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## Multi-isotope analysis demonstrates significant lifestyle changes in King Richard III

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## ABSTRACT

The discovery of the mortal remains of King Richard III provide an opportunity to learn more about his lifestyle, including his origins and movements and his dietary history; particularly focussing on the changes that Kingship brought. We analysed bioapatite and collagen from sections of two teeth which formed during Richard's childhood and early adolescence, and from two bones: the femur (which averages long-term conditions), and the rib (which remodels faster and represents the last few years of life). We applied multi element isotope techniques to reconstruct a full life history. The isotopes initially concur with Richard's known origins in Northamptonshire but suggest that he had moved out of eastern England by age seven, and resided further west, possibly the Welsh Marches. In terms of his diet, there is a significant shift in the nitrogen, but not carbon isotope values, towards the end of his life, which we suggest could be explained by an increase in consumption of luxury items such as game birds and freshwater fish. His oxygen isotope values also rise towards the end of his life and as we know he did not relocate during this time, we suggest the changes could be brought about by increased wine consumption. This is the first suggestion of wine affecting the oxygen isotope composition of an individual and thus has wider implications for isotope-based palaeodietary and migration reconstructions.

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### 1. Introduction

In August 2012, excavations at the historically documented, burial location of King Richard III uncovered human remains. These were of a young, gracile, male with scoliosis of the spine (Appleby et al., 2014) who had severe head injuries consistent with battle wounds. The skeleton was dated to within the lifetime of Richard III and Buckley et al. (2013) concluded that “all [evidence] point clearly to the identification of this individual as King Richard III.” Work on this individual is ongoing, but for the purposes of this paper we have accepted, in concurrence with Mitchell et al. (2013) and Appleby et al. (2014), that this is the body of Richard III.

The premise of isotope-based archaeological studies is to piece together the diet, geographical movements, and provenance of individuals and is a well-established field. In their seminal paper on such techniques, Sealy et al. (1995) concluded that “we sincerely hope that work such as this in the future will have access to named

individuals whose historically attested dietary histories may be checked against the chemical findings”. The 2012 discovery of Richard III beneath a car park in Leicester offers such a scenario and provides a rare opportunity to cross reference science-based archaeology with history.

Richard was born in Northamptonshire in 1452 and became King of England in 1483 at the age of 30, ruling for 26 months before being killed at the Battle of Bosworth in 1485. The unique discovery has provided an opportunity to apply isotope techniques to his skeleton in order to reconstruct the life history of this Late Medieval king, including his childhood origins and movements, the level of contamination to which he was exposed, and a recreation of his dietary history, including the impact of becoming King. From the skeleton we sequentially analysed bioapatite and collagen from two teeth (a second premolar with root intact and a second molar crown) which formed during Richard's childhood and early adolescence, and from two bones: the femur (which averages long-term conditions) and the rib (which remodels faster and represents the last few years of life). The use of isotope techniques applied to different parts of a skeleton in order to construct a life history is still unusual in archaeology but has been attempted successfully by a

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handful of authors (Sealy et al., 1995; Cox and Sealy, 1997; Schroeder et al., 2009; Pollard et al., 2012; Bell et al., 2001; Chenery et al., 2014).

