles), or even highly severe (Grade 5–7/Grade 5–5+) in some of the oldest non-adult females (20% in juveniles).

Adult individuals' dental wear can be considered high or very high. Anterior dentition and premolars displayed Grade 5–7 dental wear in 56% (9/16) and 57% (8/14) of the individuals, respectively; and Grade 8 in 19% (3/16) of anterior teeth and 14% (2/14) of premolars. For the posterior dentition, Grade 5–5++ was reached in 56% (9/16) of first molars and 40% (6/15) of second molars; while Grade 6 appeared in one individual (6%, 1/16) of M1 and none of M2 (0/15). Another interesting feature related to the severe dental wear is that none of the adult teeth have dental wear of Grade 0–1. In addition, young adults present a remarkable percentage of teeth with Grade 5–5++ , with 50% (5) of the M1 and 33% (3) for M2. Both percentages increase in middle adults, being 60% for both M1 and M2. There is no significant difference between biological sexes in terms of dental wear for the first molar (U-test 28, $p=0.46$), but there is between adults and non-adults (U-test 132, $p=0.0002$).

Table 7 Prevalence of hypercementosis and dental wear severity in permanent posterior teeth (M1 and M2) in the Pontevedra samples (together Santa Maria and San Bartolomeu individuals)

	Grade 0–1		Grade 2–4				Grade 5–5++				Grade 6				Hypercementosis					
	n _{M1}	%	n _{M2}	%	n _{M1}	%	n _{M2}	%	n _{M1}	%	n _{M2}	%	n _{M1}	%	n _{M2}	%	n _{M1}	%	n _{M2}	%
Infant/Child	4	80	4	80	1	20	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Juvenile	1	20	1	20	3	60	4	80	1	20	-	-	-	-	-	-	-	-	-	-
Young Adult	-	-	-	-	3	30	2	22	5	50	3	33	1	10	-	-	1	10	-	-
Middle Adult	-	-	-	-	-	-	-	-	3	60	3	60	-	-	-	-	-	-	1	20
Old Adult	-	-	-	-	-	-	-	-	1	100	1	100	-	-	-	-	1	100	1	100
Total adults	-	-	-	-	3	19	2	13	9	56	6	40	1	6	-	-	2	13	2	13
Total n/adults	5	50	5	50	4	40	4	40	1	10	-	-	-	-	-	-	-	-	-	-
Female	-	-	-	-	4	44	6	67	5	56	2	22	-	-	-	-	-	-	-	-
Male	-	-	-	-	1	11	2	25	5	56	5	62	1	11	-	-	2	22	2	25
Indeterminate	5	71	5	71	2	29	1	14	1	14	-	-	-	-	-	-	-	-	-	-
Juvenile ♀	-	-	-	-	3	75	4	100	1	25	-	-	-	-	-	-	-	-	-	-
Indt. Juvenile	1	100	1	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Young adult ♀	-	-	-	-	1	33	1	33	2	67	1	33	-	-	-	-	-	-	-	-
Young adult ♂	-	-	-	-	2	40	-	-	2	40	2	50	1	20	-	-	-	-	1	25
Indt. Young adult	-	-	-	-	1	50	1	50	1	50	-	-	-	-	-	-	-	-	-	-
Middle adult ♀	-	-	-	-	-	-	1	50	2	100	1	50	-	-	-	-	1	50	1	50
Middle adult ♂	-	-	-	-	-	-	-	-	2	100	2	100	-	-	-	-	-	-	-	-
TOTAL	5	20	5	20	7	28	9	36	10	40	6	24	1	4	-	-	2	8	2	8

Table 8 Prevalence of hypercementosis and dental wear severity in permanent anterior teeth (incisors, canines) and premolars in the Pontevedra samples (together Santa María and San Bartolomeu individuals)

	Grade 0–1				Grade 2–4				Grade 5–7				Grade 8				Hypercementosis			
	n _{Ant}	%	n _{PM}	%	n _{Ant}	%	n _{PM}	%	n _{Ant}	%	n _{PM}	%	n _{Ant}	%	n _{PM}	%	n _{Ant}	%	n _{PM}	%
Infant/Child	4	100	3	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Juvenile	1	20	2	40	4	80	3	60	-	-	-	-	-	-	-	-	-	-	-	-
Young Adult	-	-	-	-	4	40	2	20	5	50	7	70	1	10	1	10	-	-	1	10
Middle Adult	-	-	-	-	1	20	-	-	3	60	-	-	1	20	-	-	1	33	1	20
Old Adult	-	-	-	-	-	-	-	-	1	100	1	100	1	100	1	100	1	100	-	-
Total adults	-	-	-	-	5	31	2	14	9	56	8	57	3	19	2	14	2	14	2	13
Total n/adults	5	56	5	63	4	44	3	38	-	-	-	-	-	-	-	-	-	-	-	-
Female	-	-	1	8	7	54	4	33	4	31	6	50	2	15	1	8	1	8	1	8
Male	-	-	-	-	1	20	-	-	4	80	4	80	-	-	-	-	1	20	1	20
Indeterminate	5	71	4	80	1	14	1	14	-	-	-	-	-	-	-	-	-	-	-	-
Juvenile ♀	-	-	1	25	4	100	3	75	-	-	-	-	-	-	-	-	-	-	-	-
Indt. Juvenile	1	100	1	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Young adult ♀	-	-	-	-	3	60	1	20	1	20	3	60	1	20	1	20	-	-	-	-
Young adult ♂	-	-	-	-	-	-	-	-	4	100	4	100	-	-	-	-	-	-	1	25
Indt. Young adult	-	-	-	-	1	100	1	100	-	-	-	-	-	-	-	-	-	-	-	-
Middle adult ♀	-	-	-	-	-	-	-	-	3	75	3	100	1	25	-	-	1	33	1	25
Middle adult ♂	-	-	-	-	1	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TOTAL	5	36	5	24	9	64	5	24	9	64	8	38	3	21	2	10	2	10	2	6

Within the total sample, eight individuals (24%, 8/34; Santa María, n = 5/25; San Bartolomeu, n = 3/9) presented hypercementosis. Five (15%, 5/34) showed at least one case of hypercementosis in the anterior dentition. Hypercementosis in premolars and M1/M2 was also found in a 9% (3/34) and 6% (2/34) of individuals, respectively. When considering the adult cohort from Pontevedra (this condition rarely appeared in non-adults), 23% (5/22) showed hypercementosis in the anterior dentition, 9% (2/22) in premolars and 18% (4/22) in first and second molars. In summary, 36% (8/22) of the analysed adult individuals showed at least one case of hypercementosis in the permanent dentition, presenting 23% of those more than one affected tooth. Within the group of affected individuals 63% belong to the young adult age group (25% female n = 2; 38% male n = 3), 25% to Middle adult (100% female) and the only Old adult makes up 13%. Among the eight individuals that present hypercementosis, 50% of them (n = 4) have this lesion in several teeth.

Discussion

Fish vs millet

The diet reconstructed by the analyses of the Pontevedra collections was interpreted previously as rich in marine resources with a variable input of C₄ plants (millets or later maize), but the cereal intake was C₃-dominated

(López-Costas and Müldner 2019). Our analyses for collagen are consistent with previous results and we agree that the protein food fraction was dominated by fish/seafood consumption, mainly fish. The significant differences in $\delta^{15}\text{N}_{\text{col}}$ between San Bartolomeu and Santa María suggest different access to high-level trophic position fish or salty fish, as was previously published (see López-Costas and Müldner 2019). The $\delta^{13}\text{C}_{\text{col}}$ results are consistent with the consumption of C₃ and C₄ plants and are parallel to those obtained in other populations in the north of the Iberian Peninsula (see Guede et al. 2020; MacKinnon et al. 2019) where C₄ plants (i.e., millets, and less likely sorghum) had been consumed. However, it has been shown in the literature that both the analysis of $\delta^{13}\text{C}_{\text{col}}$ and $\delta^{13}\text{C}_{\text{car}}$ on their own does not provide a diagnostic tool for diet reconstruction, while the combined analysis of both provides models that are more representative of actual diet (Kellner and Schoeninger 2007), since $\delta^{13}\text{C}_{\text{col}}$ and $\delta^{15}\text{N}_{\text{col}}$ analyzed in extracted collagen only reflect protein intake and $\delta^{13}\text{C}_{\text{car}}$ reflects the total diet (Ambrose and Norr 1993; Price and Hopkins 2015). The Pontevedra sample shows higher $\delta^{13}\text{C}_{\text{col}}$ values (> -18‰) compatible with the consumption of some fish and/or C₄ plants. However, after comparison of carbon isotopes in carbonates from bioapatite, we found that although the whole population shows values compatible with a marine origin of diet, eleven individuals (Santa María = 7/20; San Bartolomé = 4/9) show elevated $\delta^{13}\text{C}_{\text{car}}$ values (> -12‰) pointing to a substantial intake of energy from C₄ plants.

