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ORIGINAL ARTICLE

Strontium isotope identification of possible rural immigrants in 17th century mass graves at St. Gertrude Church cemetery in Riga, Latvia

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Abstract
The aims of this study were to explore the origins of 19 children buried in two mass graves and the general cemetery at the post-medieval St Gertrude Church cemetery in Riga, Latvia, using strontium isotope analysis ($^{87}Sr/^{86}Sr$), and to establish local soil Sr biosphere ranges from faunal samples from two areas of Latvia. The results confirmed the presence of one clear outlier in the population and one child who may have had originated from the region of Vidzeme. The lack of significant differences in $^{87}Sr/^{86}Sr$ between the other individuals analysed suggested that they were representative of one population. A strong correlation between $^{87}Sr/^{86}Sr$ ratios and previously obtained mean $\delta^{13}C$ and $\delta^{15}N$ values in children from mass graves suggested possible short-term dietary changes with increased proportion of marine resources and food sources subject to sea spray. The study has yielded the first comparative $^{87}Sr/^{86}Sr$ data from archaeological skeletons in Latvia, which will be essential for future research addressing comparative mobility studies in the region.

KEYWORDS
bioarchaeology, diet, migration, non-adult individuals, post-medieval Eastern Europe

INTRODUCTION

The cemetery of St. Gertrude Church in Riga, Latvia dates from the 15th–17th centuries AD and was excavated in the autumn of 2006 in advance of planned building works. The excavation revealed two mass graves along with single burials in the general cemetery, and both were estimated to date from the 17th century (Actiņš et al., 2009). Recent radiocarbon dates have confirmed that the first burials in the cemetery do indeed date from the 15th century AD, and that both mass graves date from the 17th century AD, although they might not be contemporaneous (Petersone-Gordina et al., 2020). A number of natural disasters affecting the city and other adjacent areas east of the Baltic Sea coincide with the mass graves, including a severe famine in the winter of 1,601–02, following the beginning of the Polish-Swedish war and a particularly bad harvest in the previous season, and plague epidemics in 1602 and 1623 (Napiersky, 1890). Historical accounts suggest that the famine forced people from the rural region north-east of Riga to come to the city to seek help, and that many of those who made the journey died on the outskirts of the city. It is believed that many were buried in the St. Gertrude's cemetery (ibid.). The individuals excavated from this cemetery have provided a unique opportunity to study aspects of the lives of populations in the suburbs of Riga during the post-medieval period and to add considerably to the currently scarcely published bioarchaeological data from Latvia.

Using radiogenic strontium ($^{87}Sr/^{86}Sr$) isotope analysis of dental enamel, the main aim of this study was to explore the origins of 19 children from the St. Gertrude's cemetery and to identify whether the children buried in one or both mass graves could have been rural immigrants. The second aim was to establish local soil biosphere $^{87}Sr/^{86}Sr$ ranges from two areas of Latvia. Strontium isotope analysis had never been carried out on Latvian skeletal remains, and thus the data would provide the first comparative ratios from Riga and the Vidzeme region directly from human and non-human remains as well as reveal if there was future potential for mobility studies in that region. This study builds on previous research on carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) stable isotope analysis of incremental dentine samples from the same 19 children (Petersone-Gordina et al., 2020). No differences were found in the mean $\delta^{13}C$ and $\delta^{15}N$ values between children buried in the mass graves and the general cemetery (ibid.), which was in line with the same finding in adults from the three different contexts (Petersone-Gordina et al., 2018). Differences emerged, however, when comparing higher resolution dietary profile patterns between children from different contexts. For example, similar dietary profiles of several children from both mass graves suggested that either they had come to Riga from elsewhere or their diet might have been similar in response to short-term hardships. Of the 19 children, only one child from the general cemetery (GC_41) had a distinctly different $\delta^{13}C$ and $\delta^{15}N$ profile when compared to other children, indicating that they might not have been local to the place of their burial. Likewise, a child from one of the mass graves (MG1_156) had a lower $\delta^{13}C$ and $\delta^{15}N$ values throughout the profile compared to other children, which was explained as being the result of either individual dietary variation or the possibility that they also had originated from elsewhere (Petersone-Gordina et al., 2020).

Evidence of possible physiological stress in very early childhood and nutritional stress shortly before death was only detected in the dietary profiles of children from mass graves, expressed as high or significantly rising $\delta^{15}N$ values of the first and last incremental dentine segments, respectively (ibid.). A recent study also found the presence of *Yersinia Pestis* in individuals from both mass graves (Susat et al., 2020), thus supporting historical accounts about famine and plague in the city. Neither mean $\delta^{13}C$ and $\delta^{15}N$ values of the adults and children nor dietary profiles of most children, however, clearly pointed to the presence of different population groups in the St Gertrude's cemetery, and this possibility can be explored by strontium isotope analysis.

Strontium isotope analysis

Strontium (Sr) isotopes were first used to study mobility in past human populations in the mid-1980s (Ericson, 1985), and they have become one of the most effective methods to distinguish local and non-local individuals in early prehistory (Bentley et al., 2002; Cox & Sealy, 1997; Montgomery et al., 2000; Müller et al., 2003) as well as later periods of history (Lahtinen et al., 2021; Montgomery et al., 2005; Scheeres et al., 2013; Shaw et al., 2016). Sr is an alkaline earth metal with three non-radiogenic isotopes (^{84}Sr, ^{86}Sr and ^{88}Sr) and one radiogenic isotope (^{87}Sr). Potentially, each type of rock has different ^{87}Sr/^{86}Sr ratios, which are released into soil and groundwater by the natural weathering and degradation process. From there, Sr isotopes pass largely unmodified through the food chain and into living organisms: plants, animals, and humans (Graustein, 1989; Hurst & Davis, 1981; Kawasaki et al., 2002). Due to the similar chemical properties of Sr and calcium (Ca), when taken up by animals and humans with food and water, it substitutes for Ca in bone and enamel apatite (Bentley, 2006; Bentley et al., 2004), from where it can be extracted in archaeological faunal and human remains.

