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Sequential dentine $\delta^{13}C$ and $\delta^{15}N$ analysis of Islamic burials from medieval Al-Andalus

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A B S T R A C T

As a mixed society in which Muslims, Christians and Jews coexisted, the cultural landscape of medieval Al-Andalus offers considerable potential for study. As a contribution to this rich field, this paper explores the impact of social and religious differences on childhood dietary life histories. To achieve this, we apply the first carbon and nitrogen isotope analysis of sequential dentine for the medieval Al-Andalus region. The first molars of 11 individuals from two sites in northeastern Spain, Balaguer (urban Muslim cemetery, 8th-12th) and Santa Coloma d'Àger (rural Christian necropolis, 6th-11th), were analysed, from which details of weaning practices and childhood diets were reconstructed, and food consumption patterns by sex, age, religion and setting (urban/rural) were examined. The results indicate a preference for C_3-based foods such as wheat and barley in early child-rearing practices for both Muslims and Christians, with C_4-foods occasionally consumed. No significant gender differences were observed. Nevertheless, differences between the urban Balaguer and rural Santa Coloma d'Àger highlight the critical role of socioeconomic factors and resource accessibility. The more consistent reliance on C_3-based foods and higher $\delta^{15}N$ values at Balaguer likely reflect greater food availability and/or different agricultural practices associated with an urban setting. In contrast, Santa Coloma d'Àger's rural background may have led to a stronger dependence on locally available resources, sometimes overriding even religious dietary norms, reflecting the interplay of societal structure and contextual constraints in medieval Al-Andalus.

1. Introduction

Al-Andalus refers to the area of the Iberian Peninsula under Muslim rule from the 8th to the end of the 15th century (Salas-Salvadó et al., 2006). In AD 711, a Muslim army from North Africa invaded the Iberian Peninsula. As well as introducing Islam and intensifying the demographic movements between Iberia and North-Africa and the Near East, this brought about technological and social changes with regard to agricultural production and lifestyles (Glick, 2005). Despite prolonged confrontation with the Christian kingdoms in the north, Al-Andalus was home to a multi-faith society, in which Muslims, Christians, and Jews coexisted for over seven centuries, engaging in extensive cultural and social interaction. The intermingling and clashing of these communities and cultures have long been the subject of academic debate (Akasoy, 2010, Retamero, 2009). However, details of the society's social transformation and multicultural interaction remain unclear, calling for further research (Cressier and Gutiérre Lloret, 2021).

Diet provides an important window into the pluralistic society of Al-Andalus, as what a person eats reflects their cultural and social identity (Gumerman, 1997). Until recently, our comprehension of the dietary characteristics of medieval Spain has primarily relied on historical documentation (Ladero Quesada, 1985, García Sánchez, 1986). However, these focus mainly on the food choices of the urban upper-class, with little reference to the diets of lower-status individuals or rural populations (Garnsey, 1999, Waines, 2003, Constable, 2013). In addition, some information about foodways appears to be contradictory and needs to be used with caution (Pickard et al., 2017). Although archaeological evidence from plant and animal remains can provide some indication of the potential foods available to humans during this period (Alonso, 2005; Muñiz, 2002; Alexander et al., 2015; Cubero i Corpas et al., 2008; García, 2016; Grau-Sologestoa, 2015, 2016, 2017; Peña-Chocarro et al., 2019), it remains difficult to clearly reveal the identity of the consumers and the relative contributions of the foods consumed (Mundee, 2010). Stable isotope analysis of bone collagen is becoming an increasingly important method for studying dietary differences across religious and social boundaries in this area, as elsewhere (e.g., (Alexander et al., 2015; Dury et al., 2018; Guede et al., 2017; Inskip et al., 2018; Mundee, 2010; Pickard et al., 2017; Toso et al., 2019, 2021). Nevertheless, there are still limitations to this approach. Firstly, the available data focus mainly on the south, with far less work on the

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border areas to the north (with recent exceptions, Olivé-Busom and López-Costas, 2024; Pérez-Ramallo et al., 2022a, 2022b). Secondly, research has been primarily restricted to adult diets, lacking information on infant feeding strategies and potential dietary changes during childhood (Kwok, 2015). The traditional approach requires the use of subadult remains, of which fewer are preserved, and sex is difficult to determine (García-Collado et al., 2019). Moreover, there is also the potential of a selective mortality bias, meaning that it is challenging to confirm whether individuals who die prematurely from unknown causes are representative of normal, healthy individuals (Dewitte and Stojanowski, 2015; Wood et al., 1992).

This paper applies stable carbon and nitrogen isotope analysis of sequential dentine samples from northern Al-Andalus, in an attempt to address gaps in previous research on weaning practices and childhood diets. Two adjacent sites with different religious backgrounds in the northeastern frontier of Iberian Peninsula are studied: Balaguer (Muslim cemetery, 8th-11th centuries) and Santa Coloma d'Àger (Christian necropolis, 6th-11th centuries). First molars from 11 individuals were sampled and combined with new and previously available radiocarbon dates and paleopathological data. Accordingly, we aim: (1) to investigate individual-level weaning practices; and (2) to compare the parenting practices through childhood diets of two neighbouring groups with different faith and socioeconomic status residing in the northern border region.

2. Background

2.1. Archaeological sites

Santa Coloma d'Àger and Balaguer are located in the Ebro Valley of the northeastern Iberian Peninsula, about 25 km linear distance from each other, in the district of Lleida, one of the Upper Frontier cities in Al-Andalus (Fig. 1) (Sabaté, 2017). Lleida has a continental, semi-arid climate with seasonal variations and low rainfall, mainly in spring and autumn. Summers are hot and dry, while the winters are notably long (Pérez et al., 2011, Tao et al., 2018). Palaeobotanical remains record hulled barley and rye in the Islamic period, with smaller amounts of millet also found, and legumes including lentils and common vetch (Alonso, 2005; Alonso et al., 2014; Peña-Chocarro et al., 2019).

2.2. Balaguer

Balaguer was founded in the Islamic period, suggested to have had military origins as a defensive Andalusi fortress (Camats et al., 2015). In the 10th century, Balaguer experienced an urban expansion, which may have led to its gradual rise from a strategic military zone to an important regional administrative and economic centre (Camats et al., 2015; Sabaté, 2017; Alòs, 2015). Between the late 11th and early 12th centuries, after several repeated sieges and occupations, the city was finally conquered by the Catalan counties (Alòs et al., 2007a).

At present, one *maqbara* or cemetery is known, from which the samples in this study are drawn. The burials were in simple graves with no grave goods. Most of the skeletons were placed on their right side, with the head and feet in a NE-SW orientation, and the face towards the SE, in accordance with Islamic ritual (Olivé-Busom, 2023).

2.3. Santa Coloma d'Àger

Santa Coloma d'Àger is a church, possibly a basilica, founded ca. 5th century with an associated necropolis (Benet i Clarà, 1994; Bertran and Fité, 1986). After three centuries as part of Al-Andalus, the final Christian conquest of Àger took place in 1048, after which the Christians reorganised their economic and religious life. They implemented a new parish system, resulting in the abandonment of the necropolis. Additionally, vineyards, orchards, a church and a castle appeared, around which a new village was established (Porcheddu, 2017; Gran Enciclopèdia Catalana, 1986). Although the location of the settlement remains unknown (Benet i Clarà, 1983), hundreds of skeletons dating from the 5th to the 11th century have been unearthed in several archaeological excavations. All the skeletons are placed supine and oriented E-W, and therefore are considered Christian.