The $\delta^{13}\text{C}_{\text{col}}$ and $\delta^{13}\text{C}_{\text{car}}$ values were plotted against the linear regressions proposed by Kellner and Schoeninger (2007) in Fig. 5 for best visualization, which indicate energy source (vertical axis) and protein origin (horizontal axis). Note that the study by Kellner and Schoeninger (2007) is based on maize as a C_4 plant, while for medieval Pontevedra we also need to consider other C_4 plants that can cause a bias in the model proposed by these authors. After considering the results from Fig. 5, the present study refines previous results suggesting that, although fish consumption is prevalent in Medieval Pontevedra and it is even favoured in those individuals belonging to the fishing guild, which had easier access to salt fish (sardine) and high trophic level marine food (hake, conger, octopus), C_4 plants were also consumed in both parishes and may have had a greater role in the diet of the town than was expected. The next step is to refine the type of C_4 plant consumed.

In the Late Middle Ages, the available C_4 plants in Iberia were millets (introduced in the Bronze Age; see López-Costas et al. 2016) and sugar cane (introduced in al-Andalus; see Inskip et al. 2019). Climatic conditions in NW Iberia did not allow the optimal growth of sugar cane, but it was cultivated in Southern Iberia. The port of Pontevedra had a prominent commercial connection with Valencia although its main area of maritime operation was the Atlantic coast (Armas Castro 1992; Priegue 1998); sugar cane may therefore have arrived by boat. Molasses, in which carbohydrates predominate, would have an impact on the bioapatite signal but not on collagen. Any individual from Fig. 5 displays

this relationship between $\delta^{13}\text{C}_{\text{col}}$ and $\delta^{13}\text{C}_{\text{car}}$. However, we could not find any historical reference of sugar cane import, and in case it arrived it would not have been a staple for the middle class.

The other option for C_4 plants is millets, which were widely used in Europe due to their high tolerance to climate stress as well as for being a versatile and nutritious species (Peña-Chocarro et al. 2019). There are isotopic markers of the use of this plant as human food in the NW Iberian Peninsula since Roman times (López-Costas and Müldner 2016), or even earlier if we consider carpological remains (Peña-Chocarro et al. 2019; Teira-Brión 2022). The use of C_4 plants, probably millet, is also documented isotopically in medieval Asturias (also in NW Spain); these plants were replaced by maize in the mid-1600 s (a pest-resistant plant in Europe suitable for depleted soils) (see MacKinnon et al. 2019). In the Basque Country, millet was used for human consumption and may have supplemented the shortages of wheat which are historically documented (Martínez Martínez et al. 2015). Historical records for medieval Pontevedra (Armas Castro 1992) indicate that this cereal was transported to Pontevedra from neighbouring farms to be consumed by humans, while in the rest of the Peninsula millets were used as animal fodder (Moreno-Larrazabal et al. 2015). Faunal remains analysed in Galicia do not yet show evidence of having been fed with C_4 plants (López-Costas 2012; López-Costas and Müldner 2016, 2019). Shortages of wheat during the Middle Ages were common in the northern Iberian Peninsula due to the climate and topography,

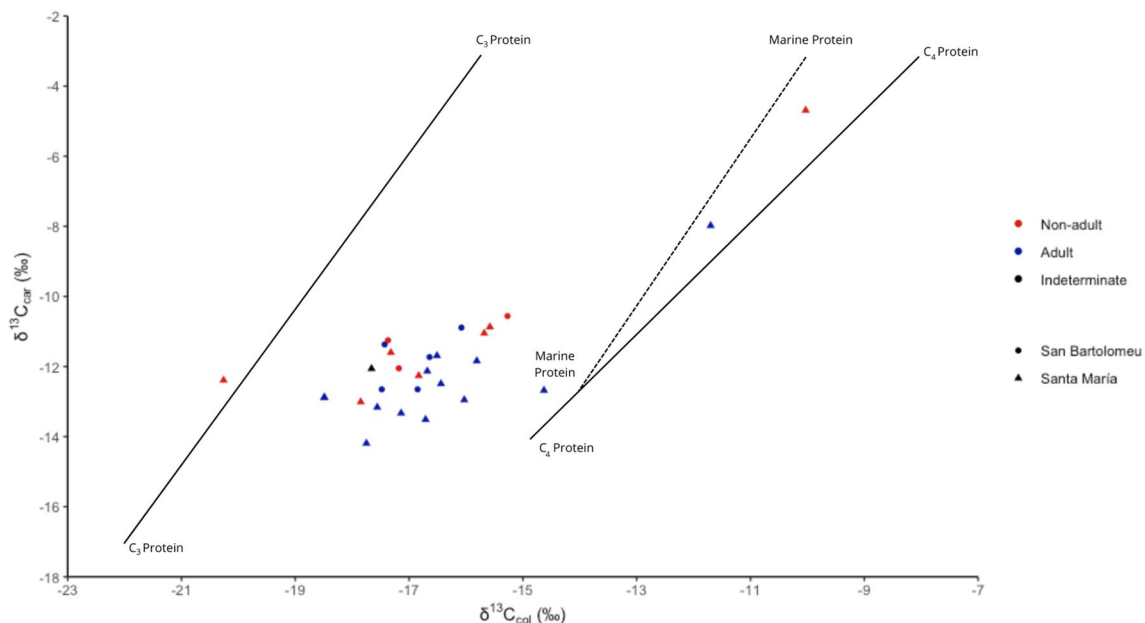


Fig. 5 Carbon apatite and carbon collagen plotted against Kellner and Schoeninger (see Kellner and Schoeninger 2007) regression lines indicating main protein and energy sources of diet. Note that C_4

plants for the regression lines are mainly maize, while millet regression line would be different. Created with RStudio

which favoured the cultivation of rye, barley, and millet (Martínez Martínez et al. 2015). Millets were consumed here as bread, porridge, and soups, especially among the lower social classes, who devoted their oats and wheat harvests as for a payment (these payments are the product of long-term agrarian usufruct transfers between a person/family and an institution—the nobility or the Church—very common in medieval Galicia) (Portela Silva and Pallares Méndez 1987; Peña-Chocarro et al. 2019). Millets, with their climatic resilience, were also well suited to the subsistence strategies of the Galician model, which relied on smallholdings, crop rotation, and diversification as part of a non-intensive agriculture philosophy (Teira-Brión 2022). Furthermore, the middle classes had limited accessibility to wheat imported from Castilian and Andalusian granaries, in contrast to the privileged upper echelons of society (Armas Castro 1992). Therefore, millets could have formed a significant part of the diet of the population of Pontevedra.

Millets have lower $\delta^{13}\text{C}$ signatures (~ -13 to -12‰) (An et al. 2015) than other C_4 plants such as maize ($\sim -10\text{‰}$) (Tieszen and Fagre 1993), which were introduced at a later historical stage. From the seventeenth century onwards, the area relied heavily on maize for human consumption (Puig 2012), so we do not rule out the intake of maize in some later individuals. Individuals STM824, STM833, and STM883 have been stratigraphically linked to the Early Modern period and point to a slightly different human feeding pattern according to their isotopic values, with much higher $\delta^{13}\text{C}_{\text{col}}$ and $\delta^{13}\text{C}_{\text{car}}$ values. Their protein input seems also to have come from fish, but there is also evidence of enrichment from C_4 plants with elevated $\delta^{13}\text{C}_{\text{col}}$ and $\delta^{13}\text{C}_{\text{car}}$ values. In Fig. 5, they fit in the regression line for maize as indicated in Kellner and Schoeninger (2007). Indeed, we have interpreted this anomalous isotopic data as belonging of a set of chronologically later individuals who may have relied on the consumption of maize.