Despite the small rate of modification while passing from the rocks through weathering into the food chain, there are factors that also influence the isotope ratios in soil. For example, some minerals with high ^{87}Sr/^{86}Sr also weather more slowly, which means that the isotope ratio in the soil is reduced compared to the whole rock (Åberg et al., 1989; Bentley, 2006). Likewise, Sr isotopes in coastal areas have been found to be dominated by seawater Sr rather than the underlying rocks, yielding ^{87}Sr/^{86}Sr closer to that of seawater, which is currently 0.7092 throughout the world's oceans (McArthur et al., 2001). However, in the northern Baltic Sea, the ratio can reach higher than 0.720 by influence of runoff from surrounding terrestrial area, whereas in the southern Baltic Sea it is between 0.7092 and 0.7097 (Price et al., 2012). The regional variations in seawater strontium in the Baltic Sea have been proven to affect biogenic ^{87}Sr/^{86}Sr in prehistoric seals (Glykou et al., 2018). This is because the Baltic Sea is a semi-enclosed sea basin. Its waters are not fully mixed with the open ocean, as indicated by its salinity, which can range between 7‰ and 25‰, compared to 35‰ in the oceans (Robson et al., 2016; Westman et al., 1999). The sea spray phenomenon has been described around the world in studies from the Hawaiian Islands (Whipkey et al., 2000), Iceland (Walser et al., 2020), and the Outer Hebrides in Scotland (Montgomery, 2002; Montgomery et al., 2003), and it can vary based on the distance from the sea (Alonzi et al., 2020; Snoeck et al., 2020) as well as the prevailing winds (Evans et al., 2018). A further complication is the averaging of ^{87}Sr/^{86}Sr in the food chain. Animals eat a variety of foods within their range; thus, their skeletal tissue averages the ^{87}Sr/^{86}Sr of the plants or animals consumed, and variation in ^{87}Sr/^{86}Sr is considerably reduced compared to the soil and plants of that area. Consequently, obtaining bulk ^{87}Sr/^{86}Sr ratios from the underlying rocks does not mean that they represent the locally available values of vegetation that grows in the soil or those found in animals and humans who sourced food in the area.

So far, a variety of methods have been used to estimate the local bioavailable ^{87}Sr/^{86}Sr, including analysing various samples such as soils, vegetation, and faunal remains, as recently reviewed by Holt, Evans, and Madgwick (2021). Water and vegetation are thought to yield the most reliable results (Lahtinen et al., 2021; Maurer et al., 2012; Ryan et al., 2018), although in some regions dental enamel samples from rodents and small mammals have also been used successfully (Ezzo et al., 1997; Kootker et al., 2016; Price et al., 2002). When estimating local bioavailable ^{87}Sr/^{86}Sr using faunal remains, dental enamel is the preferred medium, because bone is often subject to contamination and degradation during burial, so much so that the groundwater Sr can replace the existing Sr in the mineral portion of the bone (Hoppe et al., 2003; Lee–Thorp, 2002; Nelson et al., 1986). Crown dentine has similar properties to bone, and although the biogenic composition in crown dentine and enamel is similar in living individuals (Budd et al., 2000; Montgomery, 2002; Tsalev, 1984), as well as in archaeological individuals recovered from environments other than burials in soil (Montgomery et al., 2007), dentine has been proven to undergo diagenetic alteration in the burial environment. During this process the biogenic $^{87}Sr/^{86}Sr$ in dentine will gradually become closer to the local soil biosphere ratio, leading to considerable variations between co-genetic enamel and dentine samples from the same individual (Montgomery et al., 2007). In cases where meaningful environmental sampling is not an option (for example, for small-scale or pilot studies), $^{87}Sr/^{86}Sr$ ratios from archaeological bone have been used to obtain estimates of the ratio in soils as an approximate proxy for local bioavailable $^{87}Sr/^{86}Sr$, on the assumption that they are diagenetically equilibrated with the burial environment (Bentley et al., 2004).

Although no $^{87}Sr/^{86}Sr$ mapping has been done of Latvian bedrock or soils to date (Gilucis & Segliņš, 2003), it is expected that bioavailable $^{87}Sr/^{86}Sr$ would depend on the depth, composition, and origin of the Quaternary deposits, which form the dominant soil parent material in Latvia (See Supplementary material). These deposits form three main areas in the territory of Latvia, consistent with the direction of ice masses of the Baltic, Riga, and Peipsijärv ice streams during the expansion and deglaciation of the last Fennoscandian ice sheet (Zelčs et al., 2018). Noticeable variations can be expected between these areas, including the city of Riga and northern part of Vidzeme (Figure S1, Supplementary material).

Although all sampled sites in this research are located in the Riga ice stream area, differences might still be present, Pleistocene deposits in the northern part of the Riga ice stream area have a higher proportion of the far-transported Cambrian, Ordovician, Silurian, and Middle Devonian rock fragments, all of which, and particularly the Lower Palaeozoic rocks, are characterised by high $^{87}Sr/^{86}Sr$, according to McArthur et al. (2012: Figure 7.1). In the southern part of the area, their dominance in the glacial drift decreases, giving way to fragments of the local Middle and Upper Devonian sedimentary rocks, including sandstone, dolomite, dolomitic marlstone, and marlstone (Lukševičs & Stinkulis, 2018: 66), thus also potentially lowering the bioavailable $^{87}Sr/^{86}Sr$.