2.4. Diet in medieval Spain

2.4.1. Food sources

According to literary and archaeological records, cereals formed the staple of medieval diet in Iberia (Salas-Salvadó et al., 2006, García Sánchez, 2011). Wheat was considered a refined cereal with a higher status, while barley was associated with the diet of the lower classes (Montanari, 1994). Asian foxtail and broomcorn millets (*Setaria italica* and *Panicum miliaceum*, respectively) were present in Iberia since at least the Late Bronze Age (Miller et al., 2016, González-Rabanal et al., 2022). The Islamic period, however, saw the arrival of the African C_4 crops pearl millet (*Pennisetum glaucum*) and sorghum (*Sorghum bicolor*) (Glick, 2005, Miller et al., 2016, Pérez-Jordà et al., 2024). While they were considered as secondary crops both in the Islamic and Christian periods

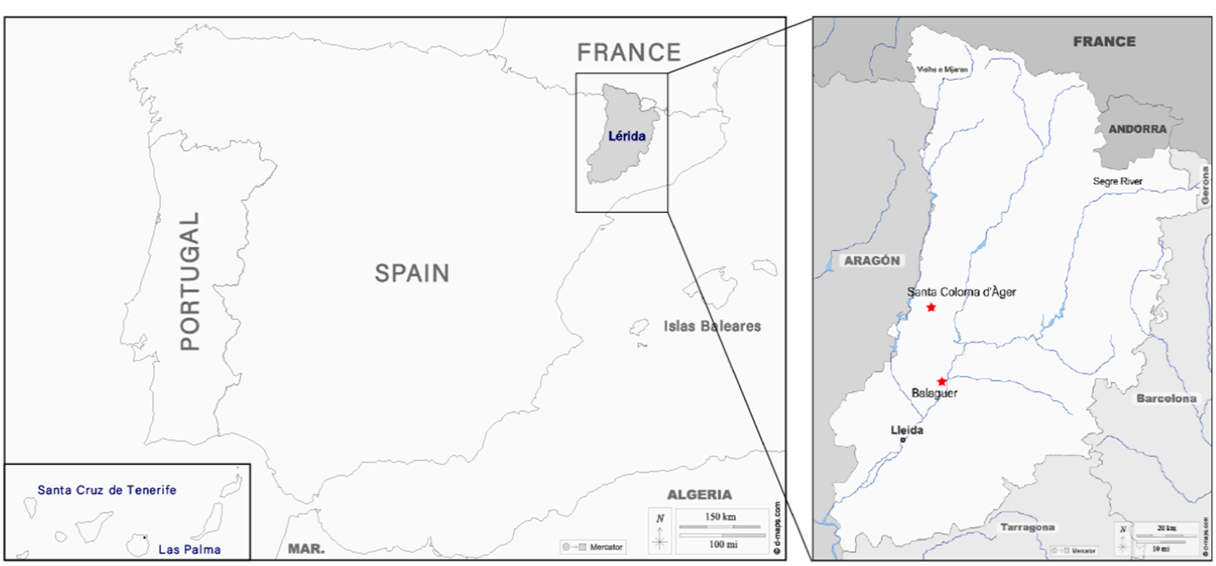

Fig. 1. Map showing site locations (adapted from https://d-maps.com/, map of Spain).

(García Sánchez, 1994), their short growth cycle and ease of storage enable them to survive in both hot and dry or rainy conditions, making them good fallback crops in early spring when other grains were in short supply, especially in rural settlements (Hernández Bermejo and García Sánchez, 2008; Spurr, 1986; Zohary et al., 2012). Legumes were also consumed in medieval Spain, their high protein content making them a suitable substitute for meat amongst the lower socioeconomic classes (Salas-Salvadó et al., 2006). Moreover, legumes played a special role in the Christian diet, serving as a high-protein food during fast days and Lent, which comprised over 150 days of the Christian calendar (Adamson, 2004, Mundee, 2010). Fruits and vegetables were also an important part of the diet (Adamson, 2004, Salas-Salvadó et al., 2006, Grumett and Muers, 2010), but their low protein content makes them difficult to distinguish from other crops by isotopic analysis of collagen (Mundee, 2010).

Sheep and goat were popular meats in Al-Andalus (Waines, 1992, Kazhdan, 1997), followed by chicken, beef and pork. It is generally accepted that meat was consumed in larger quantities by socioeconomic elites, who prized meat from young animals and possibly hunted game, such as deer and wild birds (Salas-Salvadó et al., 2006, Inskip et al., 2018). Conversely, for the lower classes, the availability of meat was limited and they may have eaten cheaper offal or eggs and dairy products (Salas-Salvadó et al., 2006, Mundee, 2010). Apart from this, there are certain religious requirements affecting meat consumption. Christians were prohibited from consuming meat on fast days, while Muslims were forbidden from consuming pork under Islamic law (Constable, 2013). Zooarchaeological evidence indicates that pig consumption declined in the Islamic period (García, 2016). Nevertheless, *Suidae* (possibly including wild boar) remains are still found at Muslim sites from this period, and have been attributed to necessity, the presence of Christian groups or a degree of religious flexibility in adherence to this prohibition (García, 2016; Lentacker and Ervynck, 1999; Mundee, 2010). The importance of aquatic resources in daily diet is difficult to evaluate both textually and archaeologically (Bourbou and Richards, 2007; Dury et al., 2018). A number of recent studies suggest that while fish was consumed, it was perhaps perceived as having lower status (Anderson, 2006; Dury et al., 2018; Salas-Salvadó et al., 2006).

2.4.2. Breastfeeding and weaning practices

Medieval texts offer specific guidance on infant feeding and weaning practices in Al-Andalus. Medical treatises and manuals recommend that infants should be breastfed by their mothers or wetnurses as much as possible until they start teething at around 6 months of age (Modanlou, 2008). The appropriate age for the cessation of weaning was around 2 years; before that time, breastfeeding should be gradually reduced and supplemented with cow's milk, light soups and bread crumbs (Adamson, 2004, Salas-Salvadó et al., 2006). Millet and sorghum are recognized in Africa as traditional weaning foods that may have ancient origins (National Research Council, 1996, Turner et al., 2007), and this practice may have been brought to Al-Andalus.

3. Stable isotope analysis in Archaeology

Stable carbon (δ^{13}C) and nitrogen (δ^{15}N) isotope analysis has been widely used to investigate aspects of past diets. For carbon, most terrestrial plants can be divided into C_3 and C_4 photosynthetic pathways (Farquhar et al., 1989). The δ^{13}C values of C_3 plants range from −35 ‰ to −20 ‰, while those of C_4 plants range from −16 ‰ to −9‰ (Van der Merwe, 1982, Tieszen, 1991). Marine primary producers have δ^{13}C values intermediate to those of terrestrial C_3 and C_4 plants (Schoeninger and Moore, 1992, Pate, 1994), which add to the difficulty of interpreting human diets. This is where stable nitrogen isotopes can play an important role. The fractionation of N isotopes in the food chain is related to trophic level, with δ^{15}N values enriching by 3 ‰ to 5 ‰ with each trophic level (Deniro and Epstein, 1981; Hedges and Reynard, 2007; Schoeninger, 1985). Aquatic ecosystems have longer food chains and therefore tend to present higher δ^{15}N values than terrestrial ecosystems (Schoeninger and DeNiro, 1984).

Both isotopes are subject to additional variation, through either external or internal factors. For instance, the application of animal manure to increase soil fertility leads to higher plant δ^{15}N values (Bogaard et al., 2013; Fraser et al., 2011). Aridity increases both δ^{13}C and δ^{15}N in plants (Farquhar et al., 1982; Szpak, 2014), and hence in the animals consuming them, including humans. For internal factors, individuals may experience positive or negative nitrogen balance, during normal growth or when suffering from physiological stress, leading to changes in δ^{15}N (Fuller et al., 2005, Waters-Rist and Katzenberg, 2010). These factors also need to be taken into account when interpreting stable isotope results.

A trophic shift of about 2–3 ‰ in δ^{15}N and an increase of about 1 ‰ in δ^{13}C values can be observed between infant and mother. As the weaning process begins and complementary foods are introduced, the δ^{15}N values of infants gradually decline, reflecting changes in diet composition until breastfeeding ceases completely (Fogel et al., 1989; Fuller et al., 2006a; Tsutaya and Yoneda, 2015).

Bone and dentine collagen are the primary materials for δ^{13}C and δ^{15}N analysis in archaeological research. However, unlike bone, primary tooth dentine does not remodel once formed (Beaumont et al., 2014; Fuller et al., 2003); for example, the first molars begin to form from birth and complete development at approximately 9 years of age (Alqahtani et al., 2010). Since its growth rate is well known, the age of dentine formation can be determined and thus aspects of an individual's dietary/physiological history can be reconstructed (Czermak et al., 2020).

4. Materials and methods

4.1. Materials

Eleven well-preserved individuals were selected for paleodietary analysis due to the availability of first molars, four from Balaguer and seven from Santa Coloma d'Àger (Table 1). Radiocarbon dates and osteological information are available for all samples (see below and Olivé-Busom, 2023).