The isotopic data of medieval Pontevedra's non-adults are similar to the adult pattern, but their $\delta^{15}\text{N}_{\text{col}}$ tends to be higher. The enrichment in $^{15}\text{N}_{\text{col}}$ in infants/children not older than 4 years old is normally interpreted as the result of breastfeeding (Katzenberg and Lovell 1999; Katzenberg and Pfeiffer 1995; Schurr and Powell 2005; Haydock et al. 2013), while absence of this enrichment is normally interpreted as a reflection of the non-existence or short duration of breastfeeding. However, this assumption is currently under debate, as it may also be a reflection of stunting processes rather than of nursing experiences, that is, due to stress relating to individual interruptions of new bone formation (Beaumont et al. 2018). However, since dentine collagen seems to reflect better the nursing effect (Beaumont et al. 2018) in addition to our very small sample for individuals under four years old, we would not want to infer aspects related to breastfeeding practices. The slightly higher $\delta^{15}\text{N}_{\text{col}}$ of some infants

could have been connected to the consumption of breast milk or physiological stress (e.g., famile disease), although they are not correlated with $\delta^{13}\text{C}$. $\Delta^{13}\text{C}_{\text{col}}$ is less susceptible to physiological processes and has been shown to be more reliable as evidence of non-adult diets (Beaumont et al. 2018). Since we found no differences in $\delta^{13}\text{C}_{\text{col}}$ in this sample, we may conclude that non-adults shared the general diet of adult individuals. Interestingly, the $\delta^{13}\text{C}_{\text{col}}$ and $\delta^{13}\text{C}_{\text{car}}$ suggest that five non-adult individuals had a moderate-high consumption of C_4 plants. The consumption of C_4 plants in the Infant/Child individuals of Santa Maria and San Bartolomeu (Santa María infant/child = 2; Santa María juveniles = 2; San Bartolomeu infant/child = 1) could be connected to porridges and similar foods based on millets. In other parts of medieval Europe that phenomenon was identified and related with weaning foods (Adamson 2004). However, adult individuals also showed values compatible with C_4 plants consumption, as well as four of those five aforementioned non-adult individuals are above the considered weaning stage (although no information about Galician weaning process is available on the literature). In summary, the non-adult group seems to have had a diet similar to that of the adults (i.e., high marine resources), with a non-negligible element of C_4 plants.

Few studies have analyzed $\delta^{13}\text{C}_{\text{car}}$ in populations of the Iberian Peninsula (Table 9), most of them in enamel that reflect childhood diet. All indicate a diet mainly based on C_3 plant energy, although enamel $\delta^{13}\text{C}_{\text{car}}$ from the Southern Iberian city of Écija (Inskip et al. 2019) suggests an energetic enrichment categorized as originating from sugar cane during childhood. In Évora (MacRoberts et al. 2020), also a Southern Iberian site, enamel $\delta^{13}\text{C}_{\text{car}}$ is slightly higher and shows important intra-site variation, in a way similar to the Pontevedra adult values. Millet in the form of porridge as a baby/infancy food or during weaning could be consumed in the village. The isotopic signal of individuals buried in the Lugo Cathedral (López-Costas et al. 2021) and Santiago de Compostela Cathedral (Pérez-Ramallo 2022) -both in Medieval Galicia and belonging to the same period and geographical location- present more negative $\delta^{13}\text{C}_{\text{car}}$ values than the Pontevedra ones (Table 9), which may be interpreted as a diet with a high consumption of C_3 -based terrestrial origin protein, possible contributions of freshwater fish, and minor intake of C_4 plants. Both sites contained skeletons belonging to elite social groups, a fact that would explain the higher access to meat, eggs, and dairy products. Textual sources mention rye and millet as cereals that were consumed by the middle and lower classes from Pontevedra, while wheat was reserved for the upper classes (Armas Castro 1992). The Lugo Cathedral books of payments indicate that millet was also available for the social elites, but according to the skeletal analyses, it was not a staple for them (López-Costas et al. 2021). In contrast, our study suggests a staple consumption of millet, but minor in comparison to fish, by the

Table 9 $\delta^{13}\text{C}_{\text{car}}$ average and standard deviation for the populations used in the comparisons

Population	Human sample size (NMI)	Chronology	$\delta^{13}\text{C}_{\text{car}}$ mean ‰ (VPDB)	SD	$\delta^{13}\text{C}_{\text{col}}$ mean ‰ (VPDB)	SD	$\delta^{15}\text{N}_{\text{col}}$ mean ‰ (AIR)	SD	Sample	Reference	Location
Écija	66	9th-13th	-11.5	0.9	-16.4	0.8	10.4	1.4	Tooth	Inskip et al. 2019	Écija, Seville—SE Spain
Évora	15	12th-13th	-10.7	1.8	-17.8	0.7	11.9	1.4	Tooth	MacRoberts et al. 2020	Évora—South Portugal
Capela do Pilar	12	14th-15th	-13.7	1	-18.6	0.4	13.4	1.2	Bone	López-Costas et al. 2021	Lugo, Galicia—NW Spain
Catedral de Santiago	33	9th-12th	-13.1	1.6	-17.8	0.8	10.9	0.8	Tooth	Pérez-Ramallo et al. 2022	Santiago de Compostela, Galicia—NW Spain
Medieval Pontevedra	27	13th-17th	-11.8	1.8	-16.4	0.8	12.6	0.9	Bone	This study	Pontevedra, Galicia—NW Spain

middle-class people from medieval Pontevedra. Considering the textual information, millet in diet could be considered an indicator of social class, at least in Northwestern Iberia.

Oral health and diet in hyperspecialized community

When the medieval sample of Pontevedra is compared with 18 other medieval sites from the Iberian Peninsula (see distribution in Fig. 6, all using similar recording methods to this study), we found poorer dental health of the former (Table 9) despite being a relatively young-age assemblage. In terms of age, oral health decreases with age. The lack of sex differences, despite the link between pregnancies and caries (Kubehl and Temple 2020; Watson et al. 2010), could be biased by the wider age distribution of the female cohort compared to the male cohort. When the oral pathology results are compared with those from other archaeological sites (Table 10), the prevalence of dental caries in the analysed sample is slightly above the average of medieval cohorts, while the calculus prevalence in Pontevedra is average. Carbohydrate-rich diets have been linked to a high prevalence of dental caries and dental calculus in contrast with low-carbohydrate and high-protein/fat diets which have been related to lower dental caries rates but high dental calculus prevalence (Hillson 2008; Bonsall and Pickard 2015; Larsen 2015; Temple 2015; Kubehl and Temple 2020; Bertilsson et al. 2022). There is no agreement in the scholarly literature about caries and calculus rates that can be connected to intense consumption of fish. Marine diets have been associated with low prevalence of dental caries and high rates of dental calculus due to the enrichment in fluoride and silica (Larsen et al. 1999; Polet and Katzenberg 2003; Ramezani et al. 2015; Yanko et al. 2021), precisely the opposite of what we observe in Pontevedra. A high prevalence of dental caries has been also associated in the literature with seafood consumption (Delgado-Darias et al. 2006; Arnay-De-La-Rosa et al. 2010). In medieval Pontevedra, occasional consumption of shellfish may have increased the caries rate; however, its consumption may have been avoided in medieval Galicia as it was seen as a sign of poverty (Priegue 1998), which is in line with the isotopic values obtained in López-Costas and Müldner (2019) that target fish consumption (plus octopus) rather than shellfish consumption. Individuals STM824 and STM833 presented the highest number of caries episodes, which coincides with their possible consumption of maize.

Despite these other features, dental wear is the most remarkable aspect of oral pathology. Pontevedra shows severe dental wear, with high severity reached by younger age groups (both in the anterior and posterior dentition). The great severity of dental wear defines the oral pathology of Pontevedra, with intense incidence from an early age. A hypothesis is that this severe dental wear could have also been a determining factor in the impoverishment of their

Table 10 Comparison of Medieval Pontevedra and eighteen medieval populations of the Iberian Peninsula regarding the prevalence of four oral pathologies. Acronym code: PM = Pontevedra Medieval (this study), VA = Valença (Marado and Silva 2018), AMM = Mesquita de Mértola (Silva 2011), CES = Capela do Espírito Santo (Ferreira 2015), INSA = Igreja da N.Sra. Anunciada (Ferreira 2015), MS = Maçbara de Shantarín (Rodrigues 2013), CNSV = Capela da Nossa Senhora da Vitória (Marques 2007), SMH = Santa Maria de Hito (Galera 1989), SPT = Sant Pere de Terrassa (Jordana Comin 2007), HCL = Poblaciones históricas de Castilla y León (López Martínez, 2000), BA = Bragança (Márquez-Grant 2008), PR = Palat del Rey (Prada Marcos 1993), LT = La Torrecilla (López-Morago 2020), SLSN = San Lorenzo y San Nicolás (López-Morago 2020), VNS = Villanueva de Sopotilla (López-Morago 2020), SBB = San Baudelito de Berlanga (López-Morago 2020), MISO = Monasterio de Suso (López-Morago 2020), EC = El Castillo (López-Morago 2020), SBM = SahI ben Malik (López-Morago 2020)