With regard to the expected ratios, they might be close to those reported in the neighbouring regions where glacial deposits from the movements of the same Fennoscandian ice sheet cover the bedrock, for example, in mainland coastal Estonia (0.7106–0.7159, faunal dental enamel) (Oras et al., 2016), Denmark (0.7092, modern and archaeological fauna) (Frei & Price, 2012), Northern Germany (between 0.7090–0.7100, archaeological fauna) (Price et al., 2012), and Northern Poland (0.7069 to 0.7123, soil samples) (Voerkelius et al., 2010). It has to be taken into account, however, that these deposits also differ in terms of composition.

Historical background

During the 17th century AD, the city of Riga was one of the major cities of Livonia (now the north-eastern part of Latvia, locally named Vidzeme, and the southern part of Estonia), a region ruled at various times by the Polish-Lithuanian Commonwealth and Germany but also claimed by Sweden and Russia (Figure 1). St. Gertrude's Church was built outside the city fortifications and is first mentioned in historical sources in 1413 as the main church that served the people who lived in Gertrude village and its vicinity, as well as patients from the nearby St. George's hospital. Likewise, the cemetery around the church mostly accommodated local people and those who died at the hospital (Šterns, 1998: 355). Nevertheless, St. Gertrude Church cemetery has also been mentioned in historical sources as the final resting place for poor rural immigrants from Vidzeme, who came to Riga for help during the famine of the winter of 1,601–2 and lived near St Gertrude's Church and St. George's hospital. Despite food being provided by the city, people died in great numbers from cold and exhaustion (Actiņš et al., 2009; Pīrangs, 1932; Rusovs, 1926). The famine of 1601–2 was caused by a poor harvest and exacerbated by the beginning of the Polish-Swedish war (1,600–29), with the invading Polish army looting the farmsteads in rural Vidzeme and leaving many subsistence farmers with

FIGURE 1 Map of Latvia, showing sampling sites for local soil biosphere and bioavailable $^{87}Sr/^{86}Sr$ range in rural Vidzeme (archaeological cemeteries located in Limbazi, Cesis, and Mazstraupe)

no food supplies. Just after the famine, a plague epidemic in 1602 then affected the same region, including the city of Riga; the city suffered a subsequent plague epidemic in 1623 (Napiersky, 1890).

With the famine and the plague epidemic in 1601–02 being almost simultaneous, it is possible that the mass graves represent different population groups to that of the cemetery, including the inhabitants of the city of Riga, the local Gertrude village population, as well as rural immigrants from Vidzeme.

MATERIAL AND METHODS

During a 2006 excavation, 721 individuals were uncovered from St. Gertrude's cemetery, and 286 of them were buried in two mass graves (166 buried in mass grave one - MG1 - and 120 in mass grave two - MG2). In total, there were 285 non-adults (0–17 years old), with 190 children buried in the general cemetery (GC), 55 in MG1, and 40 in MG2. The deceased excavated from the mass graves did not show any evidence for perimortem trauma, and some aspects of the demographic profile, especially with regard to the non-adult age groups represented in the general cemetery, point to an event that caused catastrophic mortality (Keckler, 1997) of the people buried in both mass graves (Gerhards, 2009; Petersone-Gordina et al., 2018).

To explore possible marine derived dietary component and the effect of sea spray, and to identify possible immigrants from coastal areas, the generated $^{87}Sr/^{86}Sr$ were plotted against previously obtained mean $\delta^{13}C$ and $\delta^{15}N$ values (Petersone-Gordina et al., 2020).

Age at death and sex in this population had been estimated previously, including a detailed demographic profile (Petersone-Gordina et al., 2018). For this analysis, age estimation in all children was based on tooth formation and eruption stages (AlQahtani et al., 2010). Both incremental dentine and Sr isotope analyses were to be performed using samples from the same teeth to obtain detailed information about these individuals. Incremental dentine provided a thorough insight into their life histories from the first years of life until death, thus potentially registering any short-term dietary changes before death, which would not have been possible for adult individuals whose teeth have finished forming long before death. Analysing $^{87}Sr/^{86}Sr$ from these same children would show if they were born and grew up in Riga or accompanied their parents to the city in the last years of life in response to the food shortages and/or other hardships. Selection criteria have been described previously (Petersone-Gordina et al., 2020). Six children were selected from each mass grave, and seven from the GC. Apart from enamel, crown dentine samples from four individuals were also included in the analysis to monitor any diagenetic shift in the dentine toward labile strontium in the burial soil (Montgomery et al., 2007) and also to aid in establishing the local soil biosphere $^{87}Sr/^{86}Sr$ range.

The location of the site is now in the centre of the city, and therefore obtaining samples from vegetation or small mammals to establish local biologically available $^{87}Sr/^{86}Sr$ was not possible. Because this was only a pilot study and creating a bioavailable strontium map was outside its scope, a reference for the local $^{87}Sr/^{86}Sr$ soil biosphere in Riga was obtained from four animal bone samples from broadly contemporary cemetery sites in the inner city of Riga (Figure 2). It was also possible to analyse faunal samples from medieval cemeteries in Cesis, Limbazi, and Mazstraupe in rural Vidzeme (for map, see Figure 1; for all sample details, see Table 1). The only sample showing biologically available $^{87}Sr/^{86}Sr$, rather than local $^{87}Sr/^{86}Sr$ soil biosphere, was the sheep/goat tooth enamel sample from Cesis, but because the animal could potentially have travelled large distances during its lifetime, this result has to be interpreted with caution. All faunal samples were selected subject to availability rather than with specific locations in mind.

