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Strontium isotopes as an indicator of human migration – easy questions, difficult answers

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ABSTRACT: Isotope analyses of bones and teeth allow us to study phenomena which occurred in the history of human species and which are difficult to capture by traditional anthropological methods. Measuring oxygen, nitrogen and carbon isotope levels in the skeleton makes it possible to reconstruct climatic changes, diet and/or the weaning process. Among isotopes used in such analyses are strontium isotopes, helpful in analysing migration and studying the mobility of historical and prehistoric human populations. In this respect, the proportion of two isotopes, the heavier ^{87}Sr and the lighter ^{86}Sr, is measured, following their extraction from the bioapatite of the bone mineral. Released from rocks in the weathering process, strontium permeates individual components of inanimate and animate environments, and then finds its way, together with food, to the human body. Thanks to comprehensive environmental studies and the measurement of the strontium ratio ^{87}Sr/^{86}Sr in various animal tissues it is possible to determine the local isotope background for the environment. Values obtained by analysing human skeletons referenced against the range of environmental isotope variability enable researchers to trace back the location inhabited by the individual or group.

KEY WORDS: human mobility, stable isotopes, ^{87}Sr/^{86}Sr, local isotope range

Introduction

Studying life stories of individuals from distant historical periods is not an easy task. All findings on historical human populations obtained by archaeological or osteological analyses are currently expanded by molecular tests. Researchers describing the history of our species began to use analyses of long-lived isotopes of several elements such as hydrogen (Hobson 1999; King 2012), oxygen (Hodell et al. 2004; White et al. 2004a), nitrogen (DeNiro 1987; Hedman et al. 2002; Pate et al. 2002), carbon (Scherer et al. 2007), sulphur (Fry et al. 1982; Schoeninger and Moore 1992; Oelze et al. 2012) and strontium, previously used e.g. in ecology (Reinhardt et al. 2001; Porder et al. 2003; Andrew Royle

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and Rubenstein 2004; Kennedy et al. 2005; Ravikant and Bajpai 2010; Julien et al. 2012), in paloeclimatic (Fricke et al. 1998; Prohaska et al. 2002) or geological research (Gorokhov et al. 2001; Kontak et al. 2001). Conclusions drawn from such investigations concern, among others, subjects related to such aspects of human life as migration or diet.

The origin of individuals and entire human groups is determined by methods which are based not only on paleogenetic analyses, but also on archaeological artefacts. Other, skeleton-based approaches, involve craniometrical measurements, analyses of intentional skull or teeth modifications characteristic of various groups (Schweissing and Grupe 2000; Williams and White 2006; Andrushko et al. 2009; Spence and White 2009). Interdisciplinary studies are also carried out, in which researchers draw conclusions from analyses of both historical and archaeological material such as achievements of culture, architecture, inscriptions or reliefs as well as linguistic analysis. In addition, grave accessories, ceramics, jewellery, materials, garments etc. are also taken into consideration (Budd et al. 2004; Mitchell and Millard 2009; Price et al. 2010; Shaw et al. 2011; Knudson et al. 2012b). However, a description of the migrations of a given group based only on such analyses may be ambiguous: cultural metamorphoses may have their origins in migrations, but this is not a universal rule. On the other hand, internal cultural transformations occurring independently of the impact of other groups may lead to specific cultural convergences in spite of the physical separation of convergent populations. Another explanation for such convergence may be 'transfer of goods' in the form of payment, exchange or theft (Price et al. 2010; Shaw et al. 2011). Also note that extant artefacts may constitute an incomplete representation of the flow of population, group dynamics or ethnic boundaries (Andrushko et al. 2009).

In early 20th century Erickson (1985; 1989) suggested the application of strontium isotopes in migration studies on prehistoric populations. The technique has been successfully used in anthropology ever since (including e.g. Price et al. 2000; Bentley et al. 2003; Knudson et al. 2005; Price et al. 2008; Richards et al. 2008; Bastos et al. 2011) in studies from different parts or the world such as Africa (Cox and Sealy 1997; Stanley et al. 2003), Europe (Schweissing and Grupe 2000; Haak et al. 2008; Richards et al. 2008; Knudson et al. 2012b; Kendall et al. 2013), Asia (Haverkort et al. 2008; Mitchell and Millard 2009; Gregoricka 2013; Kenoyer et al. 2013), both Americas (English et al. 2001; Hodell et al. 2004; White et al. 2007; Andrushko et al. 2009; Eerkens et al. 2010; Price et al. 2010; Thornton 2011; Wright 2012) and Oceania (Bentley et al. 2007; Shaw et al. 2010; Shaw et al. 2011). Isotope studies use material from different historical periods, starting from the beginnings of the human species (Horn et al. 1994; Sillen et al. 1995; Sillen et al. 1998) and prehistory (Haak et al. 2008; Haverkort et al. 2008; Gregoricka 2013), through the Middle Ages (Mitchell and Millard 2009; Knudson et al. 2012b; Kendall et al. 2013) up to contemporary times (Voerkelius et al. 2010; Holobinko 2012).

Strontium isotopes – basic information

Strontium is an alkaline metal, naturally occurring in the form of two minerals: strontium sulphate ($SrSO_4$), also called celestine, and strontium carbonate ($SrCO_3$), also called strontianite. Of all strontium isotopes, the most important and longest-lived ones include ^{84}Sr, naturally occurring in 0.56%, ^{86}Sr, which constitutes 9.87% of total quantity of strontium in the environment, ^{87}Sr with an abundance of 7.04% and ^{88}Sr with an abundance of 82.53% (Schweissing and Grupe 2000; Audi et al. 2003; Bentley 2006; Kenoyer et al. 2013). Among the above isotopes, ^{87}Sr deserves special attention. Although a long-lived form of the element, it is formed by radioactive decay of another element, namely rubidium (^{87}Rb; half life 4.88 x 10^{10}) (Price et al. 2000; English et al. 2001; Knudson et al. 2005; Price et al. 2006; Thornton 2011). Rubidium is also an alkaline element, a component of many minerals such as muscovite or biotite, and – due to the aforementioned dependency between rubidium and strontium – the measurement of its abundance is strictly connected with the discussed subject (Capo et al. 1998; Price et al. 2002; Bentley 2006; White et al. 2007). In all research concerning the application of strontium isotope analysis in migration studies, the unknown is expressed as the ratio of the two aforementioned isotopes, namely the heavier isotope ^{87}Sr to the lighter isotope ^{86}Sr (e.g. Faure 1986; Price et al. 2000; Wright 2005b). The natural ratios found in such analysis is generally contained within the 0.700–0.750 range (Price et al. 2002; Kenoyer et al. 2013).

