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# Reconstruction of the weaning process in the late medieval and early modern group of inhabitants of the village of Libkovice (Czech Republic): a case study

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## Abstract

Introduction
Weaning is a process strongly influenced by biological, cultural, and social factors. In bioarchaeological research, one of the direct methods used to analyze breastfeeding duration and weaning ages is stable nitrogen ($\delta^{15}N$) and carbon ($\delta^{13}C$) isotope analysis.

Study aim
The current study aimed to reconstruct breastfeeding and weaning practices (BWP) in the rural community of Libkovice (Northern Czech Republic) using stable isotope analysis of bone collagen extracted from long bone shafts.

Material and Methods
The research material originated from the cemetery at the Church of St. Nicholas and included 45 individuals (27 juveniles and 18 females) from the late Middle Ages and Early Modern periods. The reconstruction of weaning age was carried out using the Weaning Age Reconstruction with Nitrogen isotope analysis (WARN) Bayesian model. The analysis included the results of isotopic measurements performed on collagen samples isolated from the shafts of long bones of the individuals.

Original article
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Results
Weaning tended to be initiated early (around six months of age) in the samples from the Middle Ages, but the process lasted longer (until approximately 2.7 years of age) than in the Early Modern period, where weaning tended to be initiated later (around 1.1 years of age) but was completed sooner (around two years of age).

Conclusions
The observed differences may reflect adaptive changes related to socioeconomic transformations in Libkovice, such as increased fertility or the diversification of family status. The findings highlight the need for further interdisciplinary research into childcare strategies and population health in a historical context.

Keywords: human remains, isotopic analysis, Central Europe, rural communities

## Introduction

Weaning, defined as the transition from breastfeeding to a solid food diet, is strongly influenced by biological, cultural, and social factors (Czech & Szostek, 2023). In many traditional cultures, decisions regarding breastfeeding duration and method are embedded in normative systems, rituals, and intergenerational relationships (Dettwyler, 1995). From an anthropological perspective, the gradual process of weaning reflects a complex interplay between biology, parental care strategies, household economy, and environmental and cultural pressures. In prehistoric and historic communities, for whom written sources are limited or selective, bioarchaeological data become more significant, particularly those that reveal the physiological consequences of the weaning process (Lewis, 2007).

Numerous studies emphasize that the weaning period is one of the most critical developmental stages in early childhood, both physiologically and in terms of health risks. The reduction of immunoglobulin supply from breast milk, changes in diet composition and consistency, as well as increased exposure to intestinal pathogens, often led to malnutrition, heightened susceptibility to infections, and even death (Wright & Schwarcz, 1998). The physiological stress associated with weaning, known as *weaning stress*, can leave detectable traces in dental enamel (enamel hypoplasia), bone structure (growth arrest lines – Harris lines), or manifest through isotopic changes in bone collagen and apatite (Kendall et al., 2021).

Bioarchaeological research on breastfeeding and weaning relies primarily on the analysis of stable nitrogen ($\delta^{15}N$) and carbon ($\delta^{13}C$) isotopes. Breastfed children typically show elevated $\delta^{15}N$ values compared to adults from the same population, a result of the so-called "trophic level effect," analogous to a predator's dietary position relative to a primary consumer with its plant/animal meal (Richards et al., 2002). The actual difference in $\delta^{15}N$ values between a mother and an exclusively breastfed infant may exhibit a narrower range than typically observed between trophic levels. This is due to various factors influencing biochemical processes and fractionation within both the milk-producing mother and the developing infant. Malnutrition, a subsequent pregnancy during lactation, maternal stress, and rapid infant growth can all alter the body's nitrogen balance (Fuller et al., 2004; Reitsema, 2013). Studies have observed that enrichment in infants is usually around 2–3‰ relative to the mother (Chinique de Armas et al., 2022; Fuller et al., 2006). However, this range may vary depending on the type of tissue analyzed (Reitsema, 2013). Converse-

ly, gradually lower N values of $\delta^{15}N$ in a child's hard tissues indicates the cessation of maternal milk consumption and a transition to a diet based on solid food. Meanwhile, $\delta^{13}C$ values may provide insights into the types of food consumed (also during the weaning), their origin ($C_3$ vs. $C_4$ photosynthetic pathways), the proportion of animal products, and the introduction of porridges or cereals into the diet (Reitsema, 2013), which had a significant share in the diet in this part of Europe (Pedergnana et al., 2025).