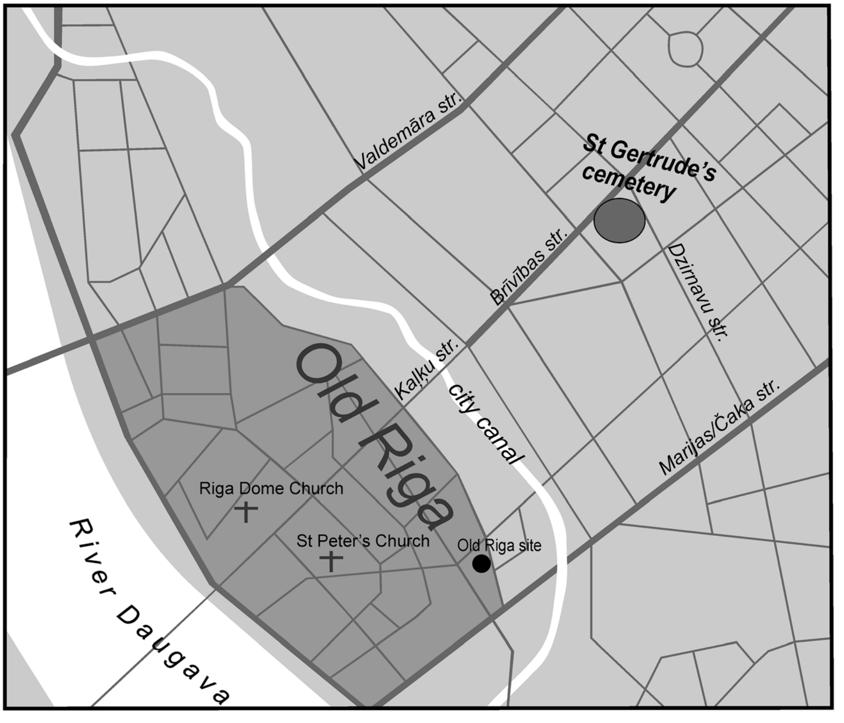

FIGURE 2 Map of Riga, showing the location of the faunal samples analysed: St. Gertrude's cemetery, Riga dome and St. Peter's churches, and old Riga

TABLE 1 Results of $^{87}Sr/^{86}Sr$ analysis from the dental enamel and dentine from the human remains and animal samples

Animal samples					
Site	**Species**	**Element**	**Tissue**	**$^{87}Sr/^{86}Sr$ norm**	**2SE**
[2]Cesis	Sheep/goat	Molar'	Enamel	0.713098	0.000008
[3]Limbazi	Cattle	Metacarpal	Bone	0.713733	0.000009
[3]Mazstraupe	Pig	Mandible	Bone	0.714905	0.000009
[2]RigaStPeter1	Cattle	Vertebra	Bone	0.712482	0.000008
[2]RigaStPeter2	Pig	Humerus	Bone	0.712057	0.000008
[2]RigaDome	Pig	Radius	Bone	0.712001	0.000010
[3]Old Riga site	Cattle	Mandible	Bone	0.712029	0.000009
Human samples					
General cemetery					
Individual	Age at death	Element	Tissue	$^{87}Sr/^{86}Sr$ norm	2SE
[1]GC_12	13–14	C′	Enamel	0.711908	0.000010
[1]GC_12 dent			Dentine	0.711941	0.000015
[1]GC_41	14-15	C,	Enamel	0.722466	0.000010
[3]GC_41 dent			Dentine	0.720451	0.000010
[1]GC_63	7-8	I1,	Enamel	0.710941	0.000010
[1]GC_85	12-13	PM2,	Enamel	0.711758	0.000009
[1]GC_85 dent			Dentine	0.711672	0.000010
[1]GC_134	13-14	C′	Enamel	0.711809	0.000007
[1]GC_283	8-9	C,	Enamel	0.711624	0.000013
[1]GC_615	10-11	C,	Enamel	0.71019	0.000009
[1]GC_615 rep				0.710159	0.000012
Mass grave 1					
[1]MG1_83	10–11	C′	Enamel	0.711803	0.000011
[1]MG1_127	11-13	C′	Enamel	0.711018	0.000010
[1]MG1_156	9-11	C′	Enamel	0.712515	0.000009
[1]MG1_497	13-14	C′	Enamel	0.710736	0.000013
[1]MG1_627	10-11	C,	Enamel	0.711195	0.000012
[1]MG1_630	11-12	C,	Enamel	0.711892	0.000010
Mass grave 2					
[1]MG2_103	10–11	C′	Enamel	0.710886	0.000010
[1]MG2_103 dent			Dentine	0.711023	0.000012
[1]MG2_177	10-11	C′	Enamel	0.710701	0.000012
[1]MG2_177 dent			Dentine	0.710674	0.000015
[1]MG2_432	10-11	C′	Enamel	0.710911	0.000009
[1]MG2_508	8-9	C,	Enamel	0.710732	0.000008
[1]MG2_516	10-11	C,	Enamel	0.713417	0.000011
[1]MG2_606	10-11	C,	Enamel	0.712617	0.000009

Notes: Superscripts in column 1 refer to analytical sessions.
[1]: Session 1 23–06-15: NBS 987 = 0.710280 ± 20 (2SD, n = 10).
[2]: Session 2 04–05-16: NBS 987 = 0.710255 ± 11 (2SD, n = 6).
[3]: Session 3 08–03-17: NBS 987 = 0.710261 ± 16(2SD, n = 8).