We can reconstruct where Richard may have resided as a child, as oxygen and strontium isotopes are fixed in enamel biogenic phosphate at the time of tooth formation and, once fixed, will not change during life, nor alter in the burial environment (Hillson, 1996; Price et al., 2002; Hoppe et al., 2003). Strontium isotopes ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) are derived from diet and largely relate to the geology of the area where the food was produced (Price et al., 2002). Oxygen isotopes are derived primarily from ingested fluids and reflect the isotopic value of available drinking water, the oxygen isotope composition ( $\delta^{18}\text{O}$ ) of which will largely be determined by global water cycles and thus will vary systematically with location (Dansgaard, 1964). Hence,  $\delta^{18}\text{O}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope ratios should provide constraints for place of origin and any subsequent geographical movements. Lead is a pollutant, and its incorporation in human tissue is related to the development of mining and metalworking. The principal causes of lead poisoning in humans are the use of lead in plumbing in soft water areas, the deliberate ingestion of bioavailable lead compounds (such as lead acetate used to sweeten wine), and the ingestion of lead compounds within, for example, medicines (Montgomery et al., 2010). Access to such materials tends to be the domain of the wealthy and hence lead contamination could be seen as a measure of status. The carbon and nitrogen isotope composition of collagen extracted from bone is the most commonly used technique for assessing dietary contributions and variations (Sealy, 2001; Ambrose and Norr, 1993; Schoeninger and DeNiro, 1984). Nitrogen isotope ratios ( $\delta^{15}\text{N}$ ) primarily reflect the trophic level of the subject. There is a step-wise increase in  $\delta^{15}\text{N}$  through each trophic level; thus herbivores will have values between +3 and +5‰ above the plants upon which they graze, while carnivores will record values +3 – +5‰ higher than herbivores from the same ecosystem. Extended food chains, involving several carnivorous steps, produce the highest  $\delta^{15}\text{N}$  values and long food chains are typical of aquatic systems. Animal tissues will also reflect the carbon isotope ratios ( $\delta^{13}\text{C}$ ) of the plants and animals consumed and can distinguish between marine and terrestrial sources of carbon (Schoeninger and DeNiro, 1984).

## 2. Construction of the age model

In order to create the fullest picture possible of Richard's life, we analysed a range of material from the skeleton, comprising dental enamel (Sr, Pb, O), sequentially sampled dentine (O, C, N) and two different bones; a section of bone from the right femur and a section of a left rib (O, C, N). These tissues vary in terms of the rate at which they remodel, or whether they remodel at all and thus what part of the individual's life they record. The phosphate component of dental enamel will preserve the isotope conditions in the body at the time of formation and will not remodel or be affected by post-depositional changes (Hillson, 1996; Price et al., 2002; Hoppe et al., 2003). We selected an upper second molar (M2) and lower second premolar (PM2) for analysis of Richard's childhood; both teeth were well preserved and devoid of caries or other significant signs of decay. Enamel mineralizes in upper M2 and lower PM2 permanent teeth from 2.5 to 3 years after birth and completes around the age of 8, providing an early childhood signal with an approximate age of 7.5 for the phosphate completion. Dentine is also not subject to remodelling (Nanci, 2003). The dentine closest to the M2 crown margin forms at ~3 years, after initial enamel calcification, and then progresses towards the pulp cavity between ~4.5–7.5 years (Hillson, 1996; Hoppe et al., 2003; Müldner and Richards, 2007a). Dentine was initially removed from the M2 crown cavity using a dental burr in 3 stages from the enamel/dentine junction,

progressively down to the pulp cavity in order to examine the earliest dentine formation (Beaumont et al., 2013). We were careful not to sample any darker dentine from the pulp cavity which may have formed as secondary dentine. The lower PM2 tooth begins to calcify at ~age 2 and the crown will be completed at ~age 7 where the dentine formation will reach the cervical margin. The root will continue to form until the age of 14, when the dentine reaches the apex, further allowing the examination of Richard's adolescence. Sequential sampling of dentine has been used successfully in animal teeth for many years, but has not been used in humans due to concerns that human dentine growth is not sequential. However, recent studies have shown that slicing the dentine can provide a time transgressive picture of childhood conditions (Beaumont et al., 2013; Eerikens et al., 2011). Dentine forms in lines of growth (Nanci, 2003), which can be picked out with magnification, but as we had to acquire enough dentine to analyse, we took slices of dentine and thus only an approximate age model was possible. After removing any cementum from the outer surface of the root, the PM2 root was sliced using a diamond saw attached to a dental drill into 7 slices of between 1.4 mm thick at the crown and 5.5 mm in thickness at the narrower apex. We wanted to analyse both C and N in the dentine collagen but also the O in the dentine phosphate in order to examine Richard's childhood diet and movements. Consequently, the dentine slices were relatively thick and each dentine sample will average approximately 1–2 years of formation. Thus they should reflect average diet and drinking water composition and not be affected by seasonal climate fluctuations within the represented years. Both  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  may enrich in weaning infant mammals due to the trophic level increase as a result of consuming maternal milk (Jenkins et al., 2001) but as the earliest samples relate to when Richard was about 3 years old we can assume that all samples are post-weaning.