For comparison to the sequential dentine samples, previously published adult human bone collagen data from Olivé-Busom and López-Costas (2024) are presented here as an adult baseline, along with faunal data (Fig. 2). The adults include all individuals sampled from Balaguer (BG) in our study and most of those from Santa Coloma d'Àger (SCA). Mean δ^{13}C and δ^{15}N values for BG adults are −18.82 ± 0.23 ‰ and 11.42 ± 0.84 ‰ respectively (n = 13), with means of −18.89 ‰ ± 0.19 ‰ and 11.51 ‰ ± 0.74 ‰ for males (n = 5) and −18.78 ± 0.36 ‰ and 11.71 ± 1.06 ‰ for females (n = 4). At SCA, the mean δ^{13}C and δ^{15}N values for adults are −18.90 ± 0.28 ‰ and 9.08 ± 0.46 ‰ respectively (n = 16), with means of −18.82 ± 0.18 ‰ and 9.26 ± 0.43 ‰ for males (n = 8); −18.88 ± 0.19 ‰ and 8.94 ± 0.48 ‰ for females (n = 7).

Table 1
Cultural attributions and age/sex estimations of the individuals in the study.

Site	Lab ID	Religion	Sex	Age (years)
Balaguer	BG0026	Islamic	Female	30–50
	BG0028	Islamic	Male	20–30
	BG0489	Islamic	Female	15–20
	BG4101	Islamic	Female	40–50
Santa Coloma d'Àger	SC0119	Christian	Male	30–40
	SC0180	Christian	Female	30–40
	SC0011	Christian	Indet	4–6
	SC0014	Christian	Female	50+
	SC0118	Christian	Indet	>18
	SC0147	Christian	Male	40–50
	SC0155	Christian	Female	30–40

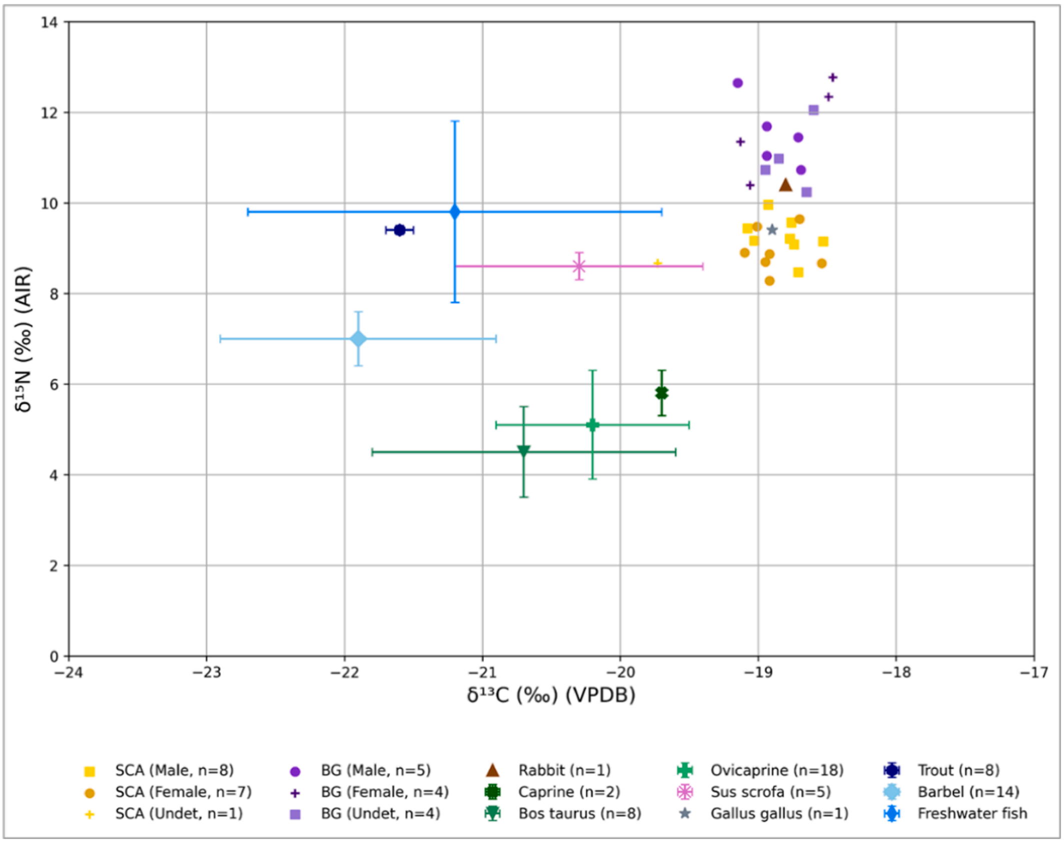

Fig. 2. δ^{13}C and δ^{15}N ($\overline{x}\pm$1SD) values of fauna (various sites) and human bone collagen (BG and SCA). Sources for comparative faunal data are shown in Table S3.

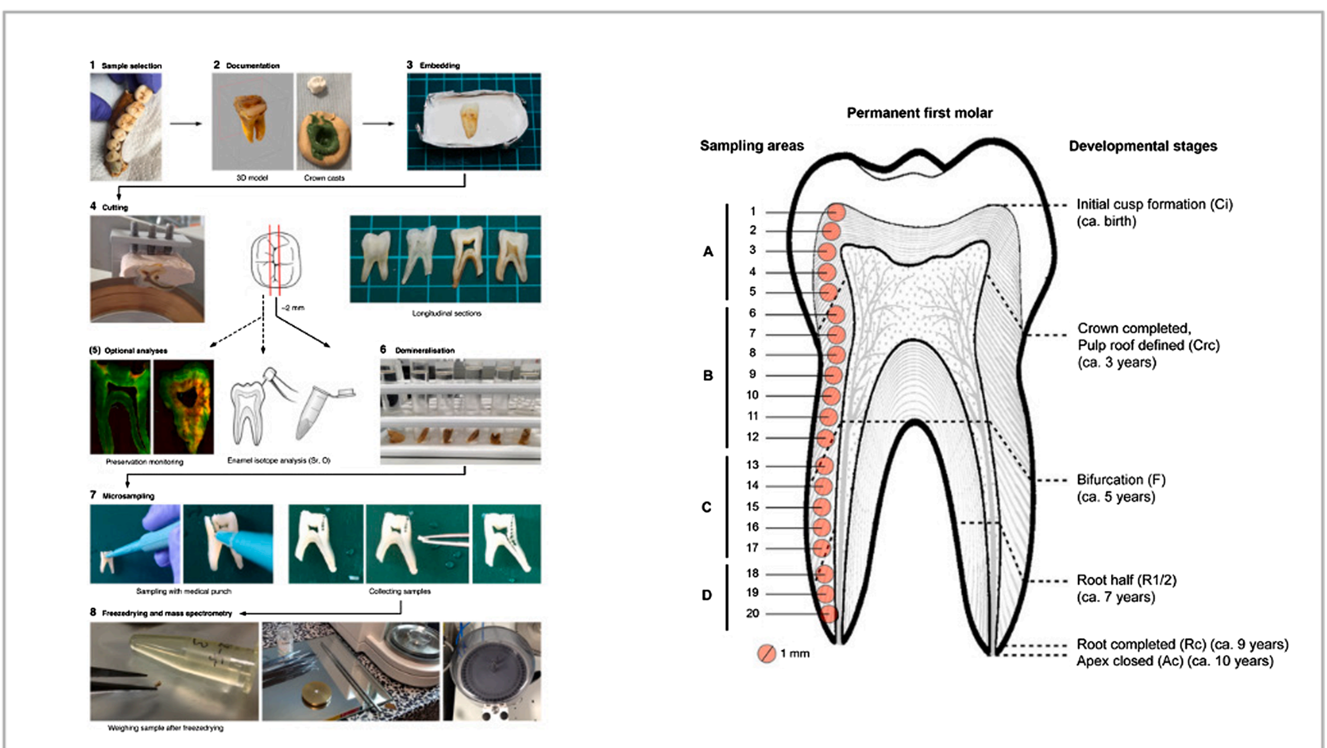

Fig. 3. Microsampling workflow (Czermak et al., 2020).