The first bioarchaeological studies on breastfeeding and weaning timing in past populations were based solely on $\delta^{15}N$ measurements in bone collagen (Halcrow et al., 2021; Powell et al., 2014). However, since isotopic values in bone reflect long-term dietary changes and populations tend to have significant dietary variability over their lifetimes, this method does not allow for precise reconstruction of the breastfeeding and weaning period (Beaumont et al., 2018; Beaumont, 2020; Fernández-Crespo et al., 2018). Nitrogen isotope analysis alone is insufficient because, in addition to dietary variability, nitrogen isotope ratios can also change for other reasons. For example, in response to physiological stress, nutritional stress, or certain diseases, changes in the nitrogen isotope signal may occur, which may mimic or mask the isotope effect associated with the weaning process (Beaumont & Montgomery, 2016; Henderson, 2015). The standard method of bone collagen analysis to reconstruct the weaning process presents a number of challenges, including the need to accurately estimate the age of the individuals being examined, and the issue of bone remodeling and its varying rates in individuals of different ages (Henderson, 2015). Many of these drawbacks are addressed by the method of incremental analysis of enamel and dentin, but this method has a significant limitation: the need to destroy the teeth being examined. Irreversible tooth cutting and the high costs associated with multiplying the number of samples require a reduction in the number of individuals analyzed, making it difficult to reconstruct the process for an entire population or group. Despite their high resolution, samples collected from incremental layers must still be considered averages over a certain period due to the imperfect arrangement of dentin layers (Curtis et al. 2022). Furthermore, because the recording of the isotopic signal in dentin begins with crown formation (which may occur after birth), in some permanent teeth it is impossible to compare the prenatal and postnatal signal, complicating the already complex interpretation.

Research into *weaning stress* takes on particular significance in historical populations, such as the former inhabitants of the now-defunct village of Libkovice near Most in Northwestern Czech Republic. Furthermore, while cross-sectional studies utilizing bulk bone collagen provide a population-level overview, they are inherently constrained by the differential remodeling rates of cortical bone, which blend dietary signals over several months or years and effectively smooth the temporal resolution of weaning events compared to incremental dentine analysis (Beaumont et al., 2018; Beaumont, 2020). On a statistical level, Bayesian estimation software such as the WARN model relies on assumptions of constant metabolic rates and fixed nitrogen fractionation values between mother and infant. Consequently, physiological anomalies—such as severe metabolic stress, nutritional deprivation,

or infant/maternal illness—can disrupt normal nitrogen balance, potentially confounding model estimates by mimicking or masking the isotopic enrichment associated with breastmilk consumption (Henderson, 2015; Reitsema, 2013). The settlement, with 12th-century origins, was depopulated and demolished in the 1990s due to the expansion of the Bylina brown coal mine in the Most region. According to a report by Pavel Vařeka (1996), who has conducted rescue archaeological excavations in Libkovice since 1996, the parish cemetery extended around the late Middle Ages Church of St. Nicholas, which dates to the 13th century. In a subsequent study, Vařeka (2001) analyzed changes in the settlement structure of the Libkovice microregion, highlighting the village's continuity into the modern era and the gradual transformation of its cultural and functional landscape. Before mining activity destroyed Libkovice's remains, rescue excavations recovered human remains from the parish cemetery by the Church of St. Nicholas (Vařeka, 2020). Notably, the osteological material from Libkovice, which includes numerous child burials, presents a unique opportunity to reconstruct dietary, health, and caregiving patterns in this community, especially in the context of weaning and its biological consequences. Previous isotopic research on this skeletal series has already provided insights into the general diet of the adult population, showing reliance on specific terrestrial resources (Karykowska et al., 2023).

When combined with isotopic analyses, these findings make it possible to determine not only the duration of breastfeeding, but also the critical point during weaning and its potential consequences. The socio-cultural context of Libkovice, as a peasant settlement operating in a shifting religious, economic, and demographic context (including the Reformation, the Thirty Years' War, and 19th-century industrialization), provides additional grounds for evaluating the impact of local caregiving practices on child health and survival (Hrozný, 1990).

The literature underscores that cultural factors such as religion (e.g., Catholic vs. Protestant norms), economic status, number of children in the family, and the availability of complementary foods may have significantly influenced the duration of breastfeeding (Czech & Szostek, 2023; Fildes, 1986). For instance, in urban populations of Early Modern Europe, aristocratic families weaned their children earlier than peasant families. Those from the poor urban groups often experienced weaning in conditions of poor hygiene and food scarcity (Robb & Harris, 2013). Aligning these cultural determinants with biological data allows for a deeper understanding of the role of weaning stress within a given community.