Unlike teeth, bone constantly remodels following initial mineralisation; the rate of which varies according to the type of bone tissue, skeletal element, time of life and health of the individual (Sealy et al., 1995). Dense, cortical bone such as the femur has a relatively slow turnover rate and isotope values for bioapatite and collagen from the femur are thought to represent an average of at least 10 years prior to death in adults, thus the femur may include some bone material produced during adolescence (Hedges et al., 2007). Hedges et al. (2007) demonstrated that femoral turnover rates were higher for males under the age of 24 and significantly decreased with age but that a person aged 35 can be expected to have synthesized between 25 and 50% of femoral collagen. In contrast, cancellous or trabecular bone with a higher surface-to-volume ratio such as rib is more active and will turnover at a faster rate (Hill and Orth, 1998) and although the turnover rate is not precisely known, rib bone is thought to regenerate approximately every 2–5 years (Cox and Sealy, 1997).

More studies are emerging that utilize the difference in bone turnover rates to demonstrate dietary or migrational changes in individuals over time (Cox and Sealy, 1997; Pollard et al., 2012). Sealy et al. (1995) analysed a range of isotopes in the enamel, dentine, femur and rib bones of several individuals and found that they reflected changes in diet and location through those individuals' lives. For example, they were able to demonstrate that an adult female found in the Cape Peninsula, South Africa, showed an increase in seafood in her diet concurrent with a move in locality. In this case they suggest a move to the Cape from a tropical location due to enslavement. Sealy et al. (1995) conclude that for people who have had major changes in diet and/or residence location, isotope analysis from a range of skeletal elements are a powerful tool for reconstructing life histories. Similarly, Schroeder et al. (2009) successfully used a variety of skeletal elements from a slave colony in Barbados to decipher which of the 25 individuals

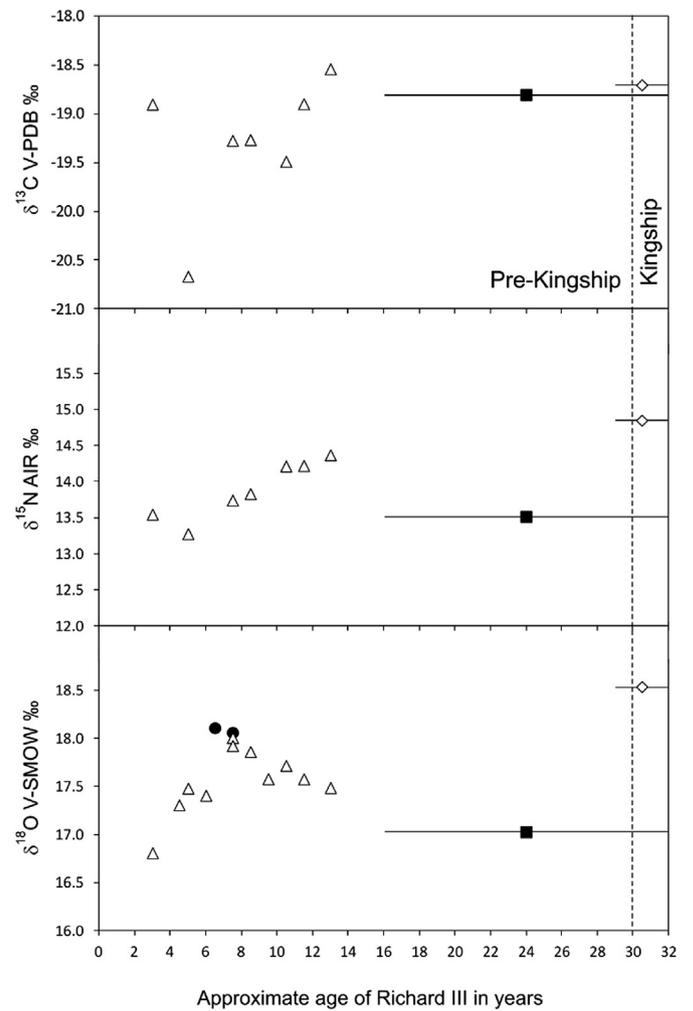
they studied were born on the island and which had travelled from elsewhere. While most of the individuals appeared to have been born on the island, seven individuals had carbon and nitrogen isotopes that differed between their dentine and their bones, which tied in with them having Sr and O tooth enamel values inconsistent with a Barbados origin. This suggests they were migrants brought to the island as slaves. Pollard et al. (2012) found higher  $\delta^{15}\text{N}$  values in the ribs of a group of tenth-century young males (mostly aged 16–24) compared to their femora by an average of  $\sim 0.5\text{--}1\text{‰}$ . To our knowledge, the only other large data set available on rib-femur isotopic offsets is from the mass burial pit of young male skeletons found on Ridgeway Hill, Dorset UK (Chenery et al., 2014). Here, 31 individuals were analysed for a range of isotopes in both their ribs and femora. The oxygen isotope data for the rib-femur pairs, indicated that the majority of individuals were sedentary during the 10+ years prior to their deaths but six individuals were highly likely to have migrated from an exceptionally cold region to a significantly less cold location. For the majority of the 31 individuals, rib  $\delta^{13}\text{C}$  is elevated in relation to femur by a mean of  $0.3 \pm 0.5\text{‰}$  and rib  $\delta^{15}\text{N}$  is elevated in relation to femur  $\delta^{15}\text{N}$  by a mean of  $0.9 \pm 1.2\text{‰}$  ( $1\sigma$ ,  $n = 31$ ).

