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Water Consumption in Iron Age, Roman, and Early Medieval Croatia

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ABSTRACT Patterns of water consumption by past human populations are rarely considered, yet drinking behavior is socially mediated and access to water sources is often socially controlled. Oxygen isotope analysis of archeological human remains is commonly used to identify migrants in the archeological record, but it can also be used to consider water itself, as this technique documents water consumption rather than migration directly. Here, we report an oxygen isotope study of humans and animals from coastal regions of Croatia in the Iron Age, Roman, and Early Medieval periods. The results show that while faunal values have little diachronic variation, the human data vary through time, and there are wide ranges of values within each period. Our interpretation is that this is not solely a result of mobility, but that human behavior can and did lead to human oxygen isotope ratios that are different from that expected from consumption of local precipitation. Am J Phys Anthropol 000:000–000, 2014. © 2014 Wiley Periodicals, Inc.

Water consumption is fundamental to all living things, but drinking is little considered in archeology beyond matters relating to different types of alcohol consumption. Nevertheless, the study of water consumption has the potential to reveal the social aspects of drinking and thus has wider significance above and beyond the biological need for water (see, for example, Dudgeon and Tromp, 2012). In particular, different cultures have different drinking behaviors, and access to water may be socially mediated with certain sections of society having preferential access to or control over particular water sources (see articles in De Garine and De Garine, 2001 for further discussion of such topics).

Oxygen isotope analysis of tooth enamel allows an assessment of water intake by a person during the time of tooth formation. The oxygen isotope values of water ingested during childhood are preserved for life in an individual's tooth enamel. When the water consumed is derived from recent, local precipitation the technique can be used to identify migrants in the archeological record, because the oxygen isotope values in precipitation vary geographically. If a person migrates during their lifetime, then the enamel oxygen isotope ratios of their teeth formed prior to migration will be different from the precipitation at their burial place and to indigenous residents of their burial population.

However, there are various behavioral factors that can lead to an individual consuming water that is not isotopically the same as the local precipitation. These include the consumption of water from sources other than the local precipitation, such as water directly or indirectly taken from, for example, different altitudes or aquifers (Gat, 1971). Other human behaviors can modify the isotopic ratio of the local precipitation through the preparation of food and drink by brewing, boiling, stewing, and alkaline cooking (Daux et al., 2008; Warriner and Tuross, 2009; Brettell et al., 2012). Such behaviors will influence the oxygen isotope value of human tooth enamel. Oxygen isotope analysis can therefore be used to consider topics such as socially mediated access to water sources, the management of water, and variations in food and drink preparation techniques.

Here we report on a study of oxygen isotopes of archeologically derived human remains from Croatia ranging in antiquity from the Iron Age to the Early Medieval period. The initial aim was to identify migrants and to consider their dietary isotopic contexts in relation to other members of the burial population. With preliminary data showing greater than expected variability, we then assessed whether intra- and interpopulation differences may be best explained through the presence of "migrants" or through differences in source, management, and/or preparation of ingested water between the three periods.

ARCHEOLOGICAL BACKGROUND

The sites under investigation are mostly situated in the area of Dalmatia known as the Ravni Kotari (*Level*

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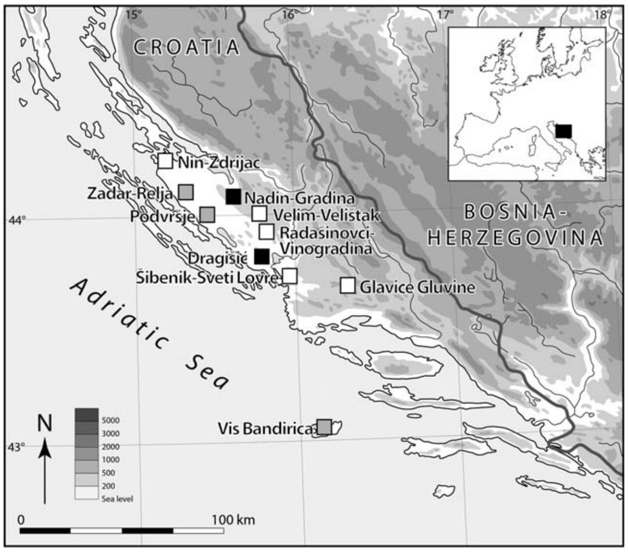

Fig. 1. Map showing location of analyzed sites. Black squares represent Iron Age sites, gray squares represent Roman sites, and white squares represent Early Medieval sites. Both Iron Age and Roman samples were obtained from Zadar-Relja.

Corner), which is one of the few flat areas of land on the Croatian coast (Fig. 1). A group known through ancient sources as the Liburni inhabited the region during the Iron Age. The archeological data exhibit no evidence for large-scale movements of people (Alexander, 1972). However, the Liburni were known to be seafarers and were heavily involved in trading with other peoples. This, combined with the establishment of Greek colonies in the area, may have led to small numbers of migrants in the samples investigated in this study.