The study aimed to provide a detailed analysis of weaning stress in the child population of Libkovice based on bioarchaeological data (isotopic analyses and morphological stress markers) and within the broader context of the cultural and socially conditioned practices of childcare in the Middle Ages and Early Modern periods. The study sought to reconstruct the health trajectories of the youngest members of the Libkovice community and, more broadly, to reflect on the significance of weaning as a biological and cultural transition point with important demographic consequences, through an interdisciplinary approach combining biological anthropology, history, and archaeology.

## Materials and Methods

The research material originated from an archaeological site in Northwestern Czech Republic – survey 138 (Figure 1), which encompassed the parish cemetery of the Church of St. Nicholas in the village of Libkovice near Most. The village was established at the end of the 12th century and persisted until the end of the 20th century. Burials at the cemetery ceased around the mid-19th century, when a new cemetery was established outside the village.

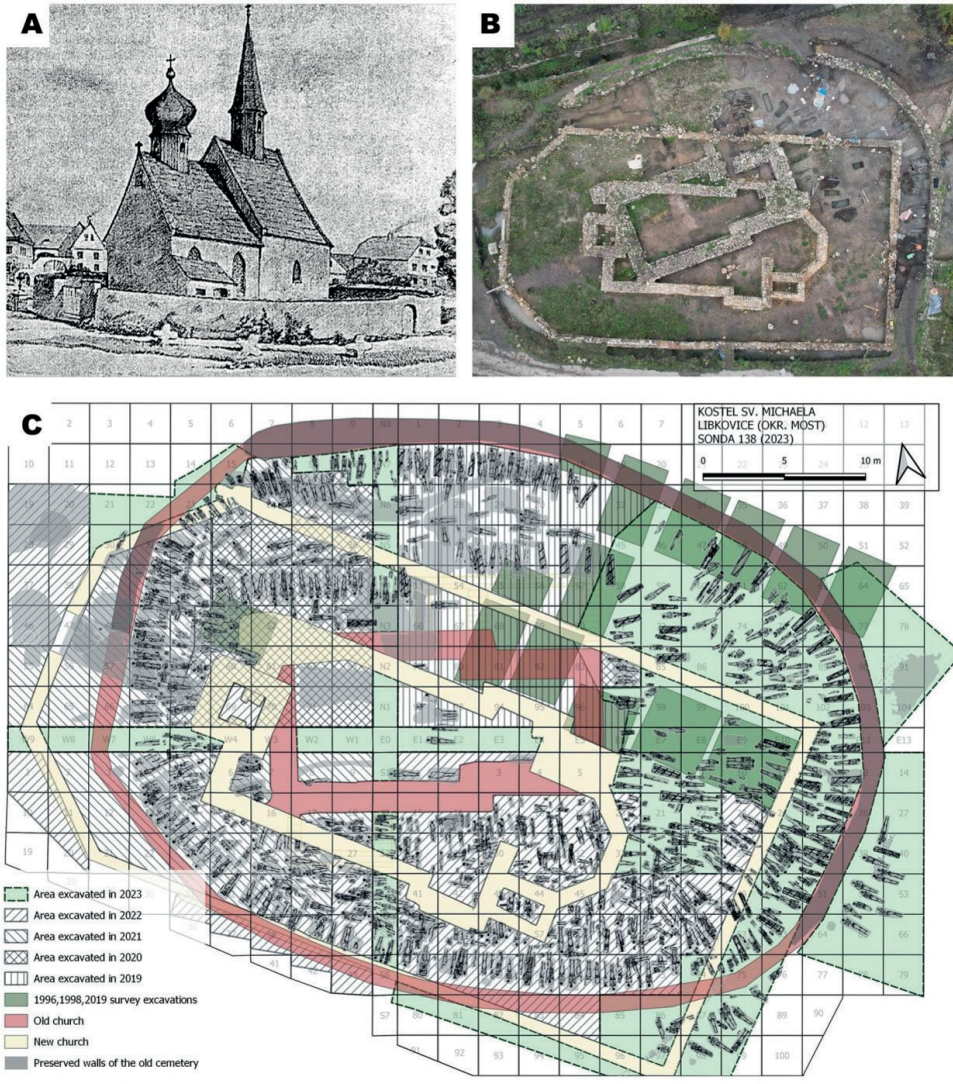


Figure 1. The Church of St. Nicholas in Libkovice (Most district): A – a 19th-century engraving (after Vařeka 2020), B – a general view of the excavations in 2023 (photo by Piotr Konczewski), and C – a general plan of the cemetery and church remains (prepared by Radosław Biel).