4.2. Methods

4.2.1. Stable carbon and nitrogen isotope analysis

This paper follows the sampling protocols in Czermak et al. (2020) as shown in Fig. 3. This involves the use of a 1 mm KAI Medical biopsy punch, providing the potential for finer temporal resolution than possible with linear slicing (Beaumont et al., 2013). An average of 14 measurements per fully-formed tooth was obtained (due in part to crown weartable 4). The entire procedure and standards are provided in S1. Sub-samples were grouped by weight class (0.3–0.49 mg, 0.5–0.79 mg, and 0.8–1.2 mg) and analysed in separate runs in order to match the weight of standards for drift correction and calibration. In a small number of cases, adjacent subsamples were combined to meet a minimum weight of 0.3 mg for analysis.

All statistical analyses were performed using IBM SPSS v30, Matplotlib and Microsoft Excel. Due to small sample size, non-parametric Mann–Whitney U-tests ($\alpha = 0.05$) were applied to compare independent datasets.

The inferred early dietary life histories of individuals were reconstructed from the sequential dentine samples following the methods of Fernández-Crespo et al. (2018) and Czermak et al. (2020). To better study the weaning process and subsequent childhood diet, several marker points were identified. Typically, the first sub-sample of the M1 crown presents the highest value and is interpreted as a more or less exclusive breastfeeding signal (in the sense that any complementary foods are not being consumed at levels that are isotopically detectable). However, cusp wear may result in the crucial first six months of life or more not being represented. A continuous decrease in early δ^{15}N values is considered as weaning signal, with the last point before weaning and the first point after weaning determining the duration of this process. Considering that positive nitrogen balance during the growth period occurs in some individuals between the ages of 4–7 years and may affect post-weaning isotopic results (Fuller et al., 2005, Waters-Rist and Katzenberg, 2010), δ^{13}C and δ^{15}N values of the last dentine sub-sample (age 8–9) were chosen to compare childhood and adult diets. In addition, individuals were also compared within each site by sex and age.

4.2.2. Radiocarbon dating

Radiocarbon dating of samples BG0489, BG4101 and SC0119 was carried out at the Oxford Radiocarbon Accelerator Unit (ORAU) following the protocol outlined in Brock et al. (2010) (details in S2). Radiocarbon dates were calibrated using IntCal20 (Reimer et al., 2020) in OxCal v4.4 (Bronk Ramsey, 2009) (https://c14.arch.ox.ac.uk/oxcal/OxCal.html). Additional radiocarbon dates are from Olivé-Busom (2023).

5. Results

All samples provided well-preserved collagen (Table 2; Table S1), except for SC0014-3 and SC0118-9, which failed to meet collagen quality control criteria (DeNiro, 1985, Ambrose, 1990, van Klinken, 1999, Guiry and Szpak, 2020). The measurement uncertainty for each weight group and the correlation between the δ^{13}C and δ^{15}N values of the samples are presented in Table S2 and Fig. S1.

5.1. Radiocarbon dating results

All individuals in this study fall between the 7th and 13th centuries (Table 3; Fig. 4). In Balaguer, most individuals date to the 8th–10th centuries, when this area was under Muslim control and city expansion began. An exception is BG0028, which dates to the 11th–13th centuries, when Balaguer was under siege and conquered by the Christian Catalan counties after the 12th century (Alòs et al., 2007b). The Santa Coloma d'Àger individuals fall under the period of Muslim rule between the second half of the 7th and 11th centuries (Porcheddu, 2017; Gran Enciclopèdia Catalana, 1986).

5.2. Stable isotope results

5.2.1. Breastfeeding and weaning

5.2.1.1. Balaguer. Due to cusp wear, data reflecting approximately the first six months of life are missing from all Balaguer samples except BG0489 (Fig. 5, Table 4). Thus, most do not exhibit the "plateau" reflecting the breastfeeding signal. Following Fernández-Crespo et al. (2018), the weaning process is indicated by a marked decrease in δ^{15}N values, ending at the lowest δ^{15}N value after a sustained decline.

All Balaguer individuals show a steady decrease in δ^{15}N values until around age 3, mostly decreasing by ca. 3 ‰. The exception is BG4101, where the first sub-sample falls below the adult average, suggesting that weaning was completed by ca. age 1.5 years. Additionally, there are differences in the pattern of changes in δ^{13}C. Those for BG0028 and BG0489 decrease by 0.5–1 ‰ during the weaning period, while BG0026 shows an increase in δ^{13}C values. The weaning process for Balaguer individuals was completed around 2.3 ± 0.3 years, suggesting that the gradual transition from breast milk to solid food lasted at least 1.4 ± 0.2

Table 2
Mean values and standard deviation of quality control indicators (excluding two sub-samples).

Site	Teeth	Dentine samples (n)	Range	C:N Mean ± SD	Range	%C Mean ± SD	Range	%N Mean ± SD
Balaguer	4	51	3.14–3.28	3.19 ± 0.03	40.30–54.85	42.85 ± 2.88	14.69–20.01	15.68 ± 1.02
Santa Coloma d'Àger	7	85	3.14–3.32	3.20 ± 0.03	16.16–59.23	42.35 ± 4.09	5.8–21.55	15.42 ± 1.50
All samples	11	136	3.14–3.32	3.20 ± 0.03	16.16–59.24	42.54 ± 3.69	5.8–21.56	15.52 ± 1.35

Table 3
Radiocarbon dating results on human bone collagen from Balaguer and Santa Coloma d'Àger.

Site	Sample	Lab code	δ^{13}C (‰)	^{14}C Age	Hist. date (95.4 % probability)
Balaguer	BG0026	PSUAMS-10218	–	1160 ± 15	772–789 calAD (14.2 %) 826–899 calAD (52.7 %) 919–957 calAD (28.5 %)
	BG0028	UBAR-1230	−18.6	850 ± 30	1054–1060 cal AD (0.9 %) 1157–1267 calAD (94.6 %)
	BG0489	OxA-42613	−18.4	1173 ± 24	772–899 calAD (82.3 %) 920–956 calAD (13.2 %)
	BG4101	OxA-42614	−18.3	1120 ± 24	886-993al AD
Santa Coloma d'Àger	SC0119	OxA-42615	−18.2	1062 ± 23	897–921 calAD (13.1 %) 955–1027 calAD (82.3 %)
	SC0180	SUERC-103772	−18.8	1096 ± 24	890–996 calAD (93.8 %) 1008–1014 calAD (1.7 %)
	SC0011	SUERC-103773	−19.6	1073 ± 24	895–926 calAD (23.4 %) 949–1024 calAD(72 %)
	SC0014	SUERC-103774	−18.9	1082 ± 20	893–928 calAD (30.6 %) 945-1020 calAD (64.8 %)
	SC0118	UBAR-522	−18.7	1230 ± 55	665–895 CE (92.2 %) 925–950 calAD (3.2 %)
	SC0147	UBAR-523	−18.3	1175 ± 45	707–726 calAD (2.8 %) 771–990 calAD (92.6 %)
	SC0155	UBAR-524	−18.3	1095 ± 45	774–786 calAD (1.7 %) 832–850 calAD (2.0 %) 875–1029 calAD (91.7 %)