The area subsequently became part of the Roman Empire when the Liburnian fleet was captured in 34 BC, but Roman traders and farmers had settled the coast before this date. Postconquest, the epigraphic evidence from cities such as Zadar indicates that there was significant movement of people (Chapman and Shiel, 1991). After the middle of the second century AD, there was increased population movement from other parts of the Empire, including tombstone evidence for immigrants, artefacts, and the settlement of veterans (Wilkes, 1969; Giunio and Gluščević, 2007).

Following the collapse of the Western Roman Empire, the area came to be ruled by Slavs, possibly under the dominion of the Avars, and later by the Croats. While the extent to which Avars settled in the Ravni Kotari is at present unclear, it is likely that the Slavs settled in relatively large numbers. The emergence of the Croats is a controversial topic, with varying opinions as to the cause, including internal development (Barada, 1952; Evans, 1996) and large-scale migration (Goldstein, 1999; Margetić, 1999; Supek, 1999). Regardless of the migratory status of these groups, various and diverse lines of evidence suggest that the transition from the Roman to the Early Medieval period corresponded with significant changes in health (Šlaus, 2008), settlement pattern (Chapman et al., 1996; Evans, 1989) and diet (Šlaus et al., 2010; Lightfoot et al., 2012).

Considered together, these data suggest that the inhabitants of coastal Croatia during the Iron Age, Roman and Early Medieval periods encompassed populations of mixed origins, consisting mainly of locally born individuals with outliers representing migrants from various other regions, potentially during all periods under study.

The location of the study area in the Dinaric karst landscape also has implications for water use in all of the time periods under consideration. The hydrology of karst areas is such that water availability can be problematic throughout the year, with surface water soaking into the permeable rock very quickly, and entire rivers appearing and disappearing into the ground. Wilkes (1969) suggests that water was probably the main hindrance to the growth of large communities and in the Ravni Kotari area today, there is a summer water deficit of sufficient severity as to restrict the growth of non-irrigated crops (Chapman et al., 1996).

Throughout the period under consideration different water sources were available to the people living in Dalmatia, such as precipitation, river water, well water, and standing pools. Furthermore, traded items included food and drink, both of which can be considered as imported water. The effect of this upon human isotope values is expected to be correlated to the amount of trade, presumably of greatest intensity in the Roman period. Similarly, brewing and vinification, plus seasonal storage of water and storage where evaporation was possible, are likely to have affected the isotopic values of ingested liquids. Alternatively, the importation of water via aqueducts could have led to the ingestion of water that had a different isotopic ratio than the local precipitation. Aqueducts were built in the Roman period with eight known in the area under consideration (Nin, Zadar, Podgrade, Plavno Polje, Skradin, Solin, Split, and Gardum; Wilkes, 1969; Talbert, 2000; http://www.romaq.org and references therein). These were up to 40 km long (Zadar aqueduct) and the Burnum aqueduct brought water from the Dinaric Mountains, which rise to 1913 m in the hinterland of the area under consideration. The aqueduct serving Roman Salona carried water sufficient for 40,000 people (Wilkes, 1969). Although many Roman structures in Zadar were damaged in an earthquake in the sixth century AD, it is possible that some aqueducts remained in use in the Early Medieval period. Water brought from higher altitudes via aqueducts was likely isotopically depleted—precipitation measured at Mount Velebit (to the north of the study area) at an altitude of 1594 m has lower oxygen isotopic ratios than the coastal areas (mean $\delta^{18}O = -9.3‰$, although the reported measurements were for only 3 years; Vreča et al., 2006). A final consideration is that the proportion of water consumed directly as water, rather than brewed or made into wine and so forth, could have changed through time as access to safe, clean drinking water varied.

ISOTOPIC BACKGROUND

Oxygen isotopic ratios in precipitation reflect the local climate and vary according to temperature and distance from the source of the water (Dansgaard, 1964; Rozanski et al., 1992, 1993). In mid to high latitudes distinct isotopic patterning can also be related to a variety of temperature-related factors, such as latitude (Förstel and Hützen, 1983), altitude (Poage and Chamberlain, 2001), and season (Simpkins, 1995). The oxygen isotopic ratios (expressed as $\delta^{18}O$) found in groundwater generally reflect the average isotopic composition of recent precipitation in the local source area. Nevertheless, variations between precipitation and groundwater $\delta^{18}O$ values can be caused by: evaporation from surface water; fractionation during water movement through the soil or aquifer; exchange within geological formations; recharge that occurred in past periods when the isotopic composition of precipitation was different from that at present; and recharge from rivers containing water derived from high altitude precipitation (Gat, 1971; Gat and Dansgaard, 1972).