Isotopic data for the analyzed samples were previously published in Karykowska et al. (2023). Detailed information on the collagen extraction method, stable isotope measurements and the assessment of bone collagen preservation can be found in Karykowska et al. (2023), which presents the original analytical results. The present study focuses specifically on female and juvenile individuals from this assemblage to investigate patterns of childhood dietary stress associated with the weaning process. Due to the unavailability of odontological material of sufficient quality, the reconstruction of the approximate breastfeeding duration was carried out using fragments of the individuals' long bones. It should be noted that the selected material does not perfectly represent mothers in the studied population, but in the absence of other material, such an approach is practiced (Britton et al., 2015; Fuller et al., 2006). The children had died between the ages of one month and 11 years. A prerequisite for inclusion in the analysis was the accurate determination of skeletal age. Skeletal age for children was estimated based on morphological features of the skull and postcranial skeleton. Following the classification by Malinowski and Bożiłow (1997), the individuals were categorized into the following age groups:

**Infans I**: birth to approx. 7 years (emergence of M1).

**Infans II**: approx. 7 to 14 years (emergence of M2).

**Juvenis**: approx. 14 to 18-22 years (ossification of *synchondrosis sphenooccipitalis*).

Sex for adults was determined using morphological features of the skull and pelvic bones according to Buikstra and Ubelaker (1994) and Todd, as cited in White et al., (2012), while age at death for adults was estimated based on dental wear and changes in the pubic symphysis and auricular surface.

## Reconstruction of the weaning process

To reconstruct the duration of breastfeeding, a mathematical model proposed by Tsutaya and Yoneda (2013) was applied. The model, unlike others (e.g., Schurr, 1997), considers the age-dependent varying rate of bone remodeling. Therefore, the model used in this study reflects the dynamics of bone turnover during childhood. The modeling was performed in R software using the WARN package (Weaning Age Reconstruction with Nitrogen isotope analysis).

Based on simulations using the WARN package, four weaning parameters were obtained that represent the maximum density estimates (MDE), such as the onset of weaning ($t_1$), the end of weaning ($t_2$), the isotopic enrichment factor between infant and mother (E), and the $\delta^{15}N$ value of collagen synthesized entirely from foods consumed during the weaning period ($W_{nfood}$). In this context, $t_1$ denotes or corresponds to the age at which non-maternal foods are introduced into the infant's diet, while the parameter $t_2$ denotes the age at which breastfeeding ends and the $\delta^{15}N$ signal of the child's bone collagen approaches that of adults. Additionally, the difference was calculated between the isotopic level represented by adult individuals in the studied groups and the $\delta^{15}N$ level of collagen synthesized entirely from foods consumed during the weaning phase in the children studied, using the formula $\Delta^{15}N_{adult-\ wnfood.}$ It should be noted that there are inherent methodological limitations associated with estimating weaning parameters, which

must be interpreted alongside the general health status of the individuals.

The reliability of the results obtained using the model was assessed through the corresponding marginal probabilities. For the model to be considered reliable, these probability values should not fall below 0.05.

## Results

Collagen preservation was assessed in the original study by Karykowska et al. (2023). All samples met the established quality criteria for stable isotope analysis and were considered suitable for isotopic interpretation. Detailed information on collagen quality assessment and the original results is provided in Karykowska et al. (2023) (Table 1 with cited results, also see Figure 2 in Karykowska et al. 2023: 31).

In light of the referenced theoretical framework, an analysis of $\delta^{15}N$ in collagen extracted from the bones of children, juveniles, and adults was carried out to describe infant feeding strategies within two chronologically distinct groups from the Libkovice population. It should be emphasized that the analysis only included children with accurately determined biological (skeletal) age. The first group represents the late Middle Ages period, and the second pertains to the Early Modern period. Figures 2 and 3 illustrate the nonlinear correlation between individual age and decreasing $\delta^{15}N$ concentrations in collagen.

Table 1. Female and juvenile individuals from the Libkovice site included in the stable isotope analysis. The isotope data were previously published by Karykowska et al. (2023) and are reproduced here for the purposes of the present study. $\delta^{15}N$ – nitrogen isotope values; $\delta^{13}C$ – carbon isotope values; %N – nitrogen content; %C – carbon content; CNMolar – diagenesis index; C/N – collagen ratio.