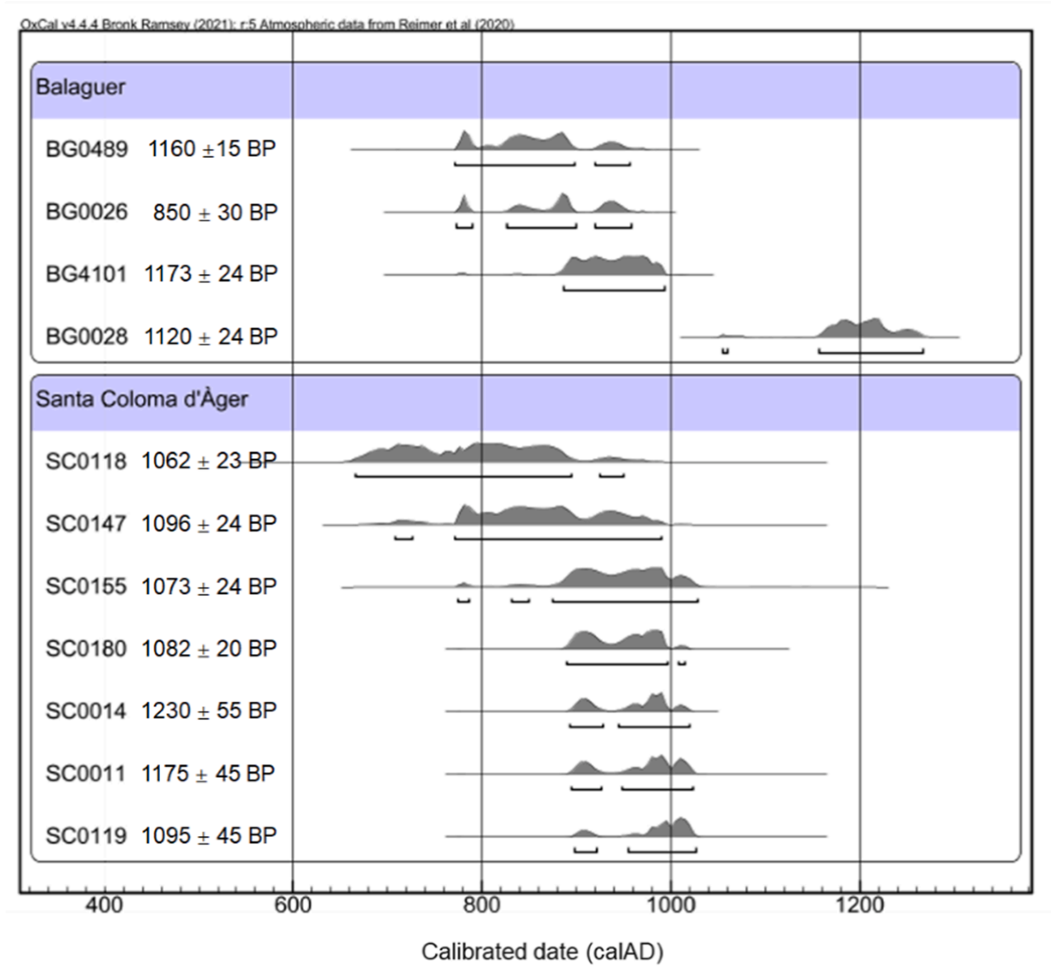

Fig. 4. Radiocarbon dating results calibrated using OxCal. v4.4 (Bronk Ramsey, 2009) and the IntCal20 atmospheric curve (Reimer et al., 2020).

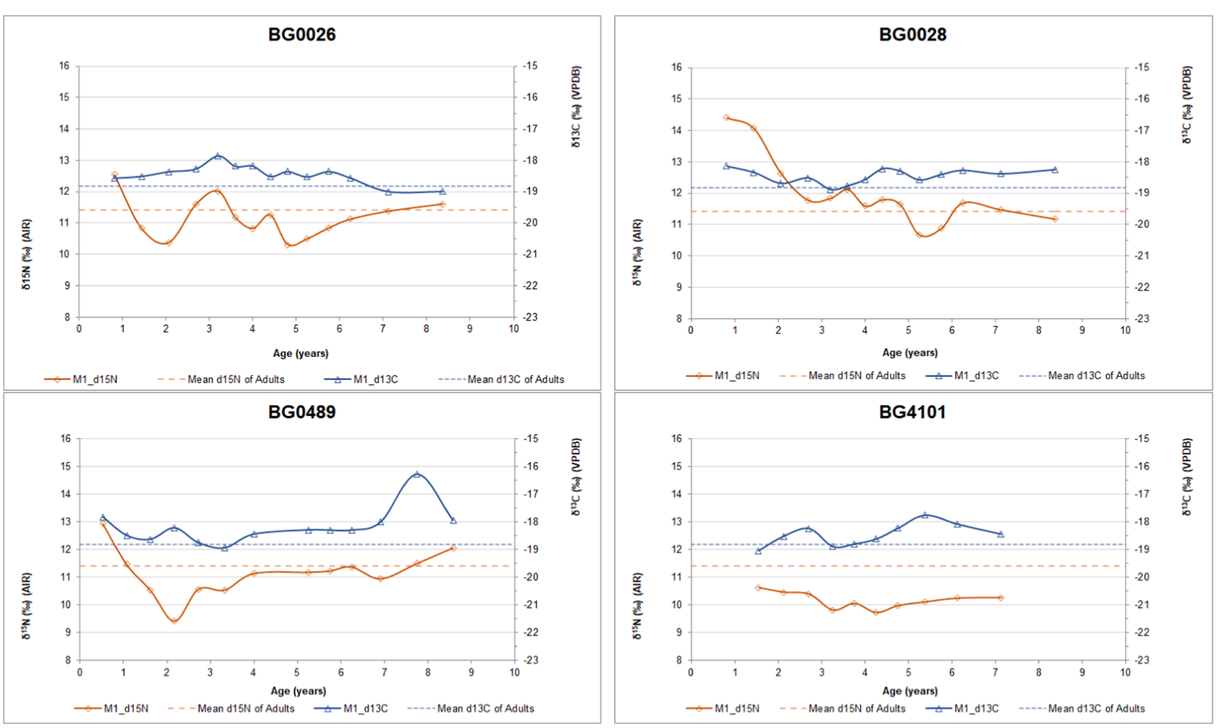

Fig. 5. Dentine collagen $\delta^{13}C$ and $\delta^{15}N$ profiles of first molars from Balaguer, against mean values of all adults.

Table 4
Duration of exclusive breastfeeding and weaning process and δ^{13}C and δ^{15}N values at some key points for Balaguer individuals.

Name	Age at death (years)	Sex	Estimated duration of exclusive breastfeeding (years)	δ^{13}C (‰) (VPDB) preweaning (dentine)	δ^{15}N (‰) (AIR) preweaning (dentine)	Estimated duration of weaning process (years)	Age at complete weaning (years)	δ^{13}C (‰) (VPDB) postweaning (dentine)	δ^{15}N (‰) (AIR) postweaning (dentine)	δ^{13}C (‰) (VPDB) last sub-sample (dentine)	δ^{15}N (‰) (AIR) last sub-sample (dentine)	δ^{13}C (‰) (VPDB) adulthood (bone)	δ^{15}N (‰) (AIR) adulthood (bone)
BG0026	30–50	Female	≤0.8	−18.57	12.54	≥1.3	2.1	−18.36	10.37	−18.99	11.61		
BG0028	20–30	Male	1.4	−18.33	14.07	1.3	2.7	−18.51	11.78	−18.24	11.18		
BG0489	15–20	Female	≤0.5	−17.82	12.95	≥1.7	2.2	−18.21	9.41	−17.94	12.07		
BG4101	40–50	Female	–	–	–	–	–	–	–	−18.44	10.26		
Mean (all)			≤0.9	−18.24	13.19	≥1.4	2.3	−18.36	10.52	−18.40	11.28	−18.82	11.42
SD			0.5	0.39	0.79	0.2	0.3	0.15	1.19	0.44	0.77	0.23	0.84
Mean (male)			1.4	−18.33	14.07	1.3	2.7	−18.51	11.78	−18.24	11.18	−18.89	11.51
SD			–	–	–	–	–	–	–	–	–	0.19	0.74
Mean (female)			≤0.7	−18.19	12.75	≥1.5	2.1	−18.29	9.89	−18.46	11.31	−18.78	11.71
SD			0.2	0.53	0.29	0.3	0.1	0.10	0.68	0.53	0.94	0.36	1.06

years.

Following weaning, the mean δ^{13}C value was −18.36 ± 0.15 ‰, indicating predominantly C_3 diets. The mean δ^{15}N of 10.52 ± 1.19 ‰ suggests relatively high animal protein consumption. Although no clear signal of aquatic resources can be observed, the contribution of fish is worth considering, given Balaguer's proximity to the River Segre, and the fact that local freshwater resources exhibit δ^{13}C values comparable to those of C_3 crops and terrestrial fauna (Fig. 2). Moreover, manuring – known to have been practiced in Al-Andalus (Bolens, 1978; García and Moreno, 2018) – may also contribute to higher δ^{15}N values. The higher δ^{15}N values of the rabbit and caprines from Balaguer compared to herbivores from other sites may indicate foraging on manured fields. Written sources note the existence of irrigated orchards in the city's vicinity, which, according to Islamic treatises, could employ manure (Batet, 2006). Furthermore, it should also be noted that pigs were potentially consumed in Al-Andalus and could raise δ^{15}N values in human consumers (Waines, 1992, Kazhdan, 1997). Although more abundant in contemporary Christian settlements, *Suidae* remains have been unearthed from a limited number of medieval Muslim sites (García, 2016; Lentacker and Ervynck, 1999; Mundee, 2010).