The use of isotope studies in the context of tracing movements of prehistoric populations results from geographical variability of measured levels of ^{87}Sr/^{86}Sr between distant environments. The variability of strontium isotope ratios depends on several factors associated with geological characteristics of the site, and location-specific ^{87}Sr/^{86}Sr ratio results from the age and type of the parent rock (Price et al. 2006; Kenoyer et al. 2013; Thornton 2011). Strontium isotope ratio is modified so that, depending on the type of bedrock, other initial values of ^{87}Sr/^{86}Sr are observable, which vary over the time in which ^{87}Rb becomes transformed into ^{87}Sr. Such dependence equally indicates an important relationship to initial ^{87}Rb concentration and ^{87}Rb/^{86}Sr proportion to the source material (Faure 1986; Price et al. 2000; English et al. 2001; Budd et al. 2004; Hodell et al. 2004; Wright 2005a; Price et al. 2006; White et al. 2007; Price et al. 2010; Thornton 2011; Knudson et al. 2012a; Gregoricka 2013). If there is no flow of Rb and Sr between the rock and the environment present during the rock formation, ^{87}Sr increases at the expense of ^{87}Rb, and the percentage of other strontium isotopes in the rock remains unchanged. Consequently, Rb/Sr ratio measurements are already used in geochronology (Stern and Hedge 1985; Capo et al. 1998; Bentley 2006; Kenoyer et al. 2013).

Rocks formed more than 100 million years ago and characterised by a high original Rb/Sr value have a relatively high proportion of heavier strontium isotope to the lighter strontium isotope, ranging from 0.7010 to 0.740. Newer rocks which were formed less more than 1–10 million years ago contain a relatively low Rb/Sr ratio, and have a lower ^{87}Sr/^{86}Sr proportion, i.e. between 0.702 and 0.704 (English et al. 2001; Bentley 2006; Price et al. 2006; Gregoricka 2013; Kenoyer et al. 2013). The question of rock origin, inextricably linked with the interdependence between both elements, is also significant. Small amounts of rubidium are present in the Earth's mantle, but its large deposits are found in the crust. Rocks from the continental crust such as granite or rhyolite contain large amounts of ^{87}Rb, which is manifested in high isotope values of about 0.716. Minerals which originated from the Earth's mantle contain little ^{87}Rb, consequently demonstrating low ^{87}Sr/^{86}Sr ratio, as exemplified by volcanic rocks of isotope levels ranging from 0.703 to 0.704 (Hodell et al. 2004).

Isotope levels of the hydrological component result from the isotopic contributions from the atmosphere and, for the most part, of mineral weathering products. In large water basins, the ^{87}Sr/^{86}Sr level is a product of the impact of weathering on the continental crust of the entire planet. The mixing of water provides the stability and independence of the above values from the depth and geographical location of deposits. In our planet's history, the ^{87}Sr/^{86}Sr ratio for water was subject to variation, as can be found by analysing marine carbonates. Currently it equals 0.7092 (Capo et al. 1998; Ehrlich et al. 2001; Hodell et al. 2004; Knudson et al. 2005; Gregoricka 2013).

Biochemical characteristics of the osteological material

Biochemical tests on historical human remains may be based on bones and teeth owing to their molecular structure (Bentley 2006; Lee-Thorp and Sealy 2008; Chenery et al. 2010; King et al. 2011). Bones are composed of mineral and organic fraction, each carrying different biochemical information (DeNiro 1987; Hedman et al. 2002; White et al. 2004a; Niedźwiedzki and Kuryszko 2007). The bone mineral, a non-soluble crystalline lattice, is built from apatite of a general formula $Ca_{10}(PO_4)_6(OH)_2$. Apatite is modified as necessary by various processes occurring in the body. Strontium and its isotopes, due to their strong chemical similarity to calcium and its atomic radius (Sr 1.32 Å, Ca 1.18 Å), become incorporated in the crystalline lattice by substituting calcium. Strontium concentration in hard tissues ranges from 40 to 400 ppm (Faure 1986; Price et al. 2000; Schweissing and Grupe 2000; Knudson et al. 2005; Wright 2005a; Fenner 2008; Richards et al. 2008; Thornton 2011; Knudson et al. 2012b; Gregoricka 2013; Kendall et al. 2013).

The choice of bones or teeth as a material for isotope analyses is linked to differences in their chemical and physical structure. The first difference is in the proportion between the organic and inorganic fraction. Bones are built in approx. 70% from inorganic ingredients, the remainder comprising organic components (about 20%) and water (nearly 10%), whereas enamel is composed in 97–98% of minerals and in 2–3% of the organic fraction (Maziarski and Nowicki 1954; Pate 1994; Hoppe et al. 2003).

Other differences include the tissue's biological activity after its formation period. Having been shaped in the early stages of life, enamel remains unchanged until death as a metabolically inactive tissue. Since enamel formation phases are strongly determined and well-studied by researchers, information on strontium isotope levels can be precisely referenced to a specific period of an individual's life, depending on tooth generation and type (Maziarski and Nowicki 1954; Lee-Thorp and Sponheimer 2003; Budd et al. 2004; White et al. 2004c; Daux et al. 2005; Dupras and Tocheri 2007; Haverkort et al. 2008).