| Sample ID | Sample Type | Age | Dating | $\delta^{15}N$ | $\delta^{13}C$ | %N | %C | CN Molar |
|---|---|---|---|---|---|---|---|---|
| 1013a | Femur/ humerus | Infans I (18 months) | 13-15th century | 15.1 | -19.8 | 14.9 | 43.4 | 3.4 |
| 1013b | Femur/ humerus | 3-4 years | 13-15th century | 12.9 | -20.2 | 14.9 | 42.9 | 3.4 |
| 1049 | Femur | Infans I (5-6 months) | 13-15th century | 14.4 | -19.8 | 14.6 | 41.4 | 3.3 |
| 1087 | Femur | 5-6 years | 13-15th century | 12.9 | -19.9 | 14.0 | 40.0 | 3.3 |
| 1089 | Tibia | 4 years | 13-15th century | 13.3 | -19.8 | 14.6 | 42.1 | 3.4 |
| 1093 | Femur | 9-10 years | 13-15th century | 13.8 | -19.8 | 14.7 | 41.8 | 3.3 |
| 1117 | Ulna | 5-6 years | 13-15th century | 13.4 | -19.6 | 14.6 | 41.6 | 3.3 |
| 1163 | Femur | Infans I (18-24 months) | 13-15th century | 14.5 | -19.9 | 14.7 | 43.1 | 3.4 |
| 1191 | Femur/ humerus | Infans I (24 months) | 13-15th century | 14.6 | -20.1 | 14.9 | 42.8 | 3.4 |
| 1259 | Femur | 10-11 years | 13-15th century | 12.4 | -20.2 | 15.0 | 42.5 | 3.3 |
| 1299 | Femur | (Infans I) 0-12 months | 13-15th century | 16.0 | -19.5 | 14.5 | 41.0 | 3.3 |
| 1307 | Femur | 6-7 years | 13-15th century | 13.1 | -19.3 | 15.0 | 41.4 | 3.2 |

Tab. 1 (cont.)

| Sample ID | Sample Type | Age | Dating | $\delta^{15}N$ | $\delta^{13}C$ | %N | %C | CN Molar |
|---|---|---|---|---|---|---|---|---|
| 1309 | Femur | 8-9 years | 13-15th century | 12.9 | -19.9 | 14.5 | 40.6 | 3.3 |
| 1343 | Femur | Infans I (7-12 months) | 13-15th century | 15.6 | -19.6 | 15.2 | 43.8 | 3.4 |
| 1349 | Femur | Infans I (0-1 months) | 13-15th century | 14.6 | -19.1 | 15.3 | 43.2 | 3.3 |
| 1353 | Femur | Infans I (6 months) | 13-15th century | 12.0 | -19.9 | 15.3 | 42.6 | 3.2 |
| 1379 | Femur | 7-8 | 13-15th century | 13.3 | -20.2 | 15.5 | 43.1 | 3.2 |
| 1179 | Clavicula | Maturus | 13-15th century | 11.4 | -20.2 | 15.7 | 42.3 | 3.1 |
| 1401 | Dens | Adultus | 13-15th century | 10.6 | -19.5 | 15.7 | 42.2 | 3.1 |
| 1493 | Humerus | Maturus | 13-15th century | 13.1 | -19.3 | 15.8 | 42.3 | 3.1 |
| 1553 | Fibula | Maturus | 13-15th century | 12.4 | -20.0 | 15.6 | 43.1 | 3.2 |
| 1561 | Clavicula | Maturus | 13-15th century | 11.8 | -20.0 | 15.7 | 42.2 | 3.1 |
| 1563 | Humerus | Adultus | 13-15th century | 12.0 | -20.0 | 15.5 | 42.6 | 3.2 |
| 1579 | Ulna | Maturus | 13-15th century | 12.2 | -20.0 | 16.0 | 42.2 | 3.1 |
| 1593 | Femur | Maturus | 13-15th century | 13.6 | -19.7 | 15.4 | 42.9 | 3.3 |
| 1601 | Femur | Adultus | 13-15th century | 13.7 | -19.3 | 15.3 | 42.1 | 3.2 |
| 1107 | Femur | Infans I/ infans II | 16-19th century | 9.0 | -20.6 | 14.0 | 40.8 | 3.4 |
| 1051 | Femur | 0-3 months | 16-19th century | 12.6 | -19.8 | 14.9 | 43.2 | 3.4 |
| 1025 | Femur | 4-5 | 16-19th century | 12.2 | -20.0 | 14.4 | 40.9 | 3.3 |
| 1145 | Tibia | 9-10 | 16-19th century | 11.3 | -20.1 | 14.1 | 39.7 | 3.3 |
| 1237a | Humerus | 8-9 | 16-19th century | 13.4 | -19.7 | 14.2 | 40.4 | 3.3 |
| 1237b | Femur | 7-8 | 16-19th century | 13.3 | -19.7 | 14.3 | 40.7 | 3.3 |
| 1301 | Femur | 2-3 | 16-19th century | 14.1 | -19.6 | 15.4 | 43.3 | 3.3 |
| 1315 | Femur | 3,5-4,5 | 16-19th century | 12.6 | -20.1 | 14.6 | 42.3 | 3.4 |
| 1329 | Femur | 8-9 | 16-19th century | 12.8 | -20.3 | 15.1 | 42.4 | 3.3 |
| 1393 | Humerus | 6-8 months | 16-19th century | 15.7 | -19.6 | 15.4 | 43.6 | 3.3 |
| 1069 | Humerus | Adultus | 16-19th century | 12.7 | -19.7 | 15.7 | 42.8 | 3.2 |
| 1101 | Ulna | Adultus | 16-19th century | 12.4 | -19.7 | 15.3 | 43.7 | 3.3 |
| 1169 | Ulna | Maturus | 16-19th century | 13.4 | -19.8 | 14.6 | 40.3 | 3.2 |
| 1197 | Ulna | Adultus | 16-19th century | 12.0 | -20.1 | 13.6 | 38.5 | 3.3 |
| 1227 | Femur | Adultus | 16-19th century | 11.8 | -19.7 | 15.2 | 42.6 | 3.3 |
| 1243 | Radius | Adultus | 16-19th century | 10.8 | -20.2 | 15.6 | 41.7 | 3.1 |
| 1317 | Humerus | Adultus | 16-19th century | 12.1 | -19.9 | 15.4 | 41.6 | 3.2 |
| 1383 | Ulna | Adultus | 16-19th century | 10.5 | -20.0 | 15.2 | 41.9 | 3.2 |
| 1395 | Ulna | Adultus | 16-19th century | 13.1 | -19.8 | 15.5 | 42.7 | 3.2 |