The $^{87}Sr/^{86}Sr$ ratios obtained from enamel, dentine and animal bone samples were compared using a Kruskal-Wallis test for more than two groups and a non-directional Mann–Whitney test for two groups with α level at 0.05. If any of the tested groups was smaller than five, significance was determined by using a standard table of Mann–Whitney critical values, as the p value could not be calculated.

Sample cleaning

The surface enamel on each tooth was abraded to a depth of ~100 μm with a tungsten carbide dental burr following the procedure given in Montgomery (2002). The core enamel was removed from the tooth wall diagonally from the cusp with a flexible diamond impregnated cutting disc. The enamel samples were then inspected for any remaining dentine or impurities that, if present, were removed with the burr. Four dentine samples were also taken from the tooth crown beneath the enamel sample. Cleaned samples were sealed in micro-centrifuge tubes and bagged for transfer.

Sr isotope analysis

Pre-cleaned enamel and dentine samples were prepared and analysed for Sr isotope determination at the Arthur Holmes Isotope Geology Laboratory, Department of Earth Sciences, Durham University, following the methods of Charlier et al. (2006).

Pre-cleaned enamel chips (6.5 – 18 mg) were weighed into clean Teflon beakers and dissolved in 0.5 mL ultra-pure Teflon distilled (TD) 3 M HNO_3. Once dissolved, Sr was separated from the sample matrix using a 1 mL column packed with 60 μL of Eichrom Sr Resin. The Sr fraction, eluted from the column in 400 μL of ultrapure (MQ) H_2O, was acidified with TD 16 M HNO_3 to make a 3% HNO_3 solution ready for isotope analysis by Multi-Collector ICP-MS (MC-ISP-MS) using a ThermoFisher Neptune. Prior to analysis the Sr fraction was tested to determine the Sr concentration by monitoring the ^{86}Sr beam and to ensure the major isotope of Sr (^{88}Sr) did not exceed the maximum voltage (50 V) for the detector amplifiers. Where necessary, samples were diluted to yield an ^{88}Sr signal of ~25 V.

A Sr isotope measurement comprised a static multi-collection routine, with ^{86}Sr in the axial detector, of 1 block of 50 cycles with an integration time of 4 sec per cycle; the total analysis time was 3.5mins. Instrumental mass bias was corrected for using an $^{88}Sr/^{86}Sr$ ratio of 8.375209 (the reciprocal of the accepted $^{86}Sr/^{88}Sr$ ratio of 0.1194) and an exponential law. Corrections were also applied for Kr interferences on ^{84}Sr and ^{86}Sr, and for Rb interference on ^{87}Sr by monitoring masses ^{82}Kr, ^{83}Kr, and ^{85}Rb. The average ^{83}Kr intensity throughout the analytical session was ~0.1 mV, which is insignificant considering the Sr beam size (^{88}Sr between 9 and 25 V). The average ^{85}Rb intensity was slightly greater at ~0.3 mV (range: 0.1–0.6 mV), but again, given the range in Sr beam size, the Rb correction on the $^{87}Sr/^{86}Sr$ was very small (<0.00001) and is accurate at that magnitude.

Samples were analysed in three analytical sessions between June 2015 and March 2017. The average $^{87}Sr/^{86}Sr$ and reproducibility for the international Sr isotope reference material NBS 987 for each session is given in the notes for Table 1. Given the slight variation in average $^{87}Sr/^{86}Sr$ ratio for NBS 987 between analytical sessions, all sample data in Table 1 have been renormalised to a constant NBS9 987 $^{87}Sr/^{86}Sr$ ratio of 0.71024. The total procedural Sr blank during chemistry was 28 pg, which is insignificant considering that all samples were >0.5 μg total Sr in size.

RESULTS

Results of $^{87}Sr/^{86}Sr$ analysis from the non-adult dental enamel, dentine, and animal bone/ enamel, including the age at death of each individual and the type of sample used, are given in Table 1.

In all but one child, enamel ratios were between 0.7102 and 0.7134, whereas the range for dentine was smaller and varied between 0.7108 and 0.7119. The lowest of these ratios was observed in individual GC_615, and the highest in MG2_516. Enamel and dentine ratios of individual GC_41 were considerably higher, at 0.7225 and 0.7205, respectively. The enamel ratio exceeded the second highest value observed in this study (MG2_516, 0.7134) by 0.0091 and was clearly an outlier (Figure 3). Enamel $^{87}Sr/^{86}Sr$ had the widest range in children from MG2 (from 0.7107 to 0.7134, range of 0.0027), whereas ratios in people from the GC and MG1 varied less when observed without individual GC_41 (ranges of 0.0017 and 0.0018, respectively).

Four individuals analysed for $^{87}Sr/^{86}Sr$ in their dentine and enamel (GC_12, GC_85, MG2_103 and MG2_177) had very similar ratios in both tissue types. In GC_12, GC_85 and MG2_177 the enamel ratio was identical to the dentine, whereas in MG2_103 the dentine ratio was only by 0.0001 higher than in the enamel, which is not considered a significant difference (Montgomery, 2002: 146). In GC_41, however, the enamel $^{87}Sr/^{86}Sr$ was 0.0020 higher than the dentine, which is significant, compared to the other four individuals.

dent-dentine; rep-repeat; C-canine; I1-first incisor; PM2-second premolar; ‘-upper;,-lower; RigaStPeter – St. Peter’s Church cemetery in Riga; RigaDome – Riga Dome Church cemetery.