In contrast, bone undergoes elemental remodelling, which involves the change of the elemental composition of the newly formed hydroxyapatite, depending on the environment in which the new crystal is generated (White et al. 2004c; Wright 2005a; Price et al. 2006; Niedźwiedzki and Kuryszko 2007; Kenoyer et al. 2013). Bones are continuously remodelled thanks to regularly appearing ossification centres, and the tempo of the changes is determined not only by the metabolic level of the individual, but also by the type and structure of the bone (compact or spongy substance) in which they occur. Information on the isotope composition of the bone dates back to a period of 10 to 20 years before the death of the individual, and the remodelling process takes longer in adults than in children (Schweissing and Grupe 2000; Hodell et al. 2004; Haverkort et al. 2008; Stepańczak et al. 2014).

Diagenesis

The condition of bone material deposited underground is another important aspect of biochemical studies. Taphonomic changes which occur *post mortem* have an damaging effect on the remains, and in extreme cases prevent researchers from drawing reliable conclusions. Detecting alterations in the elemental composition of bones and teeth is a vital part of the analysis, as it allows us to establish whether the results reflect the *intra vitam* composition of isotopes. Enamel is characterised by a greater crystallinity and lower porosity than bone, which, together with a reduced amount of the organic fraction, makes it the hardest tissue in the body, relatively resistant to post-mortem alterations. Note that although enamel is more likely to retain its original biological signal than other parts of the skeleton, it does not necessarily follow that teeth are completely immune to contamination (Maziarski and Nowicki 1954; Wright and Schwarcz 1996; Hodell et al. 2004; Daux et al. 2005; Knudson et al. 2005; Wright 2005b; Lee-Thorp and Sealy 2008).

In comparison to other isotopes used in anthropological research, strontium isotopes are not as significantly affected by diagenetic alterations in the skeleton. Therefore, the procedure whereby the outermost layers are stripped away and the sample is washed with weak acetic acid is used to remove major contamination areas, e.g. exogenous carbonates (calcite) (Price et al. 2000; Hoppe et al. 2003; Knudson et al. 2005). Still, the issue of contamination must not be neglected, as strontium incorporated in tissues *post mortem* may cause an overestimation of the final value, and thus the number of local individuals (Bentley et al. 2004).

Measurement techniques

Isotope abundance can be measured with several techniques, of which the most popular ones are ICP-MS and TIMS. The first method involves collecting samples e.g. by laser ablation (LA) technique, ionisation in inductively coupled plasma (ICP), followed by the separation of signals from ions which differ in mass-to-charge ratio (MS) (Vroon et al. 2008). The technique is commonly used in a number of fields such as geology, medical and natural sciences, and when studying historical objects which require both qualitative and quantitative analysis of elements or isotopes (Wagner and Bulska 1999; Becker 2002; Nowak et al. 2008; Szlasa-Byczek et al. 2008). The ICP-MS technique is popular due to low detectability threshold as well as the capability of performing simultaneous analyses of multiple isotopes.

Thermal ionisation mass spectrometry (TIMS) provides an accurate measurement of strontium isotope levels, in which a strontium ion beam is generated by passing current through a sample placed on a metal tube. This technique is popular for its high sensitivity. Even though it requires time-consuming chromatic strontium isolation procedures, the sample for analysis is free of other elements' ions. The issue of isobaric interference during measurements is minimised when compared to ICP-MS. In addition, analyses performed by the TIMS approach provide points of reference for precise measurements of heavy isotopes by means of other methods (Walczyk 2004). Figure 1 shows a schematic sample preparation for TIMS protocol. The entire ICP-MS procedure is radically simplified and the experiment takes less time, so the output is 20–30 samples per day. In contrast, for TIMS the value is only 4–5 samples/day (Ehrlich et al. 2001; Walczyk 2004; Vroon et al. 2008).

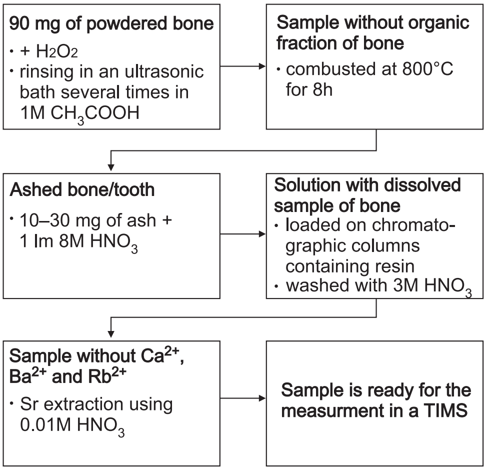

Fig. 1. Sample preparation procedure for TIMS-protocol measurement

In order to compare final results between various research centres, measured isotope levels are referenced against a standard, usually NIST SRM 987 (Schweissing and Grupe 2003; Hodell et al. 2004; Tung and Knudson 2011; Chenery et al. 2010).

Strontium isotopes and paleoenvironmental background

The use of isotope techniques in reconstructing migration processes of human populations is based on differences in isotope compositions of environments in relation to one another. Ultimately, isotope levels in bones should correspond to those in food, as the strontium released from the substrate is carried through the soil, down the food chain, and finally to the human body (Figure 2) (Budd et al. 2004; Hodell et al. 2004; Price et al. 2006; Mitchell and Millard 2009). Therefore a key step in isotope studies, but at the same time one of the most problematic ones, is to determine the level to be defined as the local value to establish whether the analysed samples represent individuals who inhabited the region. Long-lived strontium isotopes have a feature by which they differ from isotopes of lightweight isotopes such as oxygen and nitrogen. This characteristic is the lack of measurable fractionation, a naturally occurring phenomenon. Fractionation means that chemical compounds containing diverse isotopes require supplying a different amount of energy to break or form chemical bonds. The fractionation process is observable when compounds containing different isotopes are transferred to a higher level in the trophic chain and in the course of various biochemical processes, which results in a shift of isotope proportions (Schoeninger and Moore 1992; Budd et al. 2004; White et al. 2004b; Daux et al. 2005). The absence of fractionation in the case of strontium isotopes can be explained by a small difference in the masses of the various forms of the element (Schweissing and Grupe 2000; Price et al. 2006; Fenner 2008; Thornton 2011; Knudson et al. 2012b). Nevertheless, it must be noted that while there are no changes in isotope proportions in consecutive stages of the food chain, a reduction of total strontium content is noticeable as a result of preferential calcium absorption in the body (Blum et al. 2000; Balter 2004; Knudson et al. 2005).