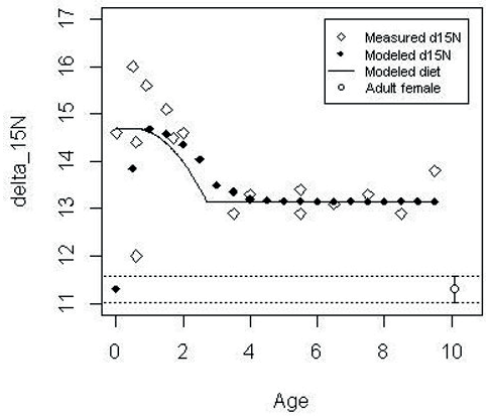


Figure 2. A model of weaning in the Middle Ages period in the Libkovice sample.

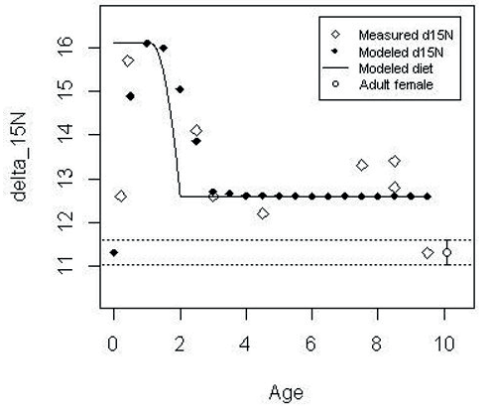


Figure 3. A model of weaning in the Early Modern period.

In the case of weaning models based on materials from the Middle Ages and Early Modern periods, the probability values for $t_1$ and $t_2$ exceeded 0.05, indicating high reliability of the obtained results (Middle Ages: $t_1$ in years = 0.5, marginal probablity = 0.063, $t_2$ in years = 2.7, marginal probablity = 0.053, E(‰) = 3.4, Wnfood (‰) = 13.15; Early Modern = 1.1, marginal probablity = 0.068, $t_2$ in years = 2.0, marginal probablity = 0.13, E(‰) = 4.8, $W_{nfood}$ (‰) = 10.2. The onset of weaning ($t_1$) occurred six months earlier in the Middle Ages group than in the Early Modern group (six months in the Middle Ages period vs. 1.1 years in the Early Modern period). However, it is noteworthy that complete weaning ($t_2$) occurred later in the Middle Ages period (two years and seven months) compared to the Early Modern period (two years). As a result, the entire transition to solid foods lasted longer in the Middle Ages group and spanned approximately two years.

## Discussion

During the reconstruction of the weaning process, it became evident that the isotopically detectable shift associable with breastfeeding/weaning occurred around six months earlier in the Middle Ages group compared to the Early Modern group. In the group of individuals from the early medieval site of Mikulčice, a similar age of children was recorded, i.e. 5–10 months, with decreased $\delta^{15}N$ values, indicating the introduction of a significant amount of non-maternal food into the diet (Drtikolová Kaupová et al., 2024). However, complete weaning occurred earlier in the Early Modern period, which ultimately resulted in a shorter total breastfeeding duration. The entire transition to solid foods was longer in the Middle Ages group and lasted approximately two years. In the case of individuals from the Czech early medieval Mikulčice, the results indicate that in the studied group there were most likely no children who consumed mother's milk for longer than 2.2 years (Drtikolová Kaupová et al., 2024). Similar results, with a weaning age of 2.8 years, were obtained for individuals from

the 14th-century site in Kutná Hora, Czech Republic (Drtikolová Kaupová et al., 2026).