Faunal samples from the Vidzeme cemeteries ranged from 0.7131 to 0.7149, whereas those from Riga were between 0.7120 and 0.7125. Although the medians of the two groups (0.7137 and 0.7120, respectively) differed by 0.0017, due to the small sample size, the differences could not be compared with a statistical significance test.

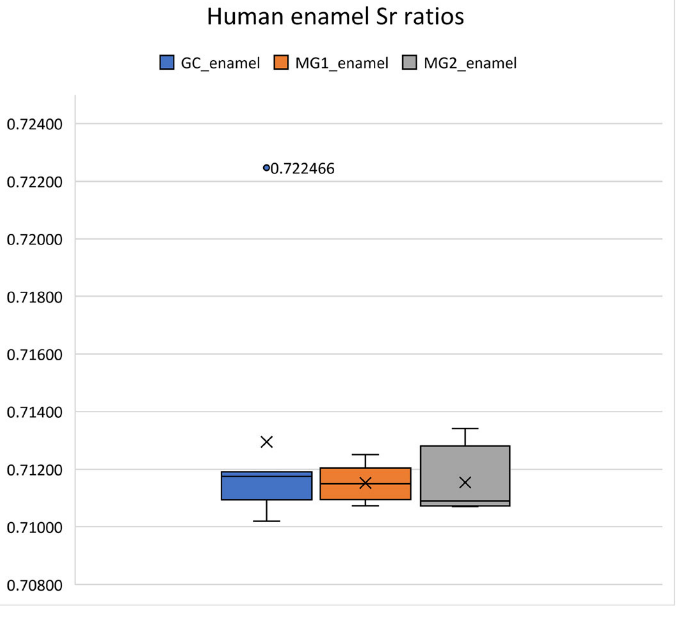

FIGURE 3 Human enamel $^{87}Sr/^{86}Sr$ ratios, including individual GC_41 (shown as an outlier) *Notes*: Boxes are formed by the first and the third quartiles; the dividing line shows the median ratio; the whiskers on each box show minimum and maximum ratios; x-mean ratio; N (GC) = 7, N (MG1) = 6, N (MG2) = 6

There were no significant differences in median human enamel $^{87}Sr/^{86}Sr$ among the three contexts (Kruskal-Wallis test, n = 18, H = 0.42, df = 2, p = 0.811). The human enamel samples were significantly different in median to the faunal samples from Vidzeme (Mann–Whitney non-directional test, n = 21, U = 1, critical value = 7), although the ratio of one child (MG2_516) overlapped with the faunal samples from Cesis and Limbazi (Figure 4). Although enamel ratios from children buried in MG1 and MG2 were not significantly different in median to faunal samples from Riga (n = 16, U = 12, critical value = 7), the opposite was true for children buried in the GC (n = 10, U = 0, critical value = 2), and all the dentine ratios (n = 8, U = 0, critical value = 0). There were no significant differences between the human enamel and dentine samples (n = 22, U = 33.5, critical value = 12).

DISCUSSION

The ratios observed in most children, except GC_41, are similar to the lower range from mainland Estonia and northern Poland but higher than those from Denmark and Northern Germany. Some of the faunal and human enamel ratios were higher, closer to the higher range of mainland Estonia. This might mean that although in general, biogenic $^{87}Sr/^{86}Sr$ from Latvia mainly derive from glacial deposits, their regional composition also has a significant input, thus resulting in noticeable differences. In this case, the local composition includes glacially rafted and reworked material of various Devonian sedimentary rocks, as discussed in Section 1.1 and the Supplementary material. The current lack of $^{87}Sr/^{86}Sr$ from these deposits and rocks prevents a more detailed discussion for the time being.

The observed significant differences between enamel ratios in children from the GC and all human dentine ratios against faunal samples from Old Riga are intriguing considering that the distance between the cemetery and the city is approximately 1 km. As discussed in Section 1.1 above, $^{87}Sr/^{86}Sr$ in archaeological bone, like in dentine, is prone to a diagenetic shift towards that of the burial soil (Hoppe et al., 2003; Lee–Thorp, 2002; Nelson et al., 1986). All four faunal samples in the current study came from different sites within the old city of Riga, but three yielded insignificant differences, with $^{87}Sr/^{86}Sr$ almost overlapping (one sample from St. Peter's Church cemetery, as well as samples from Riga Dome Church cemetery and the old city). Consequently, significantly different dentine ratios of children from all three contexts suggest a

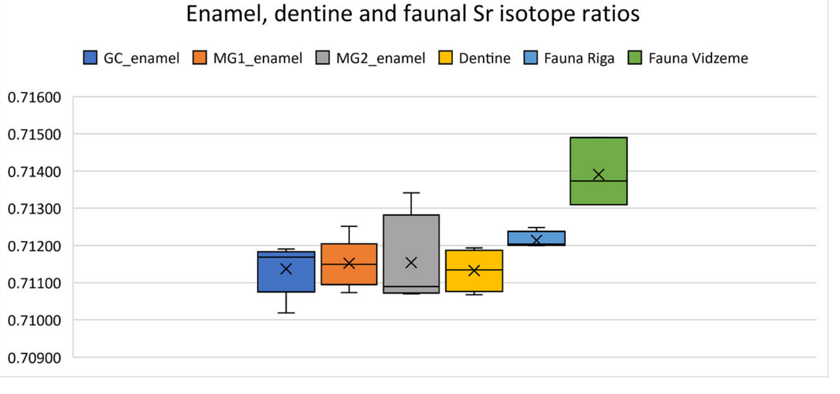

FIGURE 4 Enamel, dentine and faunal $^{87}Sr/^{86}Sr$ ratios, plotted without individual GC_41 *Notes*: Boxes are formed by the first and the third quartiles; the dividing line shows the median ratio; the whiskers on each box show minimum and maximum ratios; x-mean ratio; N (GC) = 6, N (MG1) = 6, N (MG2) = 6; N (dentine) = 5; N (Fauna Riga) = 4; N (Fauna Vidzeme) = 3

noticeable difference in soil composition between the two locations, and more research is therefore necessary to clearly define the local soil biosphere range of inner Riga.