The oxygen isotope signal in tooth enamel carbonate is derived mainly from ingested water. Both drinking water and water in food are likely to be predominantly locally sourced and to reflect local precipitation. Where this is the case, the isotopic ratios in drinking water and the water in food reflect those of the local climate (Longinelli, 1984; Luz and Kolodny, 1985). Since tooth enamel does not remodel during life, the isotopic ratios in the carbonate reflect the water ingested during the time of tooth formation, which in humans occurs during childhood.

In archeological studies, migrants are typically identified by this technique as those individuals who ingested water with an oxygen isotope value notably different from that of the local precipitation (via a series of conversions) and/or by comparison to other measured human $\delta^{18}O$ values. Those whose isotopic values are consistent with that of the local water or other analyzed human samples are interpreted either as “local,” or from an area where the ingested water was of similar isotopic composition (Budd et al., 2004; Bentley et al., 2008; Keenleyside et al., 2011).

MATERIALS AND METHODS

Tooth enamel samples were taken from individuals buried in 10 cemeteries in coastal Croatia. A total of 329 human teeth, the majority of which derive from the Early Medieval period, were sampled and analyzed successfully. Premolars were sampled wherever possible, which form between the ages of 1.8 and 6.3 years (Smith, 1991; Supporting Information Table S1). Animal enamel $\delta^{18}O$ values were used to determine whether the $\delta^{18}O$ values of precipitation varied through time. Finding closely associated fauna was problematic, as most of the main sites analyzed are cemetery sites. Nevertheless, 37 archeological animal teeth were sampled from the main domesticated species (Supporting Information Table S2). For humans and animals, samples were taken along the entire length of the tooth in order to avoid possible effects of seasonal variation in isotopic values.

For all samples tooth enamel powder was taken using a Dremel hand-held drill with a diamond drill attachment. The method followed was the standard laboratory protocol of the Department of Archaeology and Anthropology, University of Cambridge, based on that described in Balasse et al. (2002). 0.1 ml of 2–3% aqueous sodium hypochlorite was added per mg of tooth enamel powder. The samples were then left for 24 h at 4°C before being rinsed five times with distilled water to remove the sodium hypochlorite. 0.1 ml of acetic acid was then added per mg of sample. The samples were then left for 4 h at room temperature, before the acetic acid was removed and the samples rinsed. Samples were then frozen and freeze-dried to remove any remaining liquid.

Most samples were subsequently transferred to a vial with a screw cap holding a septa and PCTFE washer to make a vacuum seal and dried in an oven at 50°C overnight. They were then reacted with 100% orthophosphoric acid at 90°C using a Micromass Multicarb Sample Preparation System. This produced carbon dioxide which was dried and transferred cryogenically into a PRISM mass spectrometer for isotopic analysis. A smaller proportion of the cleaned enamel powder samples were reacted with 100% orthophosphoric acid for 2 h at 70°C in individual vessels in an automated Gasbench interfaced with a Thermo Finnigan MAT 253 isotope ratio mass spectrometer. Carbon and oxygen isotopic ratios were measured on the delta scale relative to the international standard Vienna Pee Dee Belemnite (VPDB) calibrated using the NBS19 standard (Craig, 1957; Coplen, 1995). Repeated measurements on international and in-house standards show that the analytical error is less than ±0.10‰ for oxygen and ±0.08‰ for carbon.

Comparison of in-house enamel standards indicates that there may be a small difference in oxygen isotope ratios (ca. 0.2‰) between the two spectrometry methods (PRISM vs. Gasbench), however the carbon values of the in-house enamel standards and the oxygen and carbon values of international standards show that any difference between the techniques is within machine error. Statistical comparisons of archeological samples where the two methods were applied to the same site show no differences between the results. Consequently, data obtained by the two methods are considered together.

All standard deviations reported below represent 1σ. Statistical analyses were performed using SPSS 21.0 for Mac. Samples were tested for normality using histograms, as well as Kolmogorov-Smirnoff and Shapiro-Wilk tests, while Levene’s tests were used to test for equality of variance. The parametric data were investigated using one-way analysis of variance (ANOVA) tests with post hoc Bonferroni corrections, while nonparametric data were investigated with Kruskal–Wallis tests with post hoc Mann–Whitney tests. The results of these statistical analyses are provided in Table 1.

Two commonly used statistical methods were employed to identify possible migrants: (1) individuals more than two standard deviations from the mean and (2) individuals more than 1.5 times the interquartile range (IQR) below Quartile 1 (Q1) or above Quartile 3 (Q3). Isotope studies of this nature tend to employ the former method to identify outliers, although it is of importance to note that this is only valid with parametric data and results in 5% of any normally distributed group being defined as migrants. An alternative method for the identification of migrants is the use of interquartile ranges: this method does not require parametric data, and is a standard statistical method to identify outliers in a sample (Hakenbeck et al., 2010).