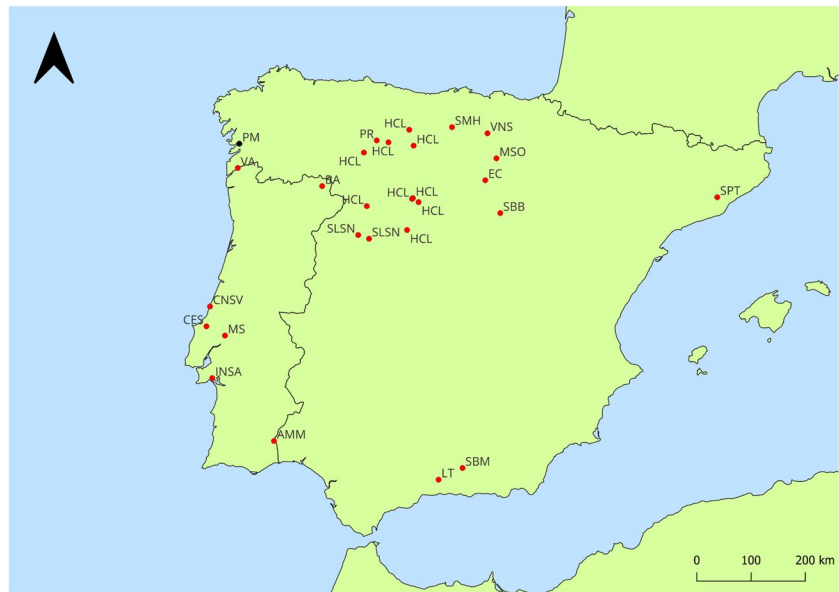
	PM	VA	AMM	CES	INSA	MS	CNSV	SMH	SPT	HCL	BA	PR	LT	SLSN	VNS	SBB	MISO	EC	SBM
DENTAL WEAR ≥ 5 IN MI (%)	48	-	11	8	-	-	6	6	-	18	-	10	9	9	17	16	36	23	15
DENTAL CARIES (%)	64	29	-	80	92	-	26	48	10	4	16	16	43	61	40	20	43	40	39
DENTAL CALCULUS (%)	72	-	-	-	-	34	37	-	59	77	60	83	70	82	90	80	100	90	65
PERIAPICAL LESIONS (%)	23	17	-	-	-	-	-	-	4	1	1	2	3	9	7	4	3	3	14
NMI	34	30	16	84	93	45	56	138	208	728	70	351	81	46	56	25	14	30	88
% adults	62	47	69	76	88	100	79	65	78	71	71	72	72	83	51	64	100	90	52
n Females:n Males	14:9	7:7	1:6	27:10	47:26	14:28	4:13	111:122	35:45	226:252	12:14	104:95	30:27	21:16	17:23	6:9	2:11	12:14	17:28
% non adults	36	33	31	15	12	0	21	35	78	29	29	28	29	17	29	36	0	10	34

global oral health since it is possible that the exposure of the pulp caused by high attrition of the enamel allows the process of compensatory eruption, exposing tooth nerves to caries and making them susceptible to colonisation by the oral microbiota, accelerating processes such as periodontal disease, plaque accumulation, and demineralization of the teeth (Hillson 1996, Ogden 2007). Therefore, the above-average rate of caries, periapical lesions and periodontal disease could be a consequence of the intense dental wear. However, more studies related to the causes/consequences of hypercementosis are needed to obtain a final answer.

The hyperspecialized fish diet observed and demonstrated by stable isotope analyses in López-Costas and Müldner (2019) would have an impact on the high rates of dental wear that also conditions the whole oral health. Once systemic conditions such as Paget’s disease, Gardner’s syndrome, and acromegaly (among others) have been ruled out (Le Cabec 2013; Bonsall and Pickard 2015; Tang et al. 2015; Massé et al. 2022), the possible causes of high dental wear include the consumption of poorly processed cereals, flours with abrasive particles implemented during processing, diet based on animal protein, and on marine products (Arnay-De-La-Rosa et al. 2010). Regarding poorly processed cereals or flours with abrasive particles, cereal milling in the NW Iberian Peninsula was mainly carried out in mills of the predominant geological material in the area, which is very abrasive (biotite and two mica granitoids) (Centro Nacional de Información Geográfica Website (n.d.). Instituto Geográfico Nacional: Geology and tectonic of Galicia map). This fact has been already suggested by Novak (2015) for granite areas in medieval Ireland, but also in areas with greater dependence on fish. In this case, most populations from Galicia and the north of Portugal might have suffered from intense dental wear since they shared geology. We have not found other sites where dental wear was studied and were located in granite areas. Nevertheless, it is expected that grain sieving and grinding in late medieval times was quite efficient. In all cases, knowing the dental wear rates from other Galician sites would be useful in the future, to address the impact of abrasive flours as an aggravating factor for dental wear. High consumption of fats and protein without vegetable intake could have also had an impact on dental wear; however, the literature is not clear (Kieser et al. 2001; Eshed et al. 2006; Watson et al. 2013). Novotná (2017) proposed that high or exclusively animal protein diets generate greater dental wear, but this idea has been criticized by Jílková et al. (2019). Regardless of the inconsistencies, the people of Pontevedra had access to vegetables by trade or self-sufficiency (Armas Castro 1992), a fact that isotopic values support, so a diet based only in animal protein is not applicable here.

Eating fish and shellfish in general, and a life connected to the sea, implies several factors that can enhance severe

Fig. 6 Political map of the current countries of Spain and Portugal showing the distribution of the samples used as comparison for oral pathology. Pontevedra is marked with a black dot. The map follows the same system of acronyms as Table 10. Created with QGIS map



dental wear, as explained by Littleton and Frohlich (1993). Diets rich in marine products result in high wear (Littleton and Frohlich 1993; Watson et al. 2013; Eshed et al. 2006; Mickleburgh 2016). Fish, especially when it is dried, has abrasive particles. Pontevedra was a centre of production of salted/smoked fish in medieval times (Armas Castro 1992; Mangas-Carrasco and López-Costas 2021). The salt could also increase the abrasive nature of fish. Contributory factors can be also windblown sand (Maat et al 1990 in Littleton and Frohlich 1993) in populations living by the sea, as was the case of Pontevedra. The church of Santa María and the corresponding neighbourhood are located in a sand deposit area. The sand contained in shellfish can also increase wear. The occasional consumption of shellfish cannot be ruled out in Pontevedra, although the isotopic values of the sample suggests that the consumed protein comes from fish rather than shellfish (López-Costas and Müldner 2019). This is consistent with the avoidance of shellfish noted in the literature, arising from the fact that it was associated with the stigma of poverty (Priegue 1998). However, consumption of abundant shellfish has been recorded in the area of Pontevedra since prehistory, as shell middens are normally present in Iron Age settlements by the sea (Rodríguez Martínez et al. 2011). It is certain that the inhabitants of Pontevedra, especially those belonging to fisher families, had access to abundant shellfish since the area is rich in these animals. Finally, fibre work in relation with fishing gear and other artisanal processes could also be producing wear; however, no marks compatible with extramasticatory wear or distinctive patterns of anterior wear were observed.

In summary, the connection between stable isotopes and oral pathology seems clear in Pontevedra, as it is supported by the results and several previous works that have

connected marine resources consumption and dental wear. Interestingly, the Asturian population of Veranés (placed in a non granite area) that consumed fish in high quantities, also displays a significant rate of dental wear (21%) (Rascón Pérez et al. 2013).

Conclusion

Multi-isotopic analysis has been crucial in determining the energy origin of the diet. We profile a local population, of middle social class with a common dietary pattern characterised by high consumption of marine protein and some input of C_4 plants (probably millet).

In the Pontevedra sites, a diet rich in marine resources, mainly fish, and C_4 plants (millet/corn) was connected to special features in oral pathology such as severe dental wear. Dental wear is shown to be very severe from a very early age and above the average of medieval Iberian populations. This can only be connected to a special feature in the diet, such as the intense dependence on fish that is revealed by stable isotopes and textual sources. Another factor for explaining the poor oral health is the consumption of flours with abrasive particles due to granite mills. The associated medium–high rates of caries and calculus could be explained by millet and other cereal consumption, but also due to the dental wear that makes dental pulp available for bacteria. The hypothesis that there is a relationship between oral pathology and stable isotopes that can be determined in hyper-specialised diets is confirmed in the Pontevedra case. We encourage other researchers to analyse those populations with hyper-specialised diets by both pathology and chemical-isotopic analysis.

We think that the connection between high dental wear (and also possibly hypercementosis) with high $\delta^{13}\text{C}_{\text{col}}$ and $\delta^{15}\text{N}_{\text{col}}$, as well as medium $\delta^{13}\text{C}_{\text{car}}$ and $\Delta^{13}\text{C}_{\text{car-col}}$, which has been traditionally interpreted as consumption of marine resources, can be applicable to other types of diets and skeletal collections. It is worth the effort to discuss in the future the consequences in oral health when the consumption of fish is a staple but not so high. However, and despite other factors such as the age of the population, fish and seafood can have an impact on attrition, even if it is minor. Another conclusion of our work is the usefulness of combining isotopic signals rather than exclusively discussing the over-studied $\delta^{13}\text{C}_{\text{col}}$ and $\delta^{15}\text{N}_{\text{col}}$, which can provide a preliminary approach to diet in order to later refine the results by taking into account other isotopic values.