There are several methods of determining local isotope levels. Some techniques are based on descriptive statistics (Wright 2005a; Knudson et al. 2012a). One of more common methods is to classify as non-locals individuals whose strontium isotope level falls outside the second standard deviation from the mean reported for the entire sample (Price et al. 1994; Wright 2005a; Waterman et al. 2014). The success of this approach strongly depends on factors such as the number of individuals in the group, the percentage of immigrants and the natural, local isotope variability of the region. In some cases, due to variability itself, the scope of two standard deviations may fail to include total isotope variability of the region, and, on the other hand, be too broad in reference to the area of interest (Wright 2005a; Shaw et al. 2011; Tung and Knudson 2011).

Worth mentioning is also a method based on creating division rows. Data are grouped by growing levels, and differences between adjacent classes are calculated. The amount of differences is used to establish likely immigrants by finding outliers (Tung and Knudson 2011).

Another approach is to compare the values obtained from human tissues to values directly measured in parent rocks. As strontium isotope level in living or-

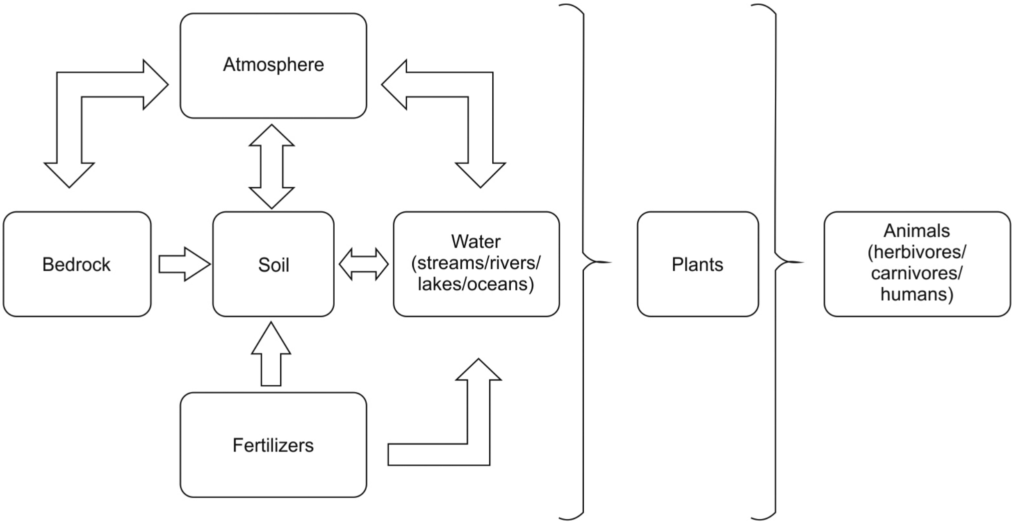

Fig. 2. Strontium transfer between ecosystem components

ganisms depends on the isotope background of the substrate, the attempt to treat the value as local seems logical (Ezzo et al. 1997; Grupe et al. 1997; Shaw et al. 2011). Differences across regions may be established on the basis of geological sources providing data on the age and type of rocks (Hodell et al. 2004; Mitchell and Millard 2009).

In practice, the method is far from perfect, which results from diverse properties of minerals forming the bedrock as well as complex geological structure of the entire area. Certain rock types are built of various minerals of different composition and properties, which leads to erratic distribution of strontium in the rock. Such structure may result from the presence of several types of feldspars, an example of which are gneiss and granite (Bentley 2006). Minerals such a biotite, muscovite and K-feldspar are rich in strontium–87. Other feldspars, such as plagioclase, have high calcium and strontium content with little Rb, hence low $^{87}Sr/^{86}Sr$ ratio (approx. 0.700). In contrast, potassium feldspars, forming a large percentage of granites, contain mostly rubidium but only a little strontium, which results in high measured isotope levels (in the region of 1.0). In addition, individual minerals have different susceptibility to environmental conditions, e.g. quartz is susceptible to weathering only to a small extent, which is quite significant for Sr transfer through consecutive components of the environment (Capo et al. 1998; Price et al. 2002; Bentley 2006; Sjögren et al. 2009).

The lack of homogeneity of the substrate leads to a high diversity of terrain in terms of strontium isotope values, and the scale of the diversity may be considered locally or globally. The extent of inter-regional differences should be high enough to enable detection of individuals' relocation, whereas any considerable variability of local $^{87}Sr/^{86}Sr$ values should not obscure differences between areas in other regions. With high variability of strontium isotopes over a limited area, we may interpret mobility within a small territorial range (Hodell et al. 2004; Waterman et al. 2014). Accordingly, we may notice that simply collecting samples from geological material and testing $^{87}Sr/^{86}Sr$ ratio should not constitute the only point of reference in migration studies, but merely offer an outlook on the estimated range of the isotope concentration in the environment.

In the case of strongly diversified geology of the environment in terms of isotopes, the local value may also be determined by measuring surface water, soil and plant samples (Budd et al. 2004; Hodell et al. 2004; White et al. 2007; Knudson et al. 2012b). As part of biosphere, not only does soil absorb Sr from bedrock, atmosphere or waters, but also acts a strontium donor through mineral weathering and the sorptive complex. Outside the sorptive complex, plants absorb Sr from weathered minerals, and, to a large extent, from the atmosphere, although it must be stressed that water is the key factor determining the value of the $^{87}Sr/^{86}Sr$ ratio in local flora. As a result, plant and animal tissues reveal high uniformity within strontium isotope ratios over the area of investigation (Gosz and Moore 1989; Capo et al. 1998; Bentley 2006; Price et al. 2002).