The human isotopic data were not converted prior to statistical analysis and interpretation. In order to compare the modern water and faunal results, all faunal data have been converted to equivalent drinking water values, with the caveat that the conversion equations increase errors of uncertainty. The equation used to convert the data from carbonate VPDB to carbonate Standard Mean Ocean Water (SMOW) is given in Coplen et al. (1983), while the equation given by Iacumin et al. (1996) was used for conversion from carbonate to phosphate. The equations used to convert from phosphate to drinking water values were those of D’Angela and Longinelli (1990) for cattle and sheep, and Huertas et al. (1995) for horse. The Iacumin and Longinelli (2002) equation for

TABLE 1. Results from statistical tests

Comparison	Test	n	$\delta^{18}O_c$ (VPDB) df	 Test statistic	 P
Human Iron Age $\delta^{18}O_c$ results by site (Dragišić, Nadin-Gradine, Relja)	Kruskal–Wallis	10, 22, 6	2	(H) 7.700	0.021
Human Roman $\delta^{18}O_c$ results by site (Podvršje, Vis-Bandirica, Zadar-Relja)	ANOVA	5, 11, 38	2	(F) 1.518	0.229
Human Early Medieval $\delta^{18}O_c$ results by site (Nin-Ždrijac, Šibenik-Sveti Lovre, Glavice Gluvine, Radašinovci Vinogradine, Velim Velištak)	Kruskal–Wallis	50, 25, 18, 52, 92	4	(F) 35.427	<0.001
Human $\delta^{18}O_c$ (VPDB) results by period (including outliers)	ANOVA	38, 54, 237	2	(F) 15.991	<0.001
Human $\delta^{18}O_c$ (VPDB) results by period (excluding 26 statistical outliers)	Kruskal–Wallis	32, 51, 220	2	(H) 24.523	<0.001
Faunal results by period (all samples)	Kruskal–Wallis	5, 19, 13	2	(H) 2.301	0.317
Faunal results by period (excluding outliers)	Kruskal–Wallis	5, 15, 12	2	(H) 0.779	0.677

ANOVA tests were used to investigate the parametric data, and Kruskal–Wallis tests were used for nonparametric data.

TABLE 2. Summary of human tooth enamel carbonate oxygen isotope results

Period	Site	n	Mean $\delta^{18}O_c$ (VPDB) (‰)	St dev (‰)	Range (‰)
Iron Age	Dragišić	10	−2.8	1.8	−6.6 to −1.4
	Nadin-Gradine	22	−4.0	0.8	−5.2 to −1.9
	Relja	6	−4.6	1.1	−6.2 to −3.1
	All	38	−3.8	1.3	−6.6 to −1.4
Roman	Zadar-Relja	38	−5.4	1.0	−7.4 to −3.6
	Vis-Bandirica	5	−4.4	1.2	−6.3 to −3.8
Late Antique	Podvršje	11	−4.9	1.0	−6.3 to −3.1
Roman and Late Antique	All	54	−5.2	1.0	−7.4 to −3.1
Early Medieval	Nin-Ždrijac	50	−5.1	1.0	−7.7 to −3.0
	Velim Velištak	92	−4.4	1.5	−7.6 to −1.4
	Glavice Gluvine	18	−5.2	1.0	−6.8 to −3.1
	Radašinovci Vinogradine	52	−3.9	0.9	−6.3 to −2.0
	Šibenik-Sveti Lovre	25	−4.3	1.0	−6.0 to −1.6
	All	237	−4.5	1.3	−7.7 to −1.4

foxes was used due to the absence of a published conversion equation for dogs.

RESULTS

Human enamel oxygen isotope results

The human tooth enamel oxygen isotope results are discussed as tooth enamel carbonate values ($\delta^{18}O_c$) on the VPDB scale. These results are summarized in Table 2, illustrated in Figure 2, and listed in full in Supporting Information Table S1. The Roman sites are not different from one another when the results are compared by site within periods, while for the Iron Age, Dragišić, and Nadin-Gradina are only marginally different, while neither site is different to Zadar-Relja (Table 1). While differences between sites exist in the Early Medieval period, these differences do not appear to be correlated with either site location or date. Given the general homogeneity (Roman period), minimal differences (Iron Age), and random patterning with regard to site location and antiquity), the sites are grouped by period in our analyses.

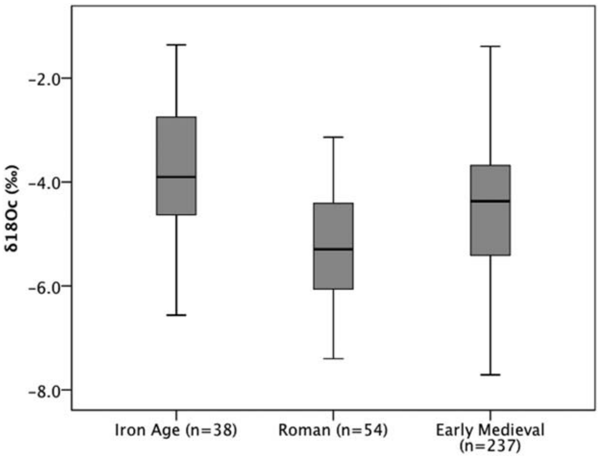

Fig. 2. Human tooth enamel $\delta^{18}O_c$ results. The line represents the median value, the shaded box represents the interquartile range, and the whiskers represent the maximum and minimum values.