A final conclusion of our work relates to the use of dental wear to estimate age. Traditionally, tooth wear has been used to determine the age of individuals on the premise that as enamel does not remodel, greater severity will be evident in direct proportion to age (Smith 1984; Brothwell 1981; Miles 2001; Burnett 2016). Although researchers are aware that factors such as hygiene, extra-masticatory uses of the mouth, or consumption of abrasive foods can directly influence the severity of dental wear (Watson and Schmidt 2020; Molnar 1971 in Faillace et al. 2017), it is used when no other proxy for age estimation is available on the premise that “it is better than nothing”. However, we encourage our colleagues to be especially cautious when determining age with dental wear in populations with a diet rich in marine products since there is a risk of overestimating the age of individuals.

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1007/s12520-024-01956-z>.

Acknowledgements The authors would like to thank the Museo de Provincial de Pontevedra and Patrimonio Histórico de la Xunta de Galicia for granting access to skeletal material. We would like to thank Simon R. Doubleday for his helpful suggestions regarding Medieval Galicia and proofreading. Also, to thank Paula González Novoa for her collaboration in the laboratory analysis, and Noelia Rivero Chaver and Marta Colmenares Prado for helping with bioapatite extraction. Thanks to Claudia López-Morago and Inmaculada Alemán Aguilera for oral pathology comparisons. Finally, we also owe thanks to the anonymous reviewers whose comments helped us to improve the manuscript.

Author contribution Clara Veiga-Rilo. Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing original draft, Writing-review and editing, Visualization, Funding acquisition.

Antonio Martínez-Cortizas. Methodology, Writing-review and editing, Visualization.

Olalla López-Costas. Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing original draft, Writing-review and editing, Visualization, Funding acquisition.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. This research was funded by the projects Bolsas de Investigación de Artes e Humanidades by Diputación

de A Coruña (BINV-AH/2021), Grupos de Referencia Competitiva (ED431C 2021/32) by Xunta de Galicia, and POLLUTIO Plan Nacional Retos project (PID2019-111683RJ-I00) Spanish Ministerio de Ciencia e Innovación. Clara Veiga-Rilo is funded by predoctoral fellowship from Xunta de Galicia (ED481A 2022/205), Olalla López-Costas is funded by Ramón y Cajal 2020 (RYC2020-030531-I). The last part of this research was co-funded by the European Union (ERC Consolidator Grant, PollutedPast, 101087832). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them.

Data availability Individual data about oral pathology will be available to other researchers upon request, individual isotopic data is listed in the article.

Declarations

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Adamson MW (2004) Food in medieval times. Greenwood Press, Westport
- Aguilera IA (1997) Determinación del sexo en el esqueleto postcraneal. Estudio de una población mediterránea actual. Dissertation, Universidad de Granada
- AlQahtani SJ, Hector MP, Liversidge HM (2010) Brief communication: The London atlas of human tooth development and eruption. *Am J Phys Anthropol* 142(3):481–490. <https://doi.org/10.1002/ajpa.21258>
- Álvarez Fernández N, Martínez Cortizas A (2020) Andurinha: make spectroscopic data processing easier. Rpackage version 0.0.2 <https://CRAN.R-project.org/package=andurinha>
- Ambrose SH, Norr L (1993) Experimental evidence for the relationship of the carbon isotope ratios of whole diet and dietary protein to those of bone collagen and carbonate. In: Lambert JB et al (eds) *Prehistoric Human Bone: Archaeology at the Molecular Level*. Springer Berlin Heidelberg, Berlin, Heidelberg, pp 1–37. https://doi.org/10.1007/978-3-662-02894-0_1
- An CB, Dong W, Li H, Zhang P, Zhao Y, Zhao X, Yu SY (2015) Variability of the stable carbon isotope ratio in modern and archaeological millets: evidence from northern China. *J Archaeol Sci* 53:316–322. <https://doi.org/10.1016/j.jas.2014.11.001>
- Armas Castro JA (1992) Transformaciones sociales y relaciones de poder en una Villa de Señorío. Pontevedra, siglos XIV-XV. Fundación Pedro Barrié de la Maza Conde de Fenosa, Pontevedra

- Arnay-De-La-Rosa M, González-Reimers E, Yanes Y, Velasco-Vázquez J, Romanek CS, Noakes JE (2010) Paleodietary analysis of the prehistoric population of the Canary Islands inferred from stable isotopes (carbon, nitrogen and hydrogen) in bone collagen. *J Archaeol Sci* 37(7):1490–1501. <https://doi.org/10.1016/j.jas.2010.01.009>
- Beaumont J, Atkins EC, Buckberry J, Haydock H, Horne P, Howcroft R, Mackenzie K, Montgomery J (2018) Comparing apples and oranges: Why infant bone collagen may not reflect dietary intake in the same way as dentine collagen. *Am J Phys Anthropol* 167(3):524–540. <https://doi.org/10.1002/ajpa.23682>
- Beck J, Bonilla MDZ, Bocherens H, Díaz-del-Río P (2018) Feeding a third millennium BC mega-site: Bioarchaeological analyses of palaeodiet and dental disease at Marroquíes (Jaén, Spain). *J Anthropol Archaeol* 52:23–43. <https://doi.org/10.1016/j.jaa.2018.07.001>
- Bertilsson C, Borg E, Sten S, Hessman E, Sjöblom H, Lingström P (2022) Prevalence of Dental Caries in Past European Populations: A Systematic Review. *Caries Res* 56(1):15–28. <https://doi.org/10.1159/000522326>
- Bonsall LA, Pickard C (2015) Stable isotope and dental pathology evidence for diet in late Roman Winchester. *England J Archaeol Sci Rep* 2:128–140. <https://doi.org/10.1016/j.jasrep.2015.01.009>
- Brothwell DR (1981) *Digging up bones*. Ithaca, New York
- Buikstra JE, Ubelaker DH (1994) Standards for data collection from human skeletal remains. In: *Proceedings of a seminar at the Field Museum of Natural History, organized by Jonathan Hass*. Fayetteville, Ark: Arkansas archaeological Survey Research Series vol 44, p 18
- Burnett SE (2016) Crown wear. In: Irish JD and Scott GR (eds) *A companion to dental anthropology*. John Wiley & Sons, Inc., West Sussex, pp 415–432. <https://doi.org/10.1002/9781118845486.ch25>
- Cardoso HF (2008a) Epiphyseal union at the innominate and lower limb in a modern Portuguese skeletal sample, and age estimation in adolescent and young adult male and female skeletons. *Am J Phys Anthropol* 135(2):161–170. <https://doi.org/10.1002/ajpa.20717>
- Cardoso HF (2008b) Age estimation of adolescent and young adult male and female skeletons II, epiphyseal union at the upper limb and scapular girdle in a modern Portuguese skeletal sample. *Am J Phys Anthropol* 137(1):97–105. <https://doi.org/10.1002/ajpa.20850>
- Centro Nacional de Información Geográfica Website (n.d.) Instituto Geográfico Nacional. https://www.ign.es/web/recursos/sismologia/tproximos/sismotectonica/pag_sismotectonicas/galicia.html. Accessed 02 Sept 2022
- Chao Álvarez FJ (2008) Actuación arqueológica no marco da rexeneración do arrabalde de Santa María, zona intramuros, Pontevedra. Excavación arqueológica das gabias de instalación nos sectores 1 e 3. 1B e 3A,B,C. Informe valorativo (CD 102A 2007/698–0). Original depositado en Consellería de Cultura e Deporte. Dirección Xeral de Patrimonio. Xunta de Galicia
- Cheung C, Zhang H, Hepburn JC, Yang DY, Richards MP (2019) Stable isotope and dental caries data reveal abrupt changes in subsistence economy in ancient China in response to global climate change. *PLoS ONE* 14(7):e0218943. <https://doi.org/10.1371/journal.pone.0218943>
- Chimeno E (2003) Perspectiva odontoestomatológica en paleopatología. En: Isidro A and Malgosa A (eds.) *Paleopatología. La enfermedad no escrita*. Masson, Barcelona, pp 151–162
- Collins MJ, Galley P (1998) Towards an optimal method of archaeological collagen extraction: the influence of pH and grinding. *Anc Biomol* 2(2/3):209–223
- Curto A, Mahoney P, Maurer AF, Barrocas-Dias C, Fernandes T, Fahy GE (2019) Diet and disease in Tomar, Portugal: Comparing stable carbon and nitrogen isotope ratios between skeletons with and without signs of infectious disease. *J Archaeol Sci* 105:59–69. <https://doi.org/10.1016/j.jas.2019.03.005>
- Curto A, Mahoney P, Maurer AF, Barrocas-Dias C, Fernandes T, Fahy GE (2020) Effect of different healing stages on stable isotope ratios in skeletal lesions. *Am J Phys Anthropol* 171(2):285–297. <https://doi.org/10.1002/ajpa.23958>
- Delgado-Darias T, Velasco-Vázquez J, Arnay-de-la-Rosa M, Martín-Rodríguez E, González-Reimers E (2006) Calculus, periodontal disease and tooth decay among the prehispanic population from Gran Canaria. *J Archaeol Sci* 33(5):663–670. <https://doi.org/10.1016/j.jas.2005.09.018>
- DeNiro MJ (1985) Postmortem preservation and alteration of in vivo bone collagen isotope ratios in relation to palaeodietary reconstruction. *Nature* 317(6040):806–809. <https://doi.org/10.1038/317806a0>
- Dlamini N, Sealy J, Mayor A (2019) Diet variability among pre-Dogon and early Dogon populations (Mali) from stable isotopes and dental diseases. *Am J Phys Anthropol* 169(2):287–301. <https://doi.org/10.1002/ajpa.23831>
- Eshed V, Gopher A, Hershkovitz I (2006) Tooth wear and dental pathology at the advent of agriculture: new evidence from the Levant. *Am J Phys Anthropol* 130(2):145–159. <https://doi.org/10.1002/ajpa.20362>
- Faillace KE, Bethard JD, Marks MK (2017) The applicability of dental wear in age estimation for a modern American population. *Am J Phys Anthropol* 164(4):776–787. <https://doi.org/10.1002/ajpa.23318>
- Featherstone JDB, Pearson S, LeGeros RZ (1984) An infrared method for quantification of carbonate in carbonated apatites. *Caries Res* 18:63–66
- Ferreira NA (2015) *Antropologia Funerária e Paleobiologia das Populações Pós-Medievais Portuguesas: Os Casos de Nossa Senhora da Anunciada e Espírito Santo*. Dissertation, Universidade Nova de Lisboa
- Figueiredo M, Gamelas J, Martins A (2012) Characterization of bone and bone-based graft materials using FTIR spectroscopy. In: Theophanides T (ed) *Infrared Spectroscopy-Life and Biomedical Sciences*. IntechOpen, Rijeka, pp 315–338
- Filgueira Valverde JE (1991) *La basílica de Santa María de Pontevedra*. Fundación Pedro Barrié de la Maza, A Coruña
- France ChAM, Sugiyama N, Aguayo E (2020) Establishing a preservation index for bone, dentin, and enamel bioapatite mineral using ATR-FTIR. *J Archaeol Sci Rep* 33:102551
- Galera V (1989) *La población medieval cántabra de Santa María de Hito. Aspectos paleobiodemográficos morfológicos paleontológicos paleoepidemiológicos y de etnogénesis*. Dissertation, Universidad de Alcalá
- Garvie-Lok SJ, Varney TL, Katzenberg MA (2004) Preparation of bone carbonate for stable isotope analysis: the effects of treatment time and acid concentration. *J Archaeol Sci* 31(6):763–776. <https://doi.org/10.1016/j.jas.2003.10.014>
- Gray DL, Crane JP, Rudloff MA (1988) Prenatal diagnosis of neural tube defects: origin of midtrimester vertebral ossification centers as determined by sonographic water-bath studies. *J Med Ultrasound* 7(8):421–427. <https://doi.org/10.7863/jum.1988.7.8.421>
- Guede I, Zuluaga MC, Ortega LA, Alonso-Olazabal A, Murelaga X, Camino IG, Iacumin P (2020) Social structuration in medieval rural society based on stable isotope analysis of dietary habits and mobility patterns: San Juan de Momoiito (Biscay, north Iberian Peninsula). *J Archaeol Sci Rep* 31:102300. <https://doi.org/10.1016/j.jasrep.2020.102300>
- Gustafson G, Koch G (1974) Age estimation up to 16 years of age based on dental development. *Odontol Revy* 25:297–306
- Haydock H, Clarke L, Craig-Atkins E, Howcroft R, Buckberry J (2013) Weaning at Anglo-Saxon raunds: Implications for changing