In light of the above information it is clear that when determining isotope points of reference in reconstructions of prehistoric populations' movements, the geological $^{87}Sr/^{86}Sr$ proportion may differ from $^{87}Sr/^{86}Sr$ in other components of the environment, as Sr isotope levels in such components may in reality be a product of various isotopes of the same element. Geological isotope level is generally different from that of living organisms, so the key to obtaining the local value, which in the case of local individuals will correspond to the values obtained for skeletons, is to determine the level of biologically available strontium. This, in turn, necessitates a thorough analysis of the environment and interdependencies between its components (Budd et al. 2004; White et al. 2007; Shaw et al. 2011; Gregoricka 2013; Kenoyer et al. 2013).

A common method of determining the regional value of isotope ratios in migration studies, not only for strontium, but also e.g. for oxygen, carbon and nitrogen isotopes, is to analyse animal remains from the area on which the graveyard was kept (Price 2002; Budd et al. 2004; White et al. 2004b; Bentley 2006; Szostek 2009; Knudson et al. 2012b; Shaw et al. 2011). A basic method of ascertaining the local Sr isotope level involving animal material is to determine the mean for all measurements, with the variability range for the entire area restricted to two standard deviations. The analyses may use contemporary animals or animals isochronous to the investigated human population (Grupe et al. 1997; Evans and Tatham 2004; Price et al. 2010; Gregoricka 2013). Local fauna provides a very reliable indicator of biologically available strontium, as many animal species live in close proximity of humans, and animal tissues reflect the natural complexity of the environment, especially if they date back to the same period as the investigated human population (Shaw et al. 2011; Knudson et al. 2012a).

The number of individuals in the animal species used as reference material is also significant. Some researchers in their studies use remains of small animals of relatively small feeding area like rodents. Another possibility is to examine skeletons of larger organisms. Analysis of large herbivorous species enables us to estimate the regional value for a larger area, since such animals eat various plant species growing all over the region, hence the $^{87}Sr/^{86}Sr$ ratio in their tissues is uniform for the entire region (Hodell et al. 2004; Knudson et al. 2005; Gregoricka 2013; Kendall et al. 2013). On the other hand, considering the limited area of their habitats, animals such as hares constitute potentially useful material for calculating the local range of values for Sr isotopes (Waterman et al. 2014). All of the above factors should be taken into account when selecting animals as reference material for studying migration. However, such parameters as animal size and its metabolic rate are not as important in analysing strontium isotope levels as in the case of studying oxygen isotopes (Budd et al. 2004; White et al. 2004b; Stepańczak et al. 2014).

The use of animal tissues is beneficial also from a statistical standpoint, since even with a limited amount of material the data obtained are characterised by relatively low standard deviation, variance and coefficient of variation; in comparison to small animals, values of the aforementioned parameters are even lower for larger species (Price et al. 2002; Haverkort et al. 2008; Gregoricka 2013).

When selecting reference material, additional benefits of the indicators of local $^{87}Sr/^{86}Sr$ level found on the site with animal skeleton should be considered. A distinct advantage of this approach is that tissues of animals co-existing with human populations represent isotope values which correspond to those of local individuals. The reason for the above observation is that, unlike in the case of contemporary animals remains, there is no exposure to contamination by atmospheric strontium, and changes in isotope levels related to the consumption of non-local nutrients in the form of fodder are limited (Fenner 2008).

Apart from the obvious benefits of using local fauna to determine the range of isotope variability of the region, there are also certain negative aspects. As mentioned before, animals living in close proximity of humans seem to be best indicators of local values. Such animals include, among others, cattle or pigs. Because of their dietary requirements and the fact that they often consume food almost identical to that eaten by humans, the isotope ratio of strontium measured e.g. in swine bones may be very precise and decisive in reconstructing the mobility of the population. Nevertheless, depending on the adaptive strategy of the group (nomadic or settled) or cultural determinants, some animal species are treated not only as food, but also as tribute, frequently playing complex roles in cultural and religious life (Bentley 2006; Bentley et al. 2007; Shaw et al. 2010; Shaw et al. 2011; Thornton 2011). This is best exemplified by pigs kept by tribes living in the Pacific, in which pigs were collected and exchanged as an indicator of social status. As a consequence, strontium isotope values obtained from pig remains show greater diversity than human tissues, which renders then useless in migration studies (Shaw et al. 2011; Thornton 2011).

There are multiple factors affecting the $^{87}Sr/^{86}Sr$ value which might suggest that the individuals moved during their ontogeny, although in fact they stayed in the same place (Figure 3). Establishing the economy, key nutrients or cultural behaviour is sometimes crucial for the correct interpretation of the results. Other sources of strontium in diets of certain populations may be related to the inclusion of Sr isotopes from other environments, which is a consequence of seasonal grazing in regions of different $^{87}Sr/^{86}Sr$ ratios or growing plants at certain distance from the settlement due to their requirements concerning e.g. soil type, and, last but not least, hunting for animals periodically present in the region (Wright 2005a; Andrushko et al. 2009; Tung and Knudson 2011; Knudson et al. 2012a).

The purpose of testing animals for isotope levels in tissues is not only to establish their local range, but also to reconstruct foreign policy and diplomacy. Mass feasts were often occasions on which standard diet was extended by luxury products, which could lead to the inclusion of non-local food. The origin of animals which were given as a gift to

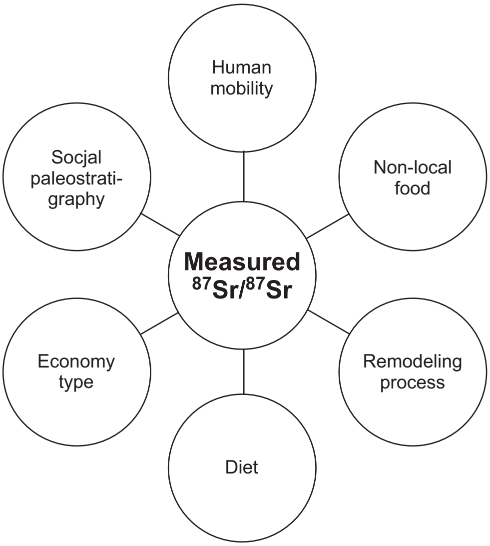

Fig. 3. Exemplary factors of Sr variability in human bones

hosts in certain populations may shed light on the range of political and economic contacts of the population (Thornton et al. 2011; Knudson et al. 2012a).