The almost identical enamel and dentine ratios of most children suggest that labile strontium ratios and $^{87}Sr/^{86}Sr$ the individuals were exposed to during their lives were very similar, thus pointing to their local origin. The very radiogenic $^{87}Sr/^{86}Sr$ of enamel for GC_41 suggests this individual most likely derived from an area with an underlying geology—solid or drift—different from that of Vidzeme or Riga and its surroundings. The closest comparator populations are from Estonian prehistoric coastal sites, which have yielded similar human $^{87}Sr/^{86}Sr$ to those in children from St. Gertrude's cemetery, as discussed above. However, two individuals from the site of Kunda on the coast of the Gulf of Finland had considerably higher values than the rest of the population, exceeding 0.7188 (Oras et al., 2016). This enabled the authors of the study to suggest that these people were non-local not only for the analysed sites but possibly for the territory of Estonia. The value of GC_41 was even higher than that for the two immigrants buried in Kunda. The closest comparable $^{87}Sr/^{86}Sr$ ratios from the wider region come from northern and central Sweden, with an average range for archaeological human and faunal samples of 0.720–0.726 (Price et al., 2012), and north-western Finland, with the range for modern plant samples between 0.7178 and 0.7347 (Lahtinen et al., 2021). Ratios from the islands in the Baltic Sea (archaeological fauna and modern snail samples) and from Poland (modern faunal, soil, and surface water samples) are lower (Gregoricka et al., 2014; Price et al., 2012), and those from south-western Finland (archaeological faunal samples) are higher (Bläuer et al., 2013).

Enamel ratios in people from all three contexts differed significantly from faunal samples from Vidzeme, thus contradicting historical sources and rejecting the hypothesis related to the presence of rural migrants from that area in St. Gertrude's cemetery. Only the $^{87}Sr/^{86}Sr$ of individual MG2_516 overlapped with faunal samples from Limbazi and Cesis, suggesting that one place where this child may potentially have derived from is Vidzeme. However, the observed differences in ratios support the possibility that Riga and Vidzeme are isotopically distinguishable, even though all sites sampled were in the Riga ice stream area. The higher $^{87}Sr/^{86}Sr$ ratios in soil biosphere from Vidzeme compared to those from Riga might reflect the higher proportion of the far-transported rock fragments in the northern part of the Riga ice stream, as discussed in Section 1.1. Caution is necessary, however, before the differences between Riga and rural Vidzeme, and thus the "local" or "non-local" origins of the sampled individuals, can be confirmed by creating a more detailed biologically available strontium map.

The child with the lowest $\delta^{13}C$ and $\delta^{15}N$ values (MG1_156), also had the second highest $^{87}Sr/^{86}Sr$ for MG samples, second only to MG2_516. Unlike individual MG2_516, who may have originated from the Vidzeme area, MG1_156 had $^{87}Sr/^{86}Sr$ 0.0003 lower than the highest ratio defined by the local Riga faunal samples (Figure 5); this suggests that this individual was perhaps from Riga. The observed differences in dietary isotope profiles thus point to different individual dietary practices, especially with regard to marine and terrestrial foods rather than a different origin for this child.

The lack of significant variation in all human enamel samples makes it plausible that most children derived from a similar location, most probably Riga and its vicinity. The lower $^{87}Sr/^{86}Sr$ observed in some children might indicate that they came from coastal areas, which were subject to sea spray but otherwise were isotopically similar to Riga. There was also a significant negative correlation between mean dentine $\delta^{13}C$ values and enamel $^{87}Sr/^{86}Sr$ in children from MG1 and MG2 ($r = -0.82$; $r^2 = 0.67$; $p = 0.047$; $df = 4$; $t = -2.84$ and $r = -0.90$; $r^2 = 0.81$; $p = 0.015$; $df = 4$; $t = -4.07$, respectively), whereby most of the individuals with higher $\delta^{13}C$ values, which indicates a higher proportion of marine protein in their diet, had Sr isotope compositions that were lower and closer to marine values (Figure 5). The same was true for dentine $\delta^{15}N$ values in children from MG2 ($r = -0.86$, $r^2 = 0.74$, $p = 0.027$, $df = 4$, $t = -3.42$), while the correlation between $\delta^{15}N$ values and $^{87}Sr/^{86}Sr$ was strong, but not