- breastfeeding practice in Britain over two millennia. *Am J Phys Anthropol* 151(4):604–612. <https://doi.org/10.1002/ajpa.22316>
- Hillson S (1996) *Dental anthropology*. Cambridge University Press
- Hillson S (2001) Recording dental caries in archaeological human remains. *Int J Osteoarchaeol* 11(4):249–289. <https://doi.org/10.1002/oa.538>
- Hillson S (2008) Dental pathology. In: Katzenberg MA, Saunders SH (eds) *Biological anthropology of the human skeleton*, 2nd edn. Blackwell, Oxford, pp 299–340
- Inskip S, Carroll G, Waters-Rist A, López-Costas O (2019) Diet and food strategies in a southern al-Andalusian urban environment during Caliphal period, Écija. *Sevilla Archaeol Anthropol Sci* 11:3857–3874. <https://doi.org/10.1007/s12520-018-0694-7>
- Jastrzebski W, Sitarz M, Rokita M, Bułat K (2011) Infrared spectroscopy of different phosphates structures. *Spectrochimica Acta Part A* 79:722–727
- Jílková M, Kaupová S, Černíková A, Poláček L, Brůžek J, Velemínský P (2019) Early medieval diet in childhood and adulthood and its reflection in the dental health of a Central European population (Mikulčice, 9th–10th centuries, Czech Republic). *Arch Oral Biol* 107:104526. <https://doi.org/10.1016/j.archoralbio.2019.104526>
- Jordana Comin X (2007) *Caracterizació i evolució d'una comunitat medieval catalana: Estudi antropològic de les inhumacions de les Esglésies de Sant Pere*. Dissertation, Universitat Autònoma de Barcelona
- Katzenberg MA, Lovell NC (1999) Stable isotope variation in pathological bone 1. *Int J Osteoarchaeol* 9(5):316–324. [https://doi.org/10.1002/\(SICI\)1099-1212\(199909/10\)9:5%3C316::AID-OA500%3E3.0.CO;2-D](https://doi.org/10.1002/(SICI)1099-1212(199909/10)9:5%3C316::AID-OA500%3E3.0.CO;2-D)
- Katzenberg MA, Pfeiffer S (1995) Nitrogen isotope evidence for weaning age in a nineteenth century Canadian skeletal sample. In: Grauer AL (ed) *Bodies of evidence: reconstructing history through skeletal analysis*. Wiley-Liss, New York, pp 221–235
- Kellner CM, Schoeninger MJ (2007) A simple carbon isotope model for reconstructing prehistoric human diet. *Am J Phys Anthropol* 133(4):1112–1127. <https://doi.org/10.1002/ajpa.20618>
- Kieser JA, Dennison KJ, Kaidonis JA, Huang D, Herbison PGP, Tayles NG (2001) Patterns of dental wear in the early Maori dentition. *Int J Osteoarchaeol* 11(3):206–217. <https://doi.org/10.1002/oa.534>
- Krogman WM (1986) Dental analysis. In: Iscan MY, Steyn M (eds) *The Human Skeleton in Forensic Medicine* IL Springfield, pp 202–208
- Kubehl K, Temple DH (2020) Reproductive life histories influence cariogenesis: Exploring sex-specific variation in dental caries and survivorship in the human past. *Am J Phys Anthropol* 172(3):376–385. <https://doi.org/10.1002/ajpa.24034>
- Larsen CS (2015) *Bioarchaeology: interpreting behavior from the human skeleton*. Cambridge University Press, United Kingdom
- Larsen MJ, Jensen AF, Madsen DM, Pearce EIF (1999) Individual variations of pH, buffer capacity, and concentrations of calcium and phosphate in unstimulated whole saliva. *Arch Oral Biol* 44(2):111–117
- Le Cabec A (2013) *Anterior dental loading and root morphology in Neanderthals*. Dissertation, Université Toulouse III-Paul Sabatier
- Le Roy LE (1971) *Times of feast, times of famine: a history of climate since the year 1000*. Doubleday & Company, New York
- Lee-Thorp JA, van der Merwe NJ (1987) Carbon isotope analysis of fossil bone apatite. *S Afr J Sci* 83:712–715
- Liland KH, Almøy T, Mevik B (2010) Optimal Choice of Baseline Correction for Multivariate Calibration of Spectra. *Appl Spectrosc* 64:1007–1016
- Lillie M, Richards MP, Jacobs K (2003) Stable isotope analysis of 21 individuals from the Epipaleolithic cemetery of Vasilyevka III, Dnieper Rapids region. *Ukraine J Archaeol Sci* 30(6):743–752. [https://doi.org/10.1016/S0305-4403\(02\)00249-2](https://doi.org/10.1016/S0305-4403(02)00249-2)
- Littleton J, Frohlich B (1993) Fish-eaters and farmers: dental pathology in the Arabian Gulf. *Am J Phys Anthropol* 92(4):427–447. <https://doi.org/10.1002/ajpa.1330920403>
- Longin R (1971) New method of collagen extraction for radiocarbon dating. *Nature* 230(5291):241–242. <https://doi.org/10.1038/230241a0>
- López Costas O (2012) *Antropología de los restos óseos humanos de Galicia: estudio de la población romana y medieval gallega*. Dissertation, Universidad de Granada
- Lopez-Costas O, Rissech C, Tranco G, Turbon D (2012) Postnatal ontogenesis of the tibia. Implications for age and sex estimation. *Forensic Sci Int* 214(1–3):207–e1. <https://doi.org/10.1016/j.forsciint.2011.07.038>
- López-Costas O, Müldner G (2016) Fringes of the empire: Diet and cultural change at the Roman to post-Roman transition in NW Iberia. *Am J Phys Anthropol* 161(1):141–154. <https://doi.org/10.1002/ajpa.23016>
- López-Costas O (2019) Boom and bust at a medieval fishing port: dietary preferences of fishers and artisan families from Pontevedra (Galicia, NW Spain) during the Late Medieval and Early Modern Period. *Archaeol Anthropol Sci* 11:3717–3731. <https://doi.org/10.1007/s12520-018-0733-4>
- López-Costas O, Lantes-Suarez O, Cortizas AM (2016) Chemical compositional changes in archaeological human bones due to diagenesis: Type of bone vs soil environment. *J Archaeol Sci* 67:43–51. <https://doi.org/10.1016/j.jas.2016.02.001>
- López-Costas O, Müldner G, Lidén K (2021) Biological histories of an elite: Skeletons from the Royal Chapel of Lugo Cathedral (NW Spain). *Int J Osteoarchaeol* 31(5):941–956
- López-Morago CC (2020) *Estudio comparativo de la calidad de vida en la Edad Media, en poblaciones musulmanas y cristianas de la Península Ibérica, a través de la Antropología Dental*. Dissertation, Universidad de Granada
- Maat G, Lonnee H, Noordhuizen H (1990) Analysis of human skeletons from the Hellenistic Period, buried at a ruined Bronze Age building on Failaka, Kuwait. In: Calvet Y, Gachet J (eds) *Failaka, Fouilles Françaises 1986–1988*. Travaux de la Maison de l'Orient, Lyon, pp 85–102
- MacKinnon AT, Passalacqua NV, Bartelink EJ (2019) Exploring diet and status in the Medieval and Modern periods of Asturias, Spain, using stable isotopes from bone collagen. *Archaeol Anthropol Sci* 11:3837–3855. <https://doi.org/10.1007/s12520-019-00819-2>
- MacRoberts RA, Dias CMB, Fernandes TM, Santos AL, Umbelino C, Gonçalves A, Santos J, Ribeiro S, Schöne RS, Barros F, Correia F, Vasconcelos Vilar H, Maurer AF (2020) Diet and mobility during the Christian conquest of Iberia: The multi-isotopic investigation of a 12th–13th century military order in Évora. *Portugal J Archaeol Sci Rep* 30:102210. <https://doi.org/10.1016/j.jasrep.2020.102210>
- Mangas-Carrasco E, López-Costas O (2021) Porotic hyperostosis, cribra orbitalia, femoralis and humeralis in Medieval NW Spain. *Archaeol Anthropol Sci* 13(10):169. <https://doi.org/10.1007/S12520-021-01432-Y>
- Marado LM, Silva AM (2018) Dental and oral nonmetric traits in a Coimbra reference sample: testing intrasample chronological and spatial variation. *Archaeol Anthropol Sci* 10:1165–1177. <https://doi.org/10.1007/s12520-016-0455-4>
- Marques RABDC (2007) *Capela de Nossa Senhora da Vitória. Paleobiologia de uma série osteológica humana proveniente de Porto do Mós, Batalha*. Dissertation, Universidade de Coimbra. <https://hdl.handle.net/10316/31146>