Factors affecting local isotope levels

The diversification of dietary components by introducing imported products exerts a significant impact, particularly in communities existing since the Middle Ages. The intake of products of non-uniform origin results not only in change in isotope level to a value different from locally established, but may also provide an explanation for the convergence of such values between two distant sites (White et al. 2007; Kendall et al. 2013).

The consumption of marine food such as fish, seafood or seaweed, which has significant influence on strontium isotope levels in tissues by bringing the $^{87}Sr/^{86}Sr$ ratios in bones and teeth closer to those measured in seawater, must not be overlooked (Knudson et al. 2005; Andrushko et al. 2009; Shaw et al. 2011; Knudson et al. 2012b; Gregoricka 2013). In addition, one must also consider the importance of atmospheric sources of strontium. In the case of coastal ecosystems, the air is enriched by aerosols from the breeze, which directly affects the soil, plants and land mammals, including humans, in a similar way as eating marine food. Note that precipitation in the vicinity of water regions demonstrates isotope ratios approximating those of the nearby water basin, but final strontium content is lower by several levels of magnitude (Capo et al. 1998; English et al. 2001; Hodell et al. 2004; Shaw et al. 2011; Knudson et al. 2012b). The concentration of individual isotopes at the site may be altered not only by the proximity of large water basin as seas and oceans. Weathering of minerals of different groups than the parent rock may be equally responsible for this phenomenon, as the products of this process are also supplied to plants from the air (Hodell et al. 2004).

Strontium is, to a large extent, absorbed by organisms together with minerals, e.g. in the form of salt. Among other elements, salt includes calcium, which is often substituted by strontium (Wright 2005a; Andrushko et al. 2009; Knudson et al. 2012b). In the history of our species, sea or land salt was a precious raw material, which is best proven by the fact that it was transported over very large distances. In certain communities the possibility of including salt in the diet resulted from an individual's high socio-economic status, because salt was treated as a luxury commodity. This may have caused some of the differences in isotope levels in human tissues within a single population. This relationship holds true for many other foodstuffs such as cacao (Wright 2005a; Knudson et al. 2012b). In situations like these, it is helpful to reconstruct trade routes or, as in the case of salt, the locations where it was mined or dried.

Strontium is consumed in large amounts along with calcium-rich products, which apart from salt, include eggs, milk and milk products. In addition, plants growing on calcium deposits contain values similar to plants such as maize, which are fertilized with substances with high Ca content. When a plant like maize, requiring substances containing calcium for its normal growth, constitutes the main component of the diet, such foreign substances should be considered the key determinant of the isotope level of the skeleton (Schutkowski

2001; 2002; Szostek et al. 2005; Wright 2005a; Shaw et al. 2011; Knudson et al. 2012b).

Analysing honey is an interesting method of determining reference values for strontium isotopes in migration studies (Voerkelius et al. 2010). Honey is made from flower pollen and secretions of insects which feed on plants. Due to its flavour, nutritional and therapeutic properties, honey is a highly valued element of human diet, largely thanks to about 300 chemical substances it contains. Apart from sugars, its ingredients include micro- and macronutrients, and strontium in the amount of 1.02–30.67 mg kg^{-1} (Hernández et al. 2005; Chudzinska and Baralkiewicz 2010; Shantal Rodríguez Flores et al. 2014). When collecting nectar, honey bees are exposed to every part of the environment such as water, air or soil. It is estimated that the area covered by these animals is about 7 km^2, so honey tests reveal the range of the variability of isotope ratios from the specified area. The usefulness of honey as the indicator of the local ^{87}Sr/^{86}Sr level is additionally enhanced by the fact that the honey-making process is totally independent from humans or other production technologies (Rashed and Soltan 2004; Hernández et al. 2005; Madejczyk and Baralkiewicz 2008; Schellenberg et al. 2010; Chudzinska and Baralkiewicz 2010; Chudzinska and Baralkiewicz 2011; Chua et al. 2012; Yücel and Sultanoğlu 2013; Shantal Rodríguez Flores et al. 2014). A drawback of honey as reference material is the fact that, along with mineral substances and other ingredients, it contains anthropogenic contaminations modifying strontium levels (Sanusi et al. 1996; Négrel and Deschamps 1996; Probst et al. 2000).

Isotope analysis

Investigating migrations and interpreting the results may take place on several levels. One of the possibilities is to conduct a detailed analysis of individuals in groups, involving measurements of several samples collected from one skeleton. Such tests, performed on the level of an individual, enable us to recreate the history of a human being. A population-level study provides the observation of relationships between individuals and reconstructing various patterns of behaviour of individuals within the population. In contrast, inter-group comparisons enable the group to be set off against other populations (Schweissing and Grupe 2000; White et al. 2004c; Dupras and Tocheri 2007; Haverkort et al. 2008; Szostek, 2009). Isotope tests are based on the principle that the isotope ratio in tissues of local individuals should vary in the range defined as local, whereas the ^{87}Sr/^{86}Sr ratio for individuals of allochthonous origin will fall outside the defined limits (Price et al. 2000). However, the above principle is not straightforward. There might have been migrations within a certain population, but they could remain undetected, as the variability of ^{87}Sr/^{86}Sr across various areas is relatively low, which often complicates reliable interpretation on the basis of gathered data (Spence and White 2009). An important step is to determine to what extent the diversity of ^{87}Sr/^{86}Sr levels results from the individuals moving in relation to geologically varied surroundings, and to what extent it corresponds to local variation between individuals (Shaw et al. 2011). When comparing isotope ratios of human skeletons with the range of biologically available strontium, one must remember that not all strontium from the region is absorbed by the body, but only the ^{87}Sr/^{86}Sr proportion which holds for the food (Tung and Knudson 2011).