Considered as a whole, the Iron Age samples have a mean $\delta^{18}O_c$ value of -3.8 ± 1.3‰, with a range from −6.6 to −1.4‰ (or −6.2 to −1.4‰, excluding all statistically identified outliers, discussed below). This is notably different from the Roman period mean of -5.2 ± 1.0‰, which has a range from −7.4 to −3.1‰ (or −7.2 to −3.6‰, excluding all identified outliers). The Early Medieval mean, -4.5 ± 1.3‰, is intermediate between the Iron Age and Roman period samples and has a range from −7.7 to −1.4‰ (or −6.8 to −1.9‰, excluding all identified “outliers”). The clear and statistically significant ($P < 0.001$) differences in mean $\delta^{18}O_c$ values

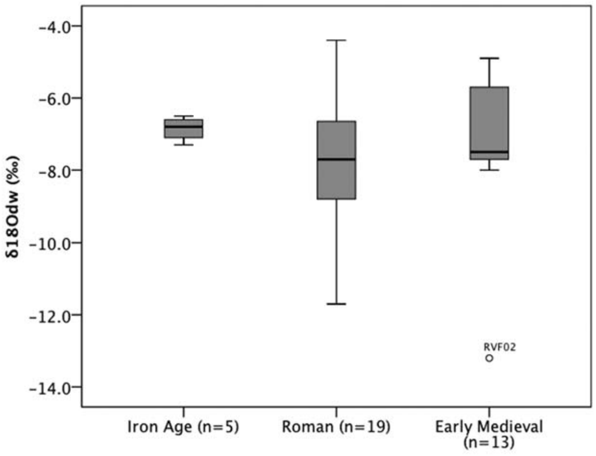

Fig. 3. Animal tooth enamel $\delta^{18}O_{dw}$ results. The line represents the median value, the shaded box represents the interquartile range, and the whiskers represent the maximum and minimum values. The outlier (RVF02) is excluded from the minimum value and shown as a circle.

between all three periods were unexpected, although the difference between the Iron Age and Early Medieval results is marginal when the 26 identified outliers are excluded from consideration (Fig. 2 and Table 1). Nevertheless, the range of $\delta^{18}O_c$ variation in each period (i.e., 5.2, 4.3 and 6.3‰, respectively, or 4.0, 3.4 and 4.9‰ with "outliers" excluded) is notably larger than the 2‰ often assumed to represent a nonmobile population (e.g., Prowse et al., 2007).

Faunal enamel oxygen isotope results

The data from archeologically derived faunal teeth are given in Supporting Information Table S2, sample size is limited as few contemporary fauna samples were available. The animal enamel carbonate results were converted to drinking water values ($\delta^{18}O_{dw}$), reported on the VSMOW scale as described earlier (Fig. 3). The faunal samples give mean $\delta^{18}O_{dw}$ values of -6.9 ± 0.3‰ for the Iron Age, -8.1 ± 2.1‰ for the Roman period (or -7.2 ± 1.5‰, with outliers removed) and -6.9 ± 2.3‰ for the Early Medieval period (or -6.4 ± 1.5‰ excluding the outlying sample). There are no statistical differences between the three periods, with or without the inclusion of the statistical outliers (Table 1; Fig. 3).

DISCUSSION

The clear statistical difference between human mean $\delta^{18}O_c$ shows that the water ingested by people in the three temporal periods had different mean $\delta^{18}O$ values. There are five possible explanations for this: (1) climate changed through time causing changes to the $\delta^{18}O$ value of precipitation; (2) different isotopic water sources (e.g., water derived from higher altitudes) were available at different sites; (3) individuals migrated from places with fairly similar oxygen isotope rainwater values for some or all of the period under discussion; (4) different water sources were utilized to differing degrees across the time periods analyzed; and (5) human manipulation of water led to alteration of $\delta^{18}O$ values.

Did the $\delta^{18}O$ value of precipitation vary through time? As precipitation oxygen isotope values are closely linked to climate, climatic change since the beginning of the Iron Age could lead to alteration of the $\delta^{18}O$ value of precipitation through time, and this could explain the shift in human $\delta^{18}O$ values. To test this possibility we compared modern water oxygen isotope values to archeological animal values, making the assumption that animals are more likely to consume water directly from precipitation than humans. If the changes in human $\delta^{18}O_c$ values are linked to changes in the $\delta^{18}O$ value of precipitation, one ought to see similar changes in animal $\delta^{18}O_c$ values when converted to $\delta^{18}O_{dw}$. However, if the animal values remain consistent throughout the entire temporal sequence under consideration, then changes in the $\delta^{18}O$ value of precipitation cannot be offered as an explanation for the human $\delta^{18}O_c$ pattern.