5.2.1.2. Santa Coloma d'Àger. Sequential results for Santa Coloma d'Áger are shown in Fig. 6 and Table 5. Due to root breakage and early death, SC011 preserves incremental isotopic information only up to around three years of age, with an unusual pattern. However, it still retains a signal reflecting the first six months of life, which is lost through cusp wear in all other individuals. SC0014 and SC0155 exhibit the "plateau" reflecting the highest values associated with the nursing signal, which are similar to the first δ^{15}N values of most of the remaining samples lacking a "plateau".

Five individuals (SC0014, SC0118, SC0119, SC0147 and SC0155) show a simultaneous decline in δ^{13}C and δ^{15}N values until ca. 3–4 years of age, with δ^{15}N values decreasing by 3–5 ‰. However, only SC0147 decreases by approximately 1 ‰ in δ^{13}C as expected for a trophic level shift (Fogel et al., 1989; Fuller et al., 2006a; Tsutaya and Yoneda, 2015); the other four individuals decrease by ca. 2 ‰, exceeding the upper limit of the usual tropic level shift for δ^{13}C. Another individual, SC0155, shows a basically stable δ^{13}C value rather than a simultaneous decrease with δ^{15}N, which may have resulted from the use of C_4 plants as a supplementary food. In addition, SC0011 is a special case as the weaning process is not observed in this individual, which instead shows a pattern of nearly synchronous rise in δ^{13}C and δ^{15}N values. This unusual signal might indicate physiological stress experienced by this child after breastfeeding (Reitsema, 2013), leading to their premature death at age 4–6. Overall, the weaning process in all individuals, with the exception of SC0011, ended around 2.8 ± 0.2 years, with the transition from breast milk to solid food lasting ca. 1.7 ± 0.6 years. Both figures are broadly comparable to those for Balaguer.

Following weaning, the mean δ^{13}C value is −18.30 ± 0.53 ‰, which demonstrates a signal dominated by C_3 foods. The mean δ^{15}N value of 9.63 ± 1.13 ‰, is comparable to that of Balaguer.

5.2.2. Age-based comparison

To better understand infant-rearing patterns, it is necessary to compare early childhood diets with those of adults and more specifically with adult females at the sites. For the Balaguer group, the carbon isotope values immediately post-weaning are slightly but significantly higher than those of all adults ($p = 0.014$, with mean values of −18.36 ± 0.15 ‰ and −18.82 ± 0.23 ‰, respectively) (Table 6), though both still reflect an isotopic signal dominated by C_3 foods. Many individuals also show a short downward fluctuation in δ^{15}N between the ages of 4 and 7 years, possibly relating to positive nitrogen balance during the growth period (Fuller et al., 2005; Waters-Rist and Katzenberg, 2010). However, the overall trend in δ^{15}N values after weaning for most of the individuals is upward, consistent with a gradual increase in animal protein intake during childhood (and incidentally suggesting that these, rather than manured cereals, were responsible). At around 8.5 years of age (the last dentine sample), δ^{15}N values are higher than seen at the end of weaning, almost reaching adult levels.

In contrast, the Santa Coloma d'Àger group shows more statistically significant differences. At the time of post-weaning, the δ^{13}C values for SCA individuals are also slightly but significantly higher than those of all adults ($p = 0.017$, with mean values of -18.30 ± 0.53 ‰ and -18.90 ± 0.28 ‰, respectively). Although no statistically differences are observed with adult females at these points (both $p = 0.051$), this is likely due to the reduced sample size and hence low statistical power.

Additionally, δ^{13}C values of the last dentine sub-sample differ significantly from all adults and adult females ($p = 0.013$, $p = 0.014$) (Table 7). The mean δ^{13}C value for children at this point (-18.43 ± 0.34 ‰) is slightly higher than the adult mean (-18.90 ± 0.28 ‰ for all adults, and -18.88 ± 0.19 ‰ for adult females). In terms of trends, some individuals (SC0155 and SC0180) display marked increases in δ^{13}C values at points after weaning, without a corresponding change in δ^{15}N values, which likely reflects a pattern of alternating consumption of C_3 and a small component of C_4 foods in their childhood diet. Conversely, others (SC0014 and SC0147) show synchronous increases in both δ^{13}C and δ^{15}N values, suggesting possible marine fish consumption or C_4-plant-fed animal protein.

After weaning, δ^{15}N values of most individuals continue to decline for some time. Although SC0155 shows a rebound in δ^{15}N values after weaning, which could reflect physiological stress or renewed breast-feeding, the decline was sustained thereafter and remains below the δ^{15}N values of the weaning process. However, between the ages of 4 and

Fig. 6. Dentine collagen δ^{13}C and δ^{15}N profiles of the first molars from the individuals from Santa Coloma d'Àger, against mean values of all adults.

Table 5
Duration of exclusive breastfeeding and weaning process and $\delta^{13}C$ and $\delta^{15}N$ values at some key points for Santa Coloma d'Àger individuals.

Name	Age at death (years)	Sex	Estimated duration of exclusive breastfeeding (years)	$\delta^{13}C$ (‰) (VPDB) preweaning (dentine)	$\delta^{15}N$ (‰) (AIR) preweaning (dentine)	Estimated duration of weaning process (years)	Age at complete weaning (years)	$\delta^{13}C$ (‰) (VPDB) postweaning (dentine)	$\delta^{15}N$ (‰) (AIR) postweaning (dentine)	$\delta^{13}C$ (‰) (VPDB) last sub-sample (dentine)	$\delta^{15}N$ (‰) (AIR) last sub-sample (dentine)	$\delta^{13}C$ (‰) (VPDB) adulthood (bone)	$\delta^{15}N$ (‰) (AIR) adulthood (bone)
SC0011	4–6	Indet	–	–	–	–	–	–	–	–	–		
SC0014	50+	Female	1.3	−17.13	12.97	2.0	3.3	−18.58	9.28	−18.54	8.88		
SC0118	>18	Indet	≤0.8	−17.22	12.08	≥2.0	2.8	−18.44	8.48	−18.79	10.82		
SC0119	30–40	Male	≤1.2	−16.63	13.20	≥1.6	2.8	−17.56	9.37	−18.11	10.69		
SC0147	40–50	Male	≤0.5	−16.95	13.26	≥2.2	2.7	−18.24	8.87	−17.99	9.24		
SC0155	30–40	Female	2.2	−17.57	13.48	0.6	2.7	−17.92	11.65	−18.37	9.42		
SC0180	30–40	Female	≤0.9	−17.13	12.91	≥1.7	2.6	−19.08	10.10	−18.80	10.22		
Mean (all)			≤1.1	−17.10	12.98	≥1.7	2.8	−18.30	9.63	−18.43	9.88	−18.90	9.08
SD			0.6	0.31	0.49	0.6	0.2	0.53	1.13	0.34	0.81	0.28	0.46
Mean (male)			≤0.9	−16.79	13.23	≥1.9	2.8	−17.90	9.12	−18.05	9.96	−18.82	9.26
SD			0.5	0.23	0.04	0.4	0.0	0.48	0.35	0.09	1.02	0.18	0.43
Mean (female)			≤1.4	−17.28	13.12	≥1.4	2.9	−18.53	10.34	−18.57	9.51	−18.88	8.94
SD			0.6	0.25	0.31	0.8	0.4	0.58	1.20	0.22	0.67	0.19	0.48

7, their $\delta^{15}N$ values rise slightly, remaining above the adult mean. Even at around age 8.5, their $\delta^{15}N$ values still differ statistically from adults ($p = 0.040$).

Sex-based comparisons are limited by sample size (see S3).

6. Discussion

To facilitate the discussion of early life isotopic profiles, it is worth reiterating the mean results for adults at Balaguer and Santa Coloma d'Àger. The $\delta^{13}C$ analysis of bone collagen show similar results for both sites, with values of −18.82 ± 0.23 ‰ and −18.90 ± 0.28 ‰ respectively, indicating C_3-based diets. In contrast, $\delta^{15}N$ values show a significant difference ($p < 0.01$), with Balaguer's mean of 11.42 ± 0.84 ‰ being clearly higher than that of 8.94 ± 0.48 ‰ at SCA, likely reflecting greater animal protein intake (Olivé-Busom and López-Costas, 2024), though differences in agricultural practices (i.e., manuring) are also possible. Since the sites are coeval and only 25 km distant from one another, there are no temporal or spatial climate differences (e.g. aridity) to consider.