The age range represented by each tissue in this study is given in Table 1 and used to construct Fig. 1. For isotope methods please see Supplementary material.

### 3. Results and discussion

In terms of the geographical movements of Richard III, we know where he was born and there is a great deal of detail about his whereabouts during his reign (Edwards, 1983), however we know very little about where he spent his childhood and early adulthood (Baldwin, 2013). As the twelfth child of Richard, Duke of York and Cecily Neville, he was never expected to become the future monarch, consequently, detail about his early life is very sparse (Baldwin, 2013). The strontium and oxygen isotope data from his skeleton should enable us to glean more information about these missing years, assuming that the isotope data representing the beginning and end of his life concur with what we do know.

Phosphate oxygen isotope ratios ( $\delta^{18}\text{O}_p$ ) are plotted for Richard III at three years old until his death at 32 (Fig. 1, Tables 1 and 2). Relatively low  $\delta^{18}\text{O}_p$  values ( $16.7\text{‰}$ ) from age  $\sim 3$  years are consistent with an early childhood spent in the east of England and tie in with his known birth place in Northamptonshire (Evans et al., 2012). A  $\delta^{18}\text{O}_p$  value of  $16.7\text{‰}$  is within the range obtained from populations residing in the low rainfall zone of eastern England:  $17.2\text{‰} \pm 1.3\text{‰}$ , ( $2\sigma$ ,  $n = 83$ ) (Evans et al., 2012). Richard's tooth



**Fig. 1.** Collagen carbon and nitrogen isotope data and phosphate oxygen isotope data on samples taken from Richard III. Symbols as follows:  $\Delta$ , dentine;  $\bullet$ , enamel;  $\blacksquare$ , femur;  $\diamond$ , rib. X-axis represents estimated mean age of Richard III at time of formation of skeletal samples. For all isotopes precision is better than  $\pm 0.15$  ( $1\sigma$ ).

enamel  $\delta^{18}\text{O}_p$  value reaches a childhood maximum of  $\sim 18\text{‰}$  at around the age of seven and this is much more typical of populations residing in the higher rainfall areas of western England  $\delta^{18}\text{O}_p$  range:  $18.2\text{‰} \pm 1\text{‰}$ , ( $2\sigma$ ,  $n = 40$ ) (Evans et al., 2012). It is worth

**Table 1**

Oxygen, carbon and nitrogen isotope data on samples taken from Richard III, including an estimation of time of development for each tissue analysed. For all isotopes precision is better than  $\pm 0.15$  ( $1\sigma$ ).