The faunal data indicate that there are no statistical differences in $\delta^{18}O_{dw}$ through time, although we note that there are numerous problems with the conversion of animal $\delta^{18}O_c$ values to $\delta^{18}O_{dw}$ values. While the species-specific conversion equation should account for variability in $\delta^{18}O$ due to body size, physiology, and metabolism, diet and drinking behavior may well vary within species with environmental context. It should also be recognized that the conversion equations are based on limited sample sizes from a limited range of environments. These issues likely account for some of the variation seen within the dataset for the Roman and Early Medieval periods.

These data can also be compared to published direct measurements on modern water from the region. These indicate that the River Krka near Šibenik has $\delta^{18}O$ values ranging from -7.8 to -6.8‰ (Lojen et al., 2004), and the mean $\delta^{18}O$ value of Zadar precipitation is -5.6‰ while that for Komiža on Vis is -6.3‰ (although note that these estimates are based on only three years of observations; Vreča et al., 2006). Estimations of modern precipitation oxygen isotope values using www.waterisotopes.org gives a $\delta^{18}O$ value -6.4‰ for Šibenik. Hence, despite the small sample size, the range of species in question and the errors associated with the conversion equations, the animal results are remarkably consistent, and suggest that there was little change in the oxygen isotope value of the water ingested by the analyzed fauna throughout the periods under study.

The animal data are further supported by both terrestrial and marine paleoclimatic records, which indicate a warm and dry Roman period, followed by a warm mid-Medieval period (Sangiorgi et al., 2003; Rudzka et al., 2012). If climatic change resulted in a shift of water oxygen isotopic values, this should have increased the Roman and mid-Medieval $\delta^{18}O$ values relative to the Iron Age and earlier Medieval samples, which is not the pattern seen here.

Does geographic variation in the $\delta^{18}O$ value of precipitation account for the differences? The shift in human $\delta^{18}O_c$ values could also be a reflection of the availability of different isotopic sources of water at different sites through patterning in the precipitation oxygen isotope values, or through the use of water derived from higher altitudes. If so, then the location of sites may lead to patterning in the isotopic results.

There is no apparent patterning in results with location when all sites are considered. Excluding Vis Bandirica (which is further south and on an island), the sites are spread across a NE-SW transect of ca. 100 km. The most northerly site, Nin-Ždrijac, has a very similar mean $\delta^{18}O_c$ value to the site located furthest to the south, Glavice Gluvine (mean values −5.1 and −5.2‰, respectively), with no patterning in the results with location. It is likely that inter-annual differences in the weather, combined with the small geographical range and the large range in the human $\delta^{18}O_c$ values, mask any potential patterning with location. After all, the large number of analyzed humans from the UK only permits a distinction between east and west Britain (Evans et al., 2012).

Beginning with the Iron Age, there is a marginal statistical difference between Dragišić and Nadin-Gradina, while neither site is different to Zadar-Relja. Such results may reflect an environmental difference in the $\delta^{18}O$ values of precipitation within this period, for Dragišić has the highest $\delta^{18}O_c$ values in this study. However, Dragišić is located close to the Early Medieval site Šibenik-Sveti Lovre, which has a 1.5‰ lower mean $\delta^{18}O_c$ value. There are no statistical differences between sites in the Roman period. The results from Vis Bandarica, the site with the most different geographical location (furthest south and located on an island) fall within the range of variation in both of the other two Roman datasets. Differences in mean $\delta^{18}O$ values between sites exist in the Early Medieval period, with Nin-Ždrijac standing apart from Radašinovci Vinogradine and Velim Velištak, while Glavice Gluvine stands apart from Radašinovci Vinogradine. However, these differences are neither correlated with site location nor date, and therefore some other factor must be responsible for the variation.

While the sample size is too small to be considered representative from the Iron Age samples from Zadar-Relja, we note that the results are lower than those from this site dated to the Roman period, which fits with the overall pattern seen between periods. This adds to our other evidence that the changes seen through time are real differences rather than a mere artifact of sampling bias.

There may be, indeed there probably are, differences between the sites in terms of the $\delta^{18}O$ values of precipitation, however, these are likely masked by the large range of variation seen within human $\delta^{18}O_c$ values, even at those sites with a small sample size. We therefore conclude that variation based on site locations between time period do not account for the changes in human $\delta^{18}O_c$ values seen through time.

Does the presence of migrants account for the differences in oxygen isotope values between periods? The changes and wide range of variation in human $\delta^{18}O_c$ values through time could be accounted for by the presence of migrants in the burial populations. To consider this scenario, we will first use statistical methods to identify migrants within the analyzed sample.[1]

When all 329 individuals are considered together, no individual lay more than 1.5 times the interquartile range below Quartile 1 or above Quartile 3. Some 19 individuals (5.8%) lay more than two standard deviations from the mean, yet none appear to be outliers by visual inspection of Figure 2. When the results are analyzed by period, no outliers are detected by IQR, but 15 (just under 5%) outliers are detected by standard deviation. These include one individual from the Iron Age, two from the Roman period and 12 from the Early Medieval period. When considered by site, four outliers are identified by IQR compared to twelve by standard deviation. In total, 26 of the 329 individuals are identified as outliers by one or more of these analyses (Table 3), but only five (1.5%) are identified as outliers through the standard deviation analysis of the entire sample set.