To better understand child-rearing practices at the two sites, the results are statistically compared according to the weaning process and childhood diet (Table 8).

6.1. Breastfeeding and weaning

In contrast to adult bone collagen, pre-weaning $\delta^{15}N$ values for the Balaguer and Santa Coloma d'Àger populations are similar, while $\delta^{13}C$ differs significantly, with mean values of −18.82 ± 0.23 ‰ for Balaguer and −17.10 ± 0.31 ‰ for SCA ($p = 0.024$). Although both exhibit consumption of predominantly C_3 foods, SCA seems to show slightly greater C_4 consumption than Balaguer. As recorded in historical documents, urban Al-Andalus society had a preference for wheat (Montanari, 1994), while millet and sorghum were primarily secondary crops, used especially in times of poor harvests (Spurr, 1986). This is supported by local archaeological evidence showing that the most common crop remains in this period were hulled barley and naked wheat, though with small amounts of millet also present (Alonso, 2005; Alonso et al., 2014; Peña-Chocarro et al., 2019). Therefore, it is reasonable to suggest that wheat or barley consumed by nursing mothers were likely the primary source of the C_3 signal in the infants at the two sites, while the slightly higher $\delta^{13}C$ values of SCA could be the result of mothers' supplemental consumption of millet or sorghum during this process and/or its use as a weaning food. Accordingly, the cereal choice at both sites likely aligns with the prevailing preferences of Al-Andalus society, where wheat and barley were commonly favoured (Guede et al., 2017; Mundee, 2010; Olivé-Busom, 2023). However, this does not mean that the two were identical in the types of cereals they consumed, as there is a dietary status gap between barley and wheat in Al-Andalus society that cannot easily be seen isotopically, especially in the absence of direct measurements on preserved grains. It can also be noted that there is earlier, pre-Christian, evidence for the likely use of millets as a complementary food during weaning and in early childhood from elevated $\delta^{13}C$ values for these age groups at the Iron Age site of La Hoya in north-central Iberia (Fernández-Crespo et al., 2019).

The isotopic changes observed during weaning exhibit distinct patterns between the two sites. The trends in $\delta^{15}N$ for most Balaguer individuals are consistent with the expected trophic level shift for 'exclusively' breastfed infants. In contrast, most individuals at SCA demonstrated a significantly greater change than at Balaguer, with an unusual 3–5 ‰ decrease in $\delta^{15}N$ values. Two possibilities may be proposed to explain such a difference. One is that this may indicate a higher-trophic-level diet of nursing mothers than that of the average adults, as isotopic data of pre-weaning infants will track their diets (Fogel et al., 1989; Fuller et al., 2006a; Tsutaya and Yoneda, 2015). As mentioned above, there is no significant difference in pre-weaning $\delta^{15}N$ values between the two sites, but this contrasts with the higher $\delta^{15}N$ values of

Balaguer adulthood diets compared to SCA. Combined with the medical view of Al-Andalus society that lactating mothers would be expected to consume what were seen as more healthful foods such as fresh fish, lamb and kid (Álvarez de Morales, 2005; Modanlou, 2008), it is reasonable to posit that mothers at SCA consumed more animal protein during lactation, making the δ^{15}N values of children who approached adult dietary patterns after weaning appear to change significantly.

Another possibility is that the choices of different supplementary foods influenced isotopic changes during the weaning process. Infants were less likely to directly consume meat when weaning, as the Al-Andalus medical treatise recommends a light soup, breadcrumbs or milk as weaning foods (Adamson, 2004; Salas-Salvadó et al., 2006). Accordingly, the consumption of animal milk products in supplemental foods may also contribute to changes in δ^{15}N values. Although it does not show the same level of ^{15}N-enrichment as human breast milk, animal milk would provide an important source of protein (Fuller et al., 2006a). As per Giladi (1999), Arabs regarded animal milk as a suitable substitute for breast milk during the medieval period. Therefore, the smaller decrease in Balaguer could be a result of the increased intake of dairy products during this period. Although this may also indicate the individual was fully weaned before the age of 1 year, in the context of the weaning information from other Balaguer individuals and the apparent norm of weaning at approximately 2 years of age in Al-Andalus, it is more plausible that this individual was not exclusively breastfed and may have been supplemented with animal milk. In contrast, until the late 18th century, negative attitudes towards animal milk were reflected in European medical theory and popular beliefs (Giladi, 1999). Therefore, the Santa Coloma d'Àger population, settled here since the Visigoth period, may have been affected by this, which provides a clue to the substantial decline in δ^{15}N values during the weaning period here. Nevertheless, at least one child (SC0011) exhibited cribra orbitalia, which is often considered an indicator of iron deficiency anaemia (Brickley, 2018), indicating possible nutritional stress in children from this site. Moreover, this individual died at ca. 4–6 years old and exhibited elevated δ^{15}N values that could reflect physiological stress. Hence, it is reasonable to consider the limited dairy resources available to the Christian population from rural backgrounds as a more likely reason for these observations.

At the end of the weaning period, although the δ^{13}C values at both sites are significantly higher than those of the corresponding adults, they differ in how they vary. At Balaguer, the δ^{13}C values in half of the individuals show an increase during the weaning process, seemingly indicating some minor complementary consumption of C_4 plants during weaning, while a decrease of ca. 2 ‰ in δ^{13}C values of individuals from SCA suggests more C_3 plant consumption. Balaguer infants potentially consumed more sorghum and millet as supplementary foods. Millet may have been used as a supplementary weaning food in Iron Age north-central Iberia (Fernández-Crespo et al., 2019), and both crops were used as traditional weaning foods in Africa probably since ancient times (National Research Council, 1996, Turner et al., 2007). The arrival of Muslim armies and peoples from North Africa popularized their consumption in Al-Andalus, particularly in urban centres and areas with large Muslim populations. This in turn may have increased the visibility of these food sources in infant diets, although no studies on Visigoth weaning patterns are available to inform us about their strategies. It should be noted here that another C_4 plant, sugarcane, may have been given to infants as a soother (Jiménez-Brobeil et al., 2021), but given that most individuals pre-date its introduction in the 10th century, this is unlikely. Nevertheless, millet and sorghum were less desirable to other medieval Western Europeans (MacKinnon et al., 2019). This may be the explanation for such change in δ^{13}C values of the Santa Coloma d'Àger population, i.e. more C_3 food in their diet for weaning infants compared to the apparent C_4 signal during nursing.

It should be noted that there seems to be a contradiction here whereby lactating mothers seem to have consumed more C_4-based food while their infants consumed more C_3 during the weaning process, but from the perspective of anthropological research, this could be the case. As Dettwyler (1987) showed in his study of the modern Mali population, pregnant and lactating women continued to work as usual and did not change their diets. In contrast, infants have lower immunity and could become ill or even die in weaning due to unsuitable foods (Pearson et al., 2010). Thus, the SCA community may have chosen more familiar wheat-based foods in an effort to reduce infant morbidity, while lactating mothers were still eating a normal adult's diet with a minor component of C_4 foods, although they could have consumed more animal protein as a nutritional supplement. In a rural setting with potentially more limited resource availability, drought-resistant and fast-growing C_4 crops could have served well as a buffer for adults when other grains were in short supply.

Additionally, the weaning age at SCA was significantly later than at BG ($p = 0.048$), though the differences in the onset and duration of the weaning process were not significant, possibly due to the small sample size. Prolonged breastfeeding is a potential strategy to address the

Table 6
Mann-Whitney *U* test results for δ^{13}C and δ^{15}N values comparing age groups (separately vs. adults and adult females) at Balaguer.

Balaguer (n = 4)	Adult All (bone, n = 13)		Adult Female (bone, n = 4)	
	z	p	z	p
δ^{13}C (‰) (VPDB) postweaning (dentine)	−2.354	**0.014**	−1.414	0.229
δ^{15}N (‰) (AIR) postweaning (dentine)	1.278	0.239	1.414	0.229
δ^{13}C (‰) (VPDB) last sub-sample (dentine)	−1.812	0.079	−1.732	0.114
δ^{15}N (‰) (AIR) last sub-sample (dentine)	0.113	1.000	0.866	0.486

Table 7
Mann-Whitney *U* test results for δ^{13}C and δ^{15}N values comparing age groups (separately vs. adults and adult females) at Santa Coloma d'Àger.