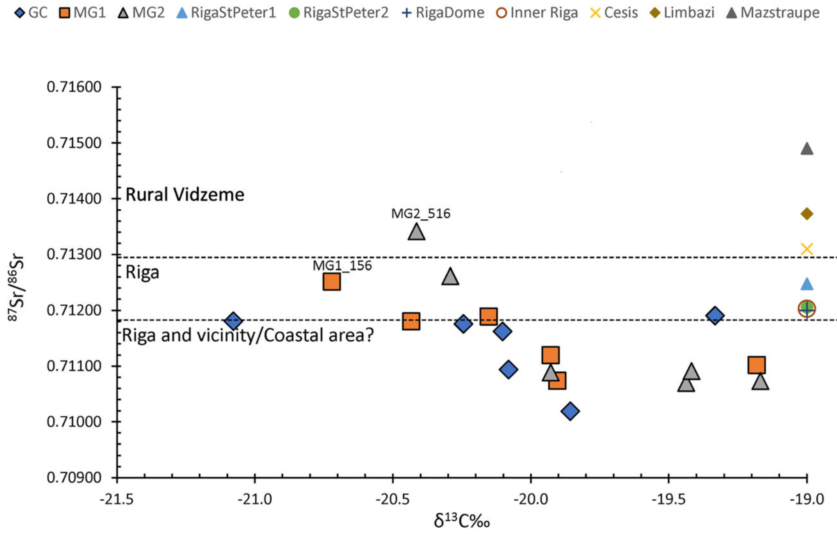

FIGURE 5 $^{87}Sr/^{86}Sr$ of the teeth of 18 children, and seven animal samples (six bones and one tooth) against mean $\delta^{13}C$ values *Notes*: Animal ratios are on the right axis; their $\delta^{13}C$ values are unknown. Individual GC_41 is not included in this figure. The lines separate tentative bioavailable $^{87}Sr/^{86}Sr$ ranges for Riga and rural Vidzeme, and possible other areas, based on enamel and faunal samples

statistically significant in children from MG1 ($r = -0.77$, $r^2 = 0.59$, $p = 0.073$, $df = 4$, $t = -2.43$). Conversely, in children from the GC, the correlation between $^{87}Sr/^{86}Sr$ and $\delta^{13}C$ and $\delta^{15}N$ values was weak ($r = -0.14$; $r^2 = 0.02$; $p = 0.786$; $df = 4$; $t = -0.29$, and $r = -0.56$, $r^2 = 0.31$, $p = 0.245$, $df = 4$, $t = -1.36$, respectively).

This points to a higher proportion of marine protein in the diet of children buried in the mass graves and especially MG2 compared to children from the general cemetery. Although it is therefore possible that most individuals from the mass graves came from a coastal region, another possibility is that they were local but simply sourced their food from areas closer to the sea and also increasingly relied on marine resources. As discussed in Section 1.2, the people who lived in the 17th century Riga experienced several hardships, including a famine, war, and plague epidemics. In such circumstances, the food supply normally available for the population may well have changed in the short term, for example, with the majority of staple foods becoming available from certain, limited areas subject to sea spray, which brought the $^{87}Sr/^{86}Sr$ closer to the current seawater ratio of 0.7092 in the tested children's dental enamel (Bentley, 2006). A shift from terrestrial to marine animal protein as a part of short-term food strategies for some families would also explain the strong negative correlation between mean dentine $\delta^{13}C$ and $\delta^{15}N$ values and enamel $^{87}Sr/^{86}Sr$ ratios in children from the mass graves, because they represent one generation who experienced hardships but not the general cemetery, which was in use for over 300 years. The collective experience of hardships of children buried in the mass graves was also supported by the similar dietary profiles and evidence for physiological and/or nutritional stress, as discussed above. A more detailed discussion, however, is limited due to the current lack of data about bioavailable $^{87}Sr/^{86}Sr$ from the coastal areas.

With regard to GC41, although their mean $\delta^{13}C$ and $\delta^{15}N$ values (−19.9 ‰ and 12.2 ‰, respectively) do not necessarily point to a significant marine input in their diet, the differences in dietary profile suggesting that this child was not local occurred between two and seven years of age, whereby either a period of nutritional stress or a marked increase in marine dietary protein was observed (Petersone-Gordina et al., 2020). The timing of crown formation of the sampled tooth (mandibular canine, 0.9 to 6.5 years of age approximately: AlQahtani et al., 2010) coincides with the observed dietary change and might point to a possible coastal origin and/or a region with good access to marine resources in the first years of life for this child.

CONCLUSIONS

This study has achieved its aim of helping to shed light on the origins of people buried in St. Gertrude's cemetery. One child from the general cemetery had notably different $^{87}Sr/^{86}Sr$ from other children, suggesting that they had come from outside of Riga and possibly a coastal area. Of the remaining children, only one child from a mass grave could potentially have originated in Vidzeme. More research, however, is necessary to clearly define the bioavailable $^{87}Sr/^{86}Sr$ ranges for parts of Vidzeme and inner Riga before "local" or "non-local" origins for people buried in the cemetery can be confidently inferred.

Although most of the analysed children from mass graves were of local Riga origin or derived from its vicinity, their $^{87}Sr/^{86}Sr$ ratios might have been influenced by short-term dietary strategies, possibly shifting to food sources subject to sea spray, and also marine resources, as indicated by a strong correlation between their $^{87}Sr/^{86}Sr$ ratios and the mean $\delta^{13}C$ and $\delta^{15}N$ values, as opposed to children from the general cemetery. This research has generated the first archaeological human and faunal $^{87}Sr/^{86}Sr$ ratios from Latvia, not only indicating the future potential for local migration studies but also producing valuable comparative data to aid future research related to migration in Europe in past populations. To extend the findings of this study, it will be necessary to obtain more $^{87}Sr/^{86}Sr$ data from different regions of Latvia, with the aim of eventually creating a regional biologically available $^{87}Sr/^{86}Sr$ map.

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PEER REVIEW

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DATA AVAILABILITY STATEMENT

All data generated during this study are presented in this paper.

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