Although, these two different statistical techniques identify a limited number of individuals as “migrants” when compared to the “local” individuals from all periods under discussion, none of their $\delta^{18}O$ results may be considered unusual. It remains entirely possible, therefore, that all of the individuals analyzed in this study were born in the Ravni Kotari. As such, long-distance migration is unlikely to account for the patterning in human $\delta^{18}O_c$ values described above.

Alternatively, short- or medium-distance migration may account for the changing patterns and the wide ranges of variation in $\delta^{18}O_c$ values. In this scenario, people may have migrated from places with fairly similar oxygen isotope rainwater values during some or all of the period under discussion. Such migration would increase the range of variation, but not necessarily lead to distinct isotopic groupings.

We find this scenario unlikely due to the high number of migrants this explanation requires. Furthermore, on the basis of the archeological evidence one would expect the Roman period samples to have the highest proportion of migrants from the most varied locations and therefore have the widest range of $\delta^{18}O_c$ values. In actuality, the Roman period sample exhibits the smallest range of variation in the three periods considered. Given that the Iron Age sample size is smaller than the Roman, this is unlikely to be an artifact of sample size. While this scenario may account for some of the diversity in $\delta^{18}O_c$ values in this and other studies, it does not offer a satisfactory explanation for the changing $\delta^{18}O_c$ values through time.

Were different water sources available in different periods? The patterning seen in human $\delta^{18}O_c$ values could be accounted for by the use of different water sources with different $\delta^{18}O$ values. As noted above, precipitation, river water, well water, and standing pools were likely available during all periods under consideration. If these sources had different $\delta^{18}O$ values, then changes in the source of drinking water could account for the pattern seen in the human $\delta^{18}O_c$ results. Furthermore, the construction of aqueducts and the scale of coastal trade in the Roman period could have made nonlocal water available to a proportion of the population of the Ravni Kotari (Wilkes, 1969; http://www.romaq.org and references therein). The shift toward more depleted human $\delta^{18}O_c$ values in the Roman period compared to the Iron Age fits with the consumption of water derived from higher altitudes.

Did human manipulation of water lead to changes in its $\delta^{18}O$ value? Finally, changes in the way that people processed water and food could have led to alterations in the human $\delta^{18}O_c$ values through time. It is well

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[1] Due to the wide range of variation in the human results, coupled with ambiguities in the choice of equation that can be used to convert human $\delta^{18}O_c$ values to $\delta^{18}O_{dw}$, it is not possible to identify migrants securely based upon differences from a determined local signal.

TABLE 3. Outliers identified by different subdivisions of the data and using different identification techniques

Period	Samples	*n*	IQR outliers	St dev outliers
Iron Age	Dragišić	10	1 (DR012)	1 (DR012)
	Nadin	22	1 (NP005A)	1 (NP005A)
	All	38	0	1 (DR012)
Roman	Zadar Relje	38	0	1 (ZRTC0156)
	Vis-Bandirica	5	0	0
Late Antique	Podvršje	11	0	0
Roman and Late Antique	All	54	0	2 (PG007A, ZRTC0156)
Early Medieval	Nin-Ždrijac	50	0	2 (NZ037, NZ328)
	Velim Velištak	92	0	1 (VV100)
	Glavice Gluvine	18	0	1 (GG049)
	Radašinovci Vinogradine	52	0	3 (RV002, RV014, RV092)
	Šibenik-Sveti Lovre	25	2 (SSL150, SSL202A)	2 (SSL150, SSL202A)
	All	237	0	12 (NZ037, SSL150, SSL202A, VV045, VV058, VV082, VV087, VV100, VV109, VV117, VV137, VV167)
All	All	329	0	19 (DR001, DR008, DR010, DR011, NP005A, ZRTC0045, ZRTC0156, NZ037, SSL150, SSL202A, VV045, VV058, VV082, VV087, VV100, VV109, VV117, VV137, VV167)

attested that food and drink preparation strategies can lead to changes in ingested water oxygen isotope values. Such preparation strategies include brewing, boiling, stewing, and alkaline cooking, which have been shown to induce isotopic changes as large as 10.2‰ (Daux et al., 2008; Warriner and Tuross, 2009; Brettell et al., 2012). The consumption of wine could also influence human $\delta^{18}O_c$ values. While fermentation has relatively little effect on the $\delta^{18}O$ values of grape juice and the resulting wine (up to 1.7‰; Dunbar, 1982a), the oxygen isotopes in grape juice are altered from the ground water value through evapotranspiration during the growing season (up to +7.2‰; Dunbar, 1982b; Ingraham and Caldwell, 1999). Such changes could therefore account for some or all the patterns seen in the human $\delta^{18}O_c$ values presented here.