The shorter duration of the transition to solid food in the Early Modern period, including the earlier point of complete weaning from maternal milk, may have stemmed from the emergence of a new adaptive strategy linked to the profound socioeconomic changes of the Early Modern era. These changes may have included increased fertility, social stratification, and the biological needs of mothers returning to fertility shortly after childbirth (Bogaard et al., 2013). Contemporary population studies confirm these trends, with the Early Modern period seeing a higher natural population increase and greater diversity in nutritional strategies among families of different socioeconomic statuses (Fildes, 1986; Humphrey, 2010).

In the Early Modern period, increased birth rates, higher fertility, and greater socioeconomic stratification among families were observed, all of which could have influenced decisions regarding breastfeeding duration (Fildes, 1986, 2017; Humphrey, 2010; Tomori et al., 2017). This 'compressed' weaning period observed in the Early Modern group—starting later but finishing significantly sooner—may reflect a more intensified transition to solid foods. Such a shift could be facilitated by the increased availability of high-protein complementary foods, such as animal milk or processed cereals, which were becoming more common in rural Central Europe during this period. This strategy would have allowed mothers to return to fertility more quickly, supporting the higher natural population increase characteristic of the era. This transition aligns with regional Bohemian historical and ethnographic evidence regarding rural infant care. In medieval and early modern rural Czech communities, infant feeding was heavily dictated by seasonal agricultural labor demands (Beranová, 2005). Mothers routinely introduced early complementary foods—predominantly flour-based or boiled grain gruels (*kaše*), rye broths, and diluted cow's or goat's milk—to allow rapid return to field labor (Fialová et al., 1996; Smrčka et al., 2006). Czech historical sources note that while prolonged nursing was traditionally valued for delaying subsequent pregnancies, the early introduction of non-sanitized cereal-based pap during intense harvest periods frequently exposed infants to intestinal infections (so-called 'summer diarrhoea'), a primary driver of historical infant mortality in rural Bohemia (Fialová et al., 1996).

At the same time, the potential impact of changing cultural norms, as well as evolving medical and childcare practices, cannot be overlooked. In the Early Modern period, moral and religious recommendations and the influence of medical literature promoting alternative feeding methods (e.g., substitute milk and wet nurses) in certain social strata played an increasing role (Fildes, 1986). In families of higher social status, breastfeeding may have been delegated to wet nurses, thereby reducing direct contact between the biological mother and the child (Fildes, 1988). Recent literature confirms the influence of cultural norms on decisions regarding the length of breastfeeding (Salahuddin et al., 2025).

In large families, where women were burdened by frequent pregnancies and births, the resulting impact on their health and fertility often dictated the duration of breastfeeding (Bentley et al., 2001; Jay, 2009).

The example of child no. 1007 (Tab. 1), with low $\delta^{15}N$ and $\delta^{13}C$ values in collagen, supports the interpretation of probable early and complete weaning, as such values typically correlate with an adult diet. Similar trends have been noted in other populations (e.g., Burt, 2013; Tomczyk et al., 2020). The isotopic signatures observed in the Libkovice subadult cohort closely interlock with previously documented skeletal stress indicators from the site. Non-specific physiological stress markers, including cribra orbitalia, linear enamel hypoplasia (LEH), and metabolic disruptions (porotic hyperostosis), were widely identified among the Libkovice children (Karykowska et al., 2023). Integrating these macroscopic findings with isotopic profiles reveals key individual dynamics. For instance, child no. 1007 (Tab. 1) displays markedly suppressed $\delta^{15}N$ (9.1‰) and $\delta^{13}C$ (-20.2‰) values alongside pronounced enamel hypoplasia, strongly indicating both early complete weaning and severe nutritional or health stress during early development. Conversely, individuals exhibiting elevated $\delta^{15}N$ values beyond the expected age curve (>2.5 years) frequently present macroscopic evidence of chronic metabolic stress or systemic infection. In these instances, the persistent enrichment likely reflects severe catabolic protein breakdown and wasting due to chronic illness rather than prolonged nursing (Drtikolová Kaupová et al., 2021; Reitsema, 2013). This alignment confirms that weaning in rural Libkovice acted as a critical period of physical vulnerability, where dietary transitions and pathogen exposure synergistically elevated childhood morbidity.