- Márquez-Grant N (2008) Restos humanos das igrejas de São João e São Vicente, Bragança. In Câmara Municipal de Bragança (ed) Bragança. Um olhar sobre a história II Bragança 66–152
- Martínez Cortizas A, López-Costas O (2020) Linking structural and compositional changes in archaeological human bone collagen: An FTIR-ATR approach. *Sci Rep* 10(1):17888. <https://doi.org/10.1038/s41598-020-74993-y>
- Martínez Martínez M, Pico Carbajo J, Gómez Pallarés M (2015) Physicochemical modification of native and extruded wheat flours by enzymatic amylolysis. *Food Chem* 167:447–453. <https://doi.org/10.1016/j.foodchem.2014.07.031>
- Massé L, Garot E, Maureille B, Le Cabec A (2022) Insights into the aetiologies of hypercementosis: A systematic review and a scoring system. *Arch Oral Biol* 146:105599. <https://doi.org/10.1016/j.archoralbio.2022.105599>
- Mickleburgh HL (2016) Dental wear and pathology in the precolonial Caribbean: evidence for dietary change in the ceramic age. *Int J Osteoarchaeol* 26(2):290–302. <https://doi.org/10.1002/oa.2421>
- Miles AEW (2001) The Miles method of assessing age from tooth wear revisited. *J Archaeol Sci* 28:973–982. <https://doi.org/10.1006/jasc.2000.0652>
- Molnar S (1971) Human tooth wear, tooth function and cultural variability. *Am J Phys Anthropol* 34:175–190
- Moreno-Larrazabal A, Teira-Brión A, Sopolana-Salcedo I, Arranz-Otaegui A, Zapata L (2015) Ethnobotany of millet cultivation in the north of the Iberian Peninsula. *Veg Hist Archaeobot* 24:541–554. <https://doi.org/10.1007/s00334-015-0518-y>
- Müldner G, Jay M (2008) Collagen extraction process (Reading version). University of Reading
- Murphy EM, Schulting R, Beer N, Chistov Y, Kasparov A, Pshenitsyna M (2013) Iron Age pastoral nomadism and agriculture in the eastern Eurasian steppe: implications from dental palaeopathology and stable carbon and nitrogen isotopes. *J Archaeol Sci* 40(5):2547–2560. <https://doi.org/10.1016/j.jas.2012.09.038>
- Nelson GC (2015) A host of other dental diseases and disorders. Crown wear. In Irish JD and Scott GR (eds) *A companion to dental anthropology*. John Wiley & Sons, Inc., West Sussex, pp 465–483
- Novak M (2015) Dental health and diet in early medieval Ireland. *Arch Oral Biol* 60(9):1299–1309. <https://doi.org/10.1016/j.archoralbio.2015.06.004>
- Novotná A (2017) The use of the stable isotope analysis of carbon and nitrogen in the dietary reconstruction of the Lombard population in relation to the health status. Dissertation, Charles University in Prague. <http://hdl.handle.net/20.500.11956/85507>
- Ogden A (2007) Advances in the palaeopathology of teeth and jaws. In: Pinhasi R, Mays S (eds) *Advances in human palaeopathology*. Wiley, Chichester, pp 283–307. <https://doi.org/10.1002/9780470724187.ch13>
- Oliva M, Ruiz-Fernández J, Barriendos M, Benito G, Cuadrat JM, Domínguez-Castro F, García-Ruiz JM, Giral S, Gómez-Ortiz A, Hernández A, López-Costas O, López-Moreno JI, López-Sáez JA, Martínez-Cortizas A, Moreno A, Prohom M, Saz MA, Serrano E, Tejedor E, Trigo R, Valero-Garcés B, Vicente-Serrano SM (2018) The little ice age in Iberian mountains. *Earth Sci Rev* 177:175–208. <https://doi.org/10.1016/j.earscirev.2017.11.010>
- Peña-Chocarro L, Pérez-Jordà G, Alonso N, Antolín F, Teira-Brión A, Tereso JP, Montes Moya EM, Reyes DL (2019) Roman and medieval crops in the Iberian Peninsula: a first overview of seeds and fruits from archaeological sites. *Quest Int* 499:49–66. <https://doi.org/10.1016/j.quaint.2017.09.037>
- Pérez-RamalloGrandal-d'Anglade PA, Organista E, Santos E, Chivall D, Rodríguez-Varela R, Götherström A, Etxeberria F, Ilgner J, Fernandez R, Arsuaga JL, LeRoux P, Higham T, Beaumont J, Koon H, Roberts P (2022) Multi-isotopic study of the earliest mediaeval inhabitants of Santiago de Compostela (Galicia, Spain). *Archaeol Anthropol Sci* 14(11):214. <https://doi.org/10.1007/s12520-022-01678-0>
- Petersone-Gordina E, Roberts C, Millard AR, Montgomery J, Gerhards G (2018) Dental disease and dietary isotopes of individuals from St Gertrude Church cemetery, Riga. Latvia *Plos One* 13(1):e0191757. <https://doi.org/10.1371/journal.pone.0191757>
- Polet C, Katzenberg MA (2003) Reconstruction of the diet in a mediaeval monastic community from the coast of Belgium. *J Archaeol Sci* 30(5):525–533. [https://doi.org/10.1016/S0305-4403\(02\)00183-8](https://doi.org/10.1016/S0305-4403(02)00183-8)
- Portela Silva E, Pallares Méndez MDC (1987) Elementos para el análisis de la aristocracia alto-medieval de Galicia: parentesco y patrimonio. In: Sociedad Española de Estudios Medievales (ed) *Galicia en la Edad Media: actas del coloquio de Santiago de Compostela-La Coruña-Pontevedra-Vigo-Betanzos*. Santiago de Compostela, pp 17–32
- Prada Marcos ME (1993) Estudio antropológico de los restos humanos medievales y modernos de la necrópolis leonesa de Palat del Rey. Dissertation, Universidad de León
- Price SA, Hopkins SS (2015) The macroevolutionary relationship between diet and body mass across mammals. *Biol J Linn Soc Lond* 115(1):173–184. <https://doi.org/10.1111/bij.12495>
- Priegue EMF (1998) O desenvolvemento da actividade pesqueira dende a Alta Idade Media ó século XVII. In: Fernández Cassanova C (ed), *Historia da pesca en Galicia*. Servicio de Publicacións e Intercambio Científico da Universidade de Santiago de Compostela, Santiago de Compostela, pp 51–86
- Puig JJ (2012) El comercio marítimo en Galicia, 1525–1640. *OMH* 21:105–130
- Ramezani G, Valaie N, Rakhshan V (2015) The effect of water fluoride concentration on dental caries and fluorosis in five Iran provinces: A multi-center two-phase study. *Dent Rest J (Isfahan)* 12(1):31. <https://doi.org/10.4103/2F1735-3327.150310>
- Rascón Pérez J, Campo Martín M, Cambra Moo Ó, Pimentel de Francisco G, González Martín A (2013) Distribución diferencial de caracteres de interés patológicos y no patológicos por edad y sexo en el cementerio medieval de veranes (Gijón). In: Universitat Autònoma de Barcelona (ed) *Vetera corpora morbo afflicta: Actas del XI Congreso Nacional de Paleopatología*, Bellaterra, pp 607–634
- Ríos L, Weisensee K, Rissech C (2008) Sacral fusion as an aid in age estimation. *Forensic Sci Int* 180(2–3):111–e1. <https://doi.org/10.1016/j.forsciint.2008.06.010>
- Rissech C (2008) Estimación de la edad biológica de los restos subadultos. In: Servei d'Investigacions Arqueològiques i Prehistòriques (ed) *Nasciturus, infans, puerulus vobis mater terra: la muerte en la infancia*, Barcelona, pp 77–92
- Rodríguez ACDP (2013) A maqbara de Shantarín: Enfermidade e saúde numa amostra esquelética de adultos. Dissertation, Universidade de Coimbra
- Rodríguez Martínez RM, Aboal Fernandez R, Castro Hierro V, Candela Cereijo C, Ayán Vila JM (2011) Una posible factoría prerromana en el noroeste. Primeras valoraciones de la intervención en el Campo de A Lanzada (Sanxenxo, Pontevedra). *Férvedes* 7:159–168. <http://hdl.handle.net/10261/137878>
- Schats R, van Hattum I, Kootker LM, Hoogland M, Waters-Rist AL (2022) Diet and urbanisation in medieval Holland. Studying dietary change through carious lesions and stable isotope analysis. *Int J Osteoarchaeol* 32(1):142–155. <https://doi.org/10.1002/oa.3051>
- Scheuer L, Black S (2004) *The juvenile skeleton*. Elsevier, Oxford
- Schour L, Massler M (1941) The development of the human dentition. *J AM Dent Assoc* 28:1153–1160
- Schurr MR, Powell ML (2005) The role of changing childhood diets in the prehistoric evolution of food production: an isotopic