Why did ingested water $\delta^{18}O$ values change?

The first three options discussed previously do not account for the patterns seen in the human $\delta^{18}O_c$ results nor does the other available evidence does not support these hypotheses. Instead, we suggest that one or both of the fourth and fifth options offer the best explanation for the shift in isotopic values over time. These are: differential utilization of multiple water sources across the periods analyzed; and human cultural manipulation of ingested water leading to variations in its isotopic composition.

The patterning of the results suggests that a change in water source and/or a different means of human modification of the isotopic signal of ingested water was introduced in the Roman period and led to a shift in the isotopic values of the individuals sampled. During the Early Medieval period, this source or means of isotopic modification remained available to some of the individuals studied, particularly those individuals at Nin-Ždrijac, Glavice-Gluvine, and some individuals at Velim-Velištak, but was not available to everyone. From these data, it is likely that Roman and Early Medieval people consumed water with a low $\delta^{18}O$ value compared to the water ingested by Iron Age individuals. We suggest that the most likely explanation for such a shift toward lower $\delta^{18}O$ values is the importation of isotopically depleted water from higher altitudes via aqueducts. Alternatively, the data could reflect a shift away from an Iron Age behavior, such as brewing or stewing, that increased $\delta^{18}O$ values. Considering that people in the past likely avoided contaminated water through the consumption of beer and/or wine, varying amounts of brewing and vinification may well account for the different oxygen results through time.

We believe, based on the fact that aqueducts are known to have been constructed during the Roman period and most likely continued in use during the subsequent Early Medieval period, that importation of water from higher altitudes in the Roman period is the more compelling of these two explanations for the shift in human $\delta^{18}O_c$ values. Although it is likely that differences in food preparation account for some of the range of variation in human $\delta^{18}O_c$ values here and in other studies, it is hard to envisage such differences as being solely responsible for the magnitude of the shift that we see from the Iron Age to the Roman period, but here we are in the realms of speculation. It is important to note that whichever explanation is preferred it did not affect the ingested water of animals, which show no change in $\delta^{18}O$ over time, indicating that at some point in time the inhabitants of Dalmatia utilized water sources that were isotopically distinct from the water ingested by their animals.

What, then, does this tell us about the social aspects of water consumption? If we accept the construction of aqueducts as the most likely cause for the pattern seen here, aqueducts represent large-scale public works carried out in the Roman period in response to the need for water. If consumption of water from high elevations is the likely cause of low $\delta^{18}O_c$ values, then it may be that the shift to higher $\delta^{18}O_c$ values during the Early Medieval period suggests that some members of the population had access to and utilized water from aqueducts, while others did not. With the collapse of the Western Roman Empire and the breakdown of centralized government, it is likely that some aqueducts fell into disrepair due to lack of maintenance. Those individuals who lived in areas with the specialized knowledge and financial resources to maintain an aqueduct might have been able to continue to use this water, while people in other areas may have had to have been reliant on natural water sources. Beyond aqueducts, cultural choices in food preparation may also have influenced the $\delta^{18}O_c$ values of the individuals analyzed here. Hence, temporal–cultural differences within a small geographic region may have led to measureable isotopic differences. Whichever of these explanations is preferred, it is clear that anthropogenic factors are highly likely to contribute to variation in isotopic signatures and the social dimensions of water consumption must be borne in mind in studies of this nature.

CONCLUSION

When carrying out diachronic and/or regional oxygen isotope studies it is often assumed that past populations accessed water from a single isotopic source. However, various sources of water are theoretically available in all time periods and locations—for example precipitation, river water, well water, and standing pools—while aqueducts, and traded food and beverages are more likely to have been prevalent during some periods than others. Furthermore, the effects of brewing and vinification, evaporation during storage or transport, seasonal storage of water and so on, can alter the isotopic composition of ingested water from that of the "local signal." It cannot therefore be assumed that people in different periods, people from neighboring sites and even people within a settlement consumed water that was isotopically the same. The results from this study show that further consideration is needed for our estimations of the "local signal," so that these estimations include the full range of potential isotopic sources, and that the use of a "local signal" to identify migrants is not always appropriate.

The difference in oxygen isotope results between periods was unexpected and while a conclusive explanation is not forthcoming, it does seem likely that these differences are the result of anthropogenic rather than climatic factors. Although more evidence is required before any hypothesis can be accepted, the most compelling explanation for the isotopic patterning reported here is the importation of water, via aqueducts, from the higher altitudes of the Dinaric Alps during the Roman period and its continued use by some individuals in the Early Medieval period. This serves as a reminder that the social dimension of water consumption needs to be considered in studies such as this because anthropogenic factors can lead to variation in isotopic signatures. Conversely, such factors can in themselves be productive avenues for archeological enquiry.

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