If several samples from the same skeleton are analysed, there is a possibility of verifying the places where the individual lived at consecutive stages of his or her ontogeny. Differences in ^{87}Sr/^{86}Sr measured in bones relative to values reported for enamel, which carries information on the individual's dwelling place in childhood, suggest not only the individual's mobility, but also the duration since the dwelling location had been changed (Hodell et al. 2004; Knudson et al. 2005). Elemental remodelling in bones is a continuous and long-term process. For this reason, the time during which individual resided in the area in which the remains were found is one of the factors affecting the ^{87}Sr/^{86}Sr ratio in bones. Accordingly, isotope levels in tissues approximating the range defined as local may indicate a relatively long dwelling period of the individual in the same region. The principle behind this is that bone remodelling process led to a partial substitution of strontium isotopes for those of local origin. An alternative explanation is time spent in a location with a similar level of ^{87}Sr/^{86}Sr to that of the investigated area (Price et al. 2000; Spence and White 2009). Unfortunately, due to the bone remodelling process, obtaining information on short-term migration episodes in the life of analysed individuals is impossible (White et al. 2004c; Andrushko et al. 2009; Mitchell and Millard 2009).

Oxygen isotopes

Migration analyses with the use of isotope techniques may be conducted not only by measuring ^{87}Sr/^{86}Sr ratios, but also proportions of other isotopes, e.g. oxygen (Longinelli, 1984, McGlynn, 2007). Geographical diversity of oxygen isotopes, expressed by the value δ^{18}O[‰], depends on weather conditions such as temperature or total annual precipitation; hydrological conditions and landform features; and involution processes (Stepańczak 2012; Stepańczak et al. 2014; Szostek 2009). The variability of isotope ratios is closely connected with the presence of isotope fractionation, which additionally results in changes in δ^{18}O across trophic forms (Stepańczak et al. 2013; Szostek et al. 2014). As a consequence of a different cause for changes in ^{87}Sr/^{86}Sr and δ^{18}O, the use both elements' isotopes allows us to draw more accurate conclusions on the origin of individuals, as in such case both climate and geology of the site are taken into account. Therefore, a common practice is to conduct analyses which combine both elements (White et al. 2007; Fenner 2008; Mitchell and Millard 2009; Spence and White 2009; Price et al. 2010; Knudson et al. 2012a; Kendall et al. 2013).

What follows naturally is the question of the elements whose isotopes provide better representation of changes significant for a specific migration analysis. There are no unanimous opinions on this matter. In the case of oxygen isotopes, deviations from local values may be caused by e.g. the breastfeeding process, differences in metabolic rate between organisms, differences between sexes, history of diseases, diets and food preparation methods as well as climate transformations (White et al. 2004b; White et al. 2004c; Thornton 2011; Brettell et al. 2012; Roberts et al. 2013). On the other hand, some researchers claim that oxygen isotopes are easier to interpret, as δ^{18}O oscillations measured in one area are not as high as for strontium (Budd et al. 2004). In addition, if food was exchanged between various centres, the exchange interfered more with strontium than oxygen isotope levels, as the main source of oxygen in the body is supplied by water rather than by solids (Kendall et al. 2013).

Lead isotopes

Lead is another isotope whose ratios can be useful in the research discussed (Gulson et al. 1997; Macfarlane 1999; Kamenov et al. 2002; Knudson et al. 2005). To this end $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ ratios are analysed. Like strontium isotopes, the ratios result from the age of formation of a given rock and the decomposition of other elements, which in the case of lead, are uranium and thorium. The results obtained from such analysis also seem complementary with measurements of $^{87}Sr/^{86}Sr$ ratios. Nevertheless, the application of lead isotopes in studying migrations in a given area requires the presence of a rock containing Pb, and the risk of sample contamination by anthropogenic lead must be considered.

Isotopes applications in mobility analysis

Discovering the phenomenon of migration in the course of a study in archaeology or cultural anthropology makes it impossible to recreate cultural characteristics typical of the population. The simplest statement that can be made is that factors triggering migrations are simultaneously components of the population's life, and that there are conclusions to be drawn from them. The environment affects population through landform features, climate, presence of mountain ranges etc. Cultural and social aspects are connected with the type of economy, grazing, military conflicts or religious events. For this reason analyses of population movements reveal dependencies which indicate ethnic assimilations, politics, economic relationships or natural disasters (Anthony 1990; Ezzo and Price 2002; Haverkort et al. 2008; Kendall et al. 2013).

A considerable advantage of isotope tests is the fact that they may prove conclusive on matters of origin when objects found in the grave are missing or lead to ambiguous conclusions, and also in situations when historical documents or archaeological evidence are incoherent and they cannot fully confirm the occurrence of migration (Schweissing and Grupe 2003; Knudson et al. 2004; Knudson et al. 2005; Andrushko et al. 2009; Kendall et al. 2013; Kenoyer et al. 2013). Schweissing and Grupe (2003) presented results of their analysis of the origin of the inhabitants of the Roman province Raetia II. The sample included 70 individuals, of which 18 females, 41 males and one skeleton of unknown origin. The origin of the population was tested by two methods. The first one was based on the analysis of archaeological finds, whereas the other one on skeletons' $^{87}Sr/^{86}Sr$ isotope values. The results of both analyses are presented in Figure 4 as percentages of individuals who arrived in the province from outside locations. The conclusion that can be drawn from the findings is that in both cases the allochthonous origin of certain inhabitants could only be ascertained thanks to isotope tests. Note also that whenever isotope levels border on the local level, archaeological artefacts may prove helpful in correctly interpreting the data obtained in the tests.