Santa Coloma d'Àger	Adult All (bone, n = 16)		Adult Female (bone, n = 7)	
(n = 6)	z	p	z	p
δ^{13}C (‰) (VPDB) postweaning (dentine)	−2.359	**0.017**	−2.000	0.051
δ^{15}N (‰) (AIR) postweaning (dentine)	−0.958	0.367	−1.000	0.366
δ^{13}C (‰) (VPDB) last sub-sample (dentine)	−2.433	**0.013**	−2.429	**0.014**
δ^{15}N (‰) (AIR) last sub-sample (dentine)	−2.064	**0.040**	−2.000	0.051

Table 8
Mann-Whitney *U* test results for dietary comparisons (BG vs. SCA) across time points in infancy and childhood.

	Mann–Whitney *U* test		BG	SCA
	z	p	(Mean ± SD)	(Mean ± SD)
Estimated duration of exclusive breastfeeding (years)	0.389	0.714	0.93 ± 0.47	1.14 ± 0.57
δ^{13}C (‰) (VPDB) preweaning (dentine)	2.324	**0.024**	−18.24 ± 0.39	−17.10 ± 0.31
δ^{15}N (‰) (AIR) preweaning (dentine)	0.000	1.000	13.19 ± 0.79	12.98 ± 0.49
Estimated duration of weaning process (years)	1.302	0.262	1.38 ± 0.23	1.67 ± 0.59
Age at complete weaning (years)	2.066	**0.048**	2.31 ± 0.33	2.81 ± 0.23
δ^{13}C (‰) (VPDB) postweaning (dentine)	0.000	1.000	−18.36 ± 0.15	−18.30 ± 0.53
δ^{15}N (‰) (AIR) postweaning (dentine)	−1.549	0.167	10.52 ± 1.19	9.63 ± 1.13
δ^{13}C (‰) (VPDB) last sample (dentine)	−0.213	0.914	−18.40 ± 0.44	−18.43 ± 0.34
δ^{15}N (‰) (AIR) last sample (dentine)	−2.132	**0.038**	11.28 ± 0.77	9.88 ± 0.81

scarcity of breastmilk substitutes and ensure infant survival (Fuller et al., 2006b; Schmidt et al., 2016). This seems to be further reflected in the sharp decline in δ^{15}N values observed in SCA infants, which may indicate potential pressures on food resources at the site.

6.2. Diet in childhood

At approximately 8–9 years of age, the δ^{13}C values of individuals at the two sites showed no statistically significant difference ($p = 0.914$). Nevertheless, the post-weaning trends differed. Most Balaguer individuals exhibited relatively stable δ^{13}C values during this period, indicating the continued predominance of C_3 foods, while Santa Coloma d'Àger showed greater fluctuation, suggesting the alternating consumption of C_3 and C_3/C_4 foods. As mentioned above, millet and sorghum may have been rather uncommon for the Christian community living in Al-Andalus which favoured wheat and barley. As such, the sudden short-term spikes of the inclusion of ca. 20 % C_4 consumption in childhood diet (SC0014, SC0155, SC0180) could be interpreted as a dietary substitution due to restricted access to resources, rather than reflecting preference. This phenomenon is associated with the presence of higher δ^{13}C values in SCA than Balaguer during the nursing period, and should be considered along with the possible preference for C_3 foods during the weaning period. For the Christian population from rural areas, both lactating females and post-weaning individuals consumed significantly more C_4 crops, but weaning infants were consistently given their familiar but seemingly inadequate C_3 crops, which may reflect a resource bias in infant rearing. This trend is likely also reflected in protein sources after weaning, as δ^{15}N values gradually increase and generally remain consistently higher than the adult mean throughout early childhood. Compared to the Balaguer group, this distinct pattern between adult and childhood diets in SCA may suggest a shift from supplemental foods to age-specific diets, indicating a preferential allocation of protein resources within the Christian population. In addition, synchronous fluctuations in δ^{13}C and δ^{15}N values were seen in some individuals (SC0014, SC0147, SC0180), a phenomenon that was not observed at Balaguer. This may be the result of consuming protein from animals fed some C_4 plants. Although the only samples available in the faunal baseline do not reflect this phenomenon, evidence of C_4 crops fed to animals has been found elsewhere, as in the case of two chickens with δ^{13}C values of −14.9 ‰ and −13.3 ‰ and two cows with values of −15.2 ‰ and −14.3 ‰ at the medieval site of Benipeixcar (Valencia, eastern Spain) (Alexander et al., 2015; MacKinnon et al., 2019). The feeding of C_4 crops to animals may have been due to the differences in animal management practices between the two sites, or a choice of necessity due to limited resources. However, the lack of local faunal baseline data precludes further discussion.

The δ^{15}N values for individuals at the two sites exhibit different patterns. After weaning, the majority of Balaguer individuals show an overall increasing trend, indicating an increased intake of animal protein, albeit with some occasional decreases that may be attributed to positive nitrogen balance. In contrast, the majority of Santa Coloma d'Àger individuals show a continuous decline in δ^{15}N after weaning. At approximately 8–9 years of age, a statistically significant difference in values between the two groups emerged ($p = 0.038$), with Balaguer individuals having a mean of 11.28 ± 0.77 ‰, consistent with local adult δ^{15}N values, while SCA individuals had a mean of 9.88 ± 0.81 ‰, significantly higher than adult levels at the site. This situation is contrary to the hypothesis that Muslim Balaguer would have lower δ^{15}N values because of prohibitions against the consumption of pork. The resolution of this discrepancy may be linked to agricultural practices and/or economic factors. Firstly, it is well known that the Muslims introduced an agricultural 'Green Revolution' to the Iberian Peninsula, including the use of fertilizers to enhance land productivity (Hernández Bermejo and García Sánchez, 2008; Watson, 1974). This practice could potentially be a contributing factor to the observed δ^{15}N values, which is supported by the two herbivores from Balaguer with relatively higher δ^{15}N values and the potential irrigated orchard there that may have used manure. Such a possibility was also mentioned by Guede et al. (2017) in explaining the high δ^{15}N values of the Muslim community at Tauste, another Upper Frontier site. Secondly, resource availability may have played a role in the intake of animal protein. Balaguer has a military background and a strategic location, which resulted in its political and economic prominence after the 10th century. In contrast, Santa Coloma d'Àger remained rural during the Andalusi period. A recent study by Pérez-Ramallo et al. (2022b) on the population of medieval northern Spain suggests that individuals in urban environments or with higher social status typically had higher average δ^{15}N values than rural dwellers, indicating increased access to animal protein. Although the urban transformation of Balaguer took place in the 10th century, its military status before then likely provided privileged access to such resources. Nevertheless, even within the potentially resource-limited context of SCA, the consistently higher δ^{15}N values of children compared to adults throughout childhood may suggest a preferential bias toward children in resource allocation within this rural Christian community.

7. Conclusion

This study presents the first application of sequential dentine collagen isotope analysis to examine childhood diets in a medieval Al-Andalus population, specifically focusing on individuals from Balaguer and Santa Coloma d'Àger in northeastern Spain. The two sites showed similarities in their preference for C_3-based cereals and weaning times, consistent with current understandings of Al-Andalus society, but they made different choices for infant supplements and early diets. Such differences may be the result of different agricultural practices or food availability, due to different religious and socio-economic backgrounds. The Christian community in the rural setting of Santa Coloma d'Àger may have had more limited food resources, such that their socio-economic standing overrode cultural and religious differences in diet. Nonetheless, the inclination of resources they give to infants and breastfeeding women is still observed, offering an insight into their lifestyle and values.

It should be noted that there are both religious and economic differences between the two areas, thus the limited food available in Santa Coloma d'Àger may be the result of its rural setting, but also the possibility of religious exclusion or associated cultural customs. Should suitable material become available, future work on the local baseline would permit more robust comparisons between agricultural practices such as fertilizer and animal management systems for urban and rural and Muslim and Christian communities. As we hope to have demonstrated, the wider application of sequential dentine isotope analysis in medieval Spain will enrich our understanding of the social landscape of Al-Andalus.

CRediT authorship contribution statement

Huhongyan Tian: Writing – original draft, Visualization, Formal analysis. **Júlia Olivé-Busom:** Writing – review & editing, Supervision. **Andrea Czermak:** Writing – review & editing. **Rick J. Schulting:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2024.104958.

Data availability

All data produced are included in the paper.

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