- assessment. *Am J Phys Anthropol* 126(3):278–294. <https://doi.org/10.1002/ajpa.20034>
- Silva RFD (2011) *A Mesquita de Mértola e o Segredo dos Ossos: análise antropológica de 16 indivíduos da Baixa Idade Média*. Masther dissertation, Universidade de Coimbra
- Silva-Sánchez N, Tim K, Fernández-Ferreiro M, López-Salas E, Turner S, Sánchez-Pardo JC (2022) Written in soil and paper. Investigating environmental transformations of a monastic landscape by combining geoarchaeology and palynology with historical analysis at Samos (Spain). *J Archaeol Sci Rep* 45:103575. <https://doi.org/10.1016/j.jasrep.2022.103575>
- Smith BH (1984) Patterns of Molar Wear in Hunter-Gatherers and Agriculturalists. *Am J Phys Anthropol* 63(1):39–46. <https://doi.org/10.1002/ajpa.1330630107>
- Smith DR, Martin E, Kayfman BJ, Callaghan M, Cardona K, Kovacevich B, Toyne JM (2023) The bottom line: exploring analytical methods for assessing bioapatite preservation in archaeological bone using FRTIR-ATR. *J Archaeol Sci Rep* 50:104014
- Tang N, Le Cabec A, Antoine D (2015) Dentine and cementum structure and properties. In: Irish JD, Scott GR (eds) *A companion to dental anthropology*. John Wiley & Sons Inc., West Sussex, pp 204–222
- Teira-Brión A (2022) Traditional millet cultivation in the Iberian Peninsula: Ethnoarchaeological reflections through the lens of social relations and economic concerns. In: Kirleis W, Dal Corso M, Filipović (eds) *Millet and what else*. Sidestone, Leiden, pp 263–278
- Temple DH (2015) Caries: the ancient scourge. In: Irish JD andb Scott GR (eds) *A companion to dental anthropology*. John Wiley & Sons Inc., West Sussex, pp 433–449
- Tieszen LL, Fagre T (1993) Effect of diet quality and composition on the isotopic composition of respiratory CO₂, bone collagen, bioapatite, and soft tissues. In: Lambert JB, Grupe G (eds) *Prehistoric human bone: archaeology at the molecular level*. Springer, pp 121–155. https://doi.org/10.1007/978-3-662-02894-0_5
- Toso A, Gaspa S, Banha da Silva R, Garcia SJ, Alexander M (2019) High status diet and health in Medieval Lisbon: a combined isotopic and osteological analysis of the Islamic population from São Jorge Castle. *Portugal Archaeol Anthropol Sci* 11:3699–3716. <https://doi.org/10.1007/s12520-019-00822-7>
- Ubelaker DH, Ripley CE (1999) Ossuary of San Francisco Church, Quito, Ecuador: Human skeletal biology. In: Smithsonian Institution Press (ed) *Smithsonian Contributions to Anthropology*, vol 42, Washington D.C., pp 1–32. <https://doi.org/10.5479/si.00810223.42.1>
- Valentin F, Bocherens H, Gratuze B, Sand C (2006) Dietary patterns during the late prehistoric/historic period in Cikobia island (Fiji): insights from stable isotopes and dental pathologies. *J Archaeol Sci* 33(10):1396–1410. <https://doi.org/10.1016/j.jas.2006.01.012>
- Van der Linden FP, Duterloo HS (1976) *Development of the human dentition: an atlas*. Harper Collins Publishers, Hagerstown
- Van Klinken GJ (1999) Bone collagen quality indicators for palaeodietary and radiocarbon measurements. *J Archaeol Sci* 26(6):687–695. <https://doi.org/10.1006/jasc.1998.0385>
- Watson JT, Fields M, Martin DL (2010) Introduction of agriculture and its effects on women’s oral health. *Am J Hum Biol* 22(1):92–102
- Watson JT, Arriaza B, Standen V, Muñoz Ovalle I (2013) Tooth Wear Related to Marine Foraging, Agro-Pastoralism and the Formative Transition on the Northern Chilean Coast. *Int J Osteoarchaeol* 23(3):287–302. <https://doi.org/10.1002/oa.1247>
- Watson J, Schmidt CW (2020) *Dental wear in evolutionary and bio-cultural context*. Academic Press, London, pp 1–10. <https://doi.org/10.1016/B978-0-12-815599-8.00001-0>
- Yanko NV, Artemyev AV, Kaskova LF (2021) Dental health indicators of the Chernyakhov population from Shyshaki (Ukraine). *Anthropol Rev* 84(1):17–28

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.