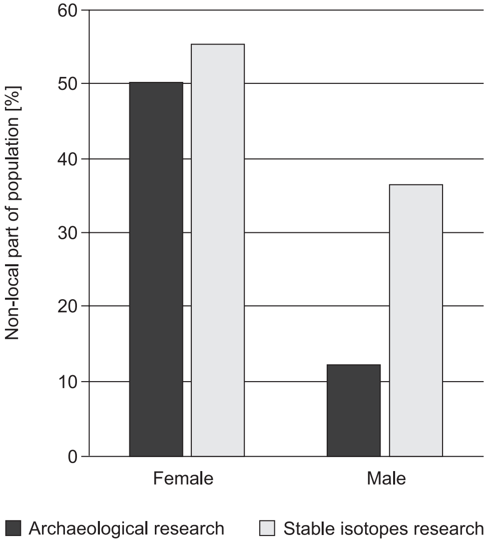

Fig. 4. Non-local female and male individuals determined using archaeological and anthropological – stable isotopes methods in Bavaria during the late Roman period based on table 3 in Schweissing and Grupe 2003
*Those results argue with common knowledge about women's movement between populations (f.eg. Shaw et al. 2011). In this case both sex were mobile and came from geologically different regions

A juxtaposition of biochemical results with biological data (such as age or sex), traces of traumas and archaeological information such as grave context allows researchers to recreate the migratory behaviour of the population. One of the possibilities emerging from studying the mobility of individuals is recreating of the group's social structure (Ezzo and Price 2002; Budd et al. 2004; White et al. 2004c; Bentley 2006; Price et al. 2010; Shaw et al. 2011). Role division in a society such as patriarchy or matriarchy may manifest itself in varied origins of individuals. Female migrations frequently observable in populations occurred largely for matrimonial purposes. Marriage was very often seen as a kind of payment or a manifestation of political relations. Conclusions on women's allochthonous origin may be drawn if females indicate a different place of birth than males and children in the group, and the fact that the female sex in the population was migrating may indicate patriarchal structure of the society (Gorokhov et al. 2001; Haak et al. 2008; Andrushko et al. 2009; Shaw et al. 2011; Kenoyer et al. 2013). A unique arrangement of skeletons of grave locations may suggest a specific lineage of the individuals. Obtaining information on the common origin of the inhumed individuals may indirectly confirm familial relationships (Grupe et al. 1997; Scheeres et al. 2013).

A study by Mitchell and Millard (2009), in which the discussed technique was applied, was aimed to establish the origin of individuals buried in the times of crusades in Jerusalem. The aforementioned historical period was noted for the European populations' tendency to move eastward. The phenomenon affected many social groups such as knights, merchants or pilgrims. An attempt to reconstruct the place of origin of the individuals on the basis of their inhumation site and its equipment is largely complicated, since the burial location was determined not by origin but wealth and the socio-economic status gained in the target location. Measuring isotope ratios of human remains enabled the researchers to conclude that the individuals found at the site came mostly from France or other parts of Europe. The authors paid special attention to one case, which was characterised by a rarely reported level of ^{87}Sr/^{86}Sr, thanks to which it can be assumed that the person had lived either in Norway or in Central Alps.

At the end of the 20th century, in the Tisenjoch mountain range in the Alps male remains dating back to 5000 years ago were found. Because of the unique character of Ötzi (also called "Iceman"), his body and belongings were carefully investigated. In order to determine the location of the individual's origin, enamel, dentine and bone samples were collected from the skeleton, and subsequently subjected to isotope analysis. Samples of soil, water from nearby rivers and contemporary human teeth were used as background material in the study (Hoogewerff et al. 2001; Kutschera and Müller 2003; Müller et al. 2003). Having analysed the enamel, the researchers reported that the $^{87}Sr/^{86}Sr$ ratio in Ötzi was in line with the strontium isotope level measured for the region in which he had been found. Still, higher values obtained from the man's bones suggested that for the last 10–20 years of his life the Iceman had been migrating or feeding in a location geologically different from that of his childhood. Finally, on the basis of the entire set of test, it was concluded that Ötzi had presumably been born approximately 10–20 km from the town of Merano in northern Italy (Müller et al. 2003).

Summary

This article focused on the relationship between two strontium isotopes, ^{87}Sr and ^{86}Sr, and on the possibility of their application in tracing human migration. Certain strontium isotopes are not subject to measurable isotope fractionation. Although Sr isotope ratios used in migration analyses do not undergo fractionation, values of other isotopes, namely $\delta^{88/86}Sr$, do vary in trophic networks (Knudson et al. 2010). Physiological preference for the lighter isotope leads to augmented levels of $\delta^{88/86}Sr$ in organisms situated on a lower level in the trophic chain. A similar situation can be observed in the soil (substrate)/plants system. A reduction in the above value due to fractionation proceeds in the same manner, with certain geographic differences, albeit smaller than those between higher- and lower-level consumers (Halicz et al. 2008; de Souza et al. 2010; Knudson et al. 2010). In addition, it was reported that fractionation and, ultimately, the extent of the relationship discussed in this study, is influenced by temperature, which also provides an opportunity to draw conclusions on the paleoclimate (Fietzke and Eisenhauer 2006; Rüggeberg et al. 2008). Last but not least, differences in $\delta^{88/86}Sr$ and $^{87}Sr/^{86}Sr$ ratios occur for different reasons, therefore the changes in the proportions in the two isotope pairs may vary.

Isotope analyses relating to human and animal migrations present complex problems. Most of them may be solved by improved analytical procedures or instrumentation, but certain issues – like correct determination of local isotope levels and boundaries of the area regarded as local – still remain open (Bentley et al. 2004). Moreover, changes tracked in tissue isotope levels provide information not exactly on the individual's movements, but on varying source of diet, which may (but need not) be related to migration.

Analyses based on isotopes of various elements involve not only bone material, but to an equal extent also fingernails, hair or other preserved tissues such e.g. skin (Schoeninger and Moore 1992; Wilson et al. 2007). In conclusion, it should be emphasised that isotope tests are becoming popular not only due to the possibility of analysing tissues of organisms, but also of tracing material goods that may indicate inter-group relations or trade routes (English et al. 2001; Eerkens et al. 2010) and, due to hugely successful contemporary analyses, are applied in investigating food products (Rummel et al. 2010; Voerkelius et al. 2010; Liu et al. 2014), as well as in criminal forensics (West et al. 2009; Holobinko 2012).

Authors' contributions

KSz the main concept and merit care, KM collected the literature and wrote the manuscript, BC-S made figures and gave technical support. All authors read and approved the final version of the manuscript.

Conflict of interest

The authors declare that there is no conflict of interest.

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