On the other hand, the longer process of transitioning to solid foods in the Middle Ages may be interpreted as a result of greater reliance on breast milk as the primary source of nutrients and immune protection. Human milk served not only a nutritional role but also an immunological one, which, under conditions of lower hygiene standards, poorer sanitation, frequent infectious diseases, and limited access to safe food, was crucial for child survival (Fuller et al., 2006; Lewis, 2007). The extended breastfeeding period may thus have been part of a conservative health-oriented strategy employed by mothers under increased risk conditions such as those assumed in the Middle Ages. The physiological stress of weaning likely peaked during the transition phase, which was notably more prolonged in the Middle Ages. This extended breastfeeding period likely served as a critical buffer, providing essential immunological protection even as the children were exposed to the risks associated with the introduction of non-maternal foods.

From a bioarchaeological perspective, the $\delta^{15}N$ values obtained for children of various biological ages and their comparison with adult individuals allowed for the approximate determination of the start and end of breastfeeding. The applied model enabled the identification of two parameters: $t_1$ – the moment weaning began, and $t_2$ – the moment of complete weaning. High probability values (>0.05) for both the Middle Ages and Early Modern models confirm their statistical reliability and usefulness for interpreting past feeding practices (Jay et al., 2008). Additionally, recent analyses (e.g., WEAN tool; Ganiatsou et al., 2023) suggest that incorporating the so-called *"post-weaning dip"* can improve the accuracy of weaning age reconstruction and is worth considering in future studies.

It should be mentioned that the variation in isotopic delta values in children's

tissues may result not only from the trophic effect associated with breastfeeding (Fuller et al. 2006; Herrscher et al., 2017). Stress resulting from illness or malnutrition may also increase or decrease the mentioned carbon or nitrogen isotope values (e.g., Craig-Atkins et al., 2018; Mekota et al., 2006), although there are also studies that have noted different conclusions (e.g., Canterbury et al., 2020; D'Ortenzio et al., 2015; Drtikolová Kaupová et al., 2021).

It is also worth noting that changes in feeding practices may reflect not only maternal decisions but also shifting macro-social conditions, such as population migration, the development of food markets, and the availability of complementary foods. The diet of children transitioning to solid food in the Early Modern period may have been more diverse, as might also be reflected in the $\delta^{13}C$ values, although this requires further analysis.

In summary, the presented results confirm the existence of changes in child-feeding strategies between the Middle Ages and Early Modern periods. These differences align with observations made in other historical populations, as well as with theoretical adaptive models described in the anthropological and bioarchaeological literature. The isotopic analysis of bone collagen has proven to be an effective tool for reconstructing dietary practices and exploring broader cultural and demographic phenomena in the past.

## Conclusions

The chronological variation observed in breastfeeding models in Libkovice is of particular interest. The study contributes new information to the existing body of knowledge while also partially confirming previous findings. Direct comparisons of the age at the onset and completion of weaning between the Middle Ages and Early Modern populations remain relatively rare in the literature. The shorter transition period to solid food in the Early Modern period, as well as the earlier timing of complete weaning, appears to be the result of a newly emerging adaptive strategy, the details of which remain unclear. It is hypothesized that this strategy is linked to significant socioeconomic changes in the Libkovice community (e.g., higher fertility rates, population growth, and socioeconomic diversity among mothers/families raising children). However, testing this hypothesis requires continued isotopic research on a larger osteological sample, as well as an expanded contextual framework through further bioarchaeological studies (osteological, genetic, archaeobotanical, and archaeozoological), which would enable a more comprehensive consideration of the proposed shifts in adaptive strategies among the inhabitants of Libkovice, a representative rural community in Central Europe, existing for approximately 800 years.

### Contributions from individual authors

A.K.: conceptualization, preparation of the manuscript, discussion of the results; A.L.G.: laboratory analyses, conceptualization, preparation of the manuscript, preparation of figures P.K.: substantive supervision of the archaeological component; B.K.: supervision and consultation of the anthropological component; P.L.: consultation and archaeological background; K.S.: statistical analyses and data processing, preparation of figures.

### Ethics Statement

Permission to conduct research on the historical skeletal remains from Libkovice was granted by the Director of the Institute for Preservation of Archaeological Heritage of Northwest Bohemia (*Ústav archeologické památkové péče sz. Čech*). The skeletal material is currently curated and stored at the Institute for Preservation of Archaeological Heritage of Northwest Bohemia in Most, Czech Republic, in accordance with national regulations and ethical guidelines governing the study and handling of human remains.

### Data availability statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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### Conflict of interest

The authors declare that they have no competing interests. The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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