Description	Sample code	Estimated age of development (years)	$\delta^{18}\text{O}_p$ v-SMOW	$\delta^{13}\text{C}_{\text{PBD}}$ collagen	$\delta^{15}\text{N}_{\text{AIR}}$ collagen	%C	%N	C/N
L. Rib	R3R	29–32	18.5	–18.7	14.9	43.0	15.2	3.3
R. Femur	R3F	17–32	17.0	–18.8	13.5	41.4	14.7	3.3
U. LHS M2 enamel	R3M	2.5–8	18.1					
M2 crown dentine, pulp	R3MD-01	6.0–7.5	17.9					
M2 crown dentine	R3MD-02	4.5–6.0	17.4					
M2 crown dentine	R3MD-03	3.0–4.5	17.3					
M2 crown dentine, crown	R3MD-04	3	16.8	–18.9	13.5	38.7	12.5	3.6
L. LHS PM2, enamel	R3P	2.25–7	18.1					
PM2 root slice 01 = base	R3PR-01,02	12.0–14	17.5	–18.5	14.4	39.4	12.9	3.6
PM2 root slice	R3PR-03	11.0–12	17.6	–18.9	14.2	40.9	13.5	3.5
PM2 root slice	R3PR-04	10.0–11	17.7	–19.5	14.2	37.7	12.5	3.5
PM2 root slice	R3PR-05	9.0–10	17.6	–19.1	13.7	40.2	12.3	3.8
PM2 root slice	R3PR-06	8.0–9	17.9	–19.3	13.8	44.8	16.2	3.2
PM2 root slice 07 = crown	R3PR-07	7–8.0	18.0	–19.3	13.7	44.7	15.9	3.3
PM2 08 = crown dentine	R3PR-08	2.25–7	17.5	–20.7	13.3	43.6	15.4	3.3

**Table 2**  
Strontium and lead isotope analysis of tooth enamel from a 2nd premolar (R3P) and 2nd molar tooth (R3M) taken from Richard III.

Sample	Sr ppm	$^{87}\text{Sr}/^{86}\text{Sr}$	Pb ppm	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{208}\text{Pb}/^{206}\text{Pb}$
R3P	79.2	0.711057	24.4	18.4736	15.6318	38.442	0.84618	2.08091
R3M	82.6	0.711002	27.7	18.4735	15.6314	38.436	0.84618	2.08071

noting that the  $\delta^{18}\text{O}_p$  values from the M2 enamel sample and the dentine samples from both teeth (assessed to be equivalent in age) agree within analytical error, suggesting that the dentine is not diagenetically altered. When we examine the Sr isotope data from the same teeth samples ( $^{87}\text{Sr}/^{86}\text{Sr} = 0.711$ ;  $n = 2$ ), they also give a more elevated value than is estimated for the area of Northamptonshire which has a predicted  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio predominantly in the range of 0.709–0.710 (Evans et al., 2010). More elevated  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios are commonly found in Palaeozoic aged rocks that crop out on the western side of southern Britain (Evans et al., 2010). The combined O and Sr data thus suggest he was living in western Britain by the age of seven or eight and there is some support for this in the historical literature. Although Richard was born and spent his very early childhood in Northamptonshire, he was recorded as residing at Ludlow Castle in the Welsh Marches in 1459 (Baldwin, 2013). This location can be reconciled with the enamel Sr and O data which show that he was living in an area of Britain that was more westerly than Northampton, based on oxygen data, and in an area where the Sr isotope composition was elevated relative to eastern England. Although the data do not provide a tightly constrained location they are consistent with domicile in the Ludlow area. The oxygen isotope composition recorded in his dentine and femoral bone then decrease through adolescence and into adulthood, and this is consistent with the majority of his life being spent back in eastern England, which is well documented (Baldwin, 2013). The relatively high  $\delta^{18}\text{O}_p$  value, recorded in his rib bone at the end of his life, will be discussed further below.

Richard's tooth enamel records Pb concentrations of 26 ppm ( $n = 2$ ) due to exposure to bioavailable Pb. This value is high relative to Neolithic pre-metalworking communities: median = 0.1 ppm,  $n = 31$ ; (Montgomery et al., 2010) but is within the range found in later Roman and Medieval tooth enamel. The isotope composition is consistent with typical pre-industrial levels in Britain (Montgomery et al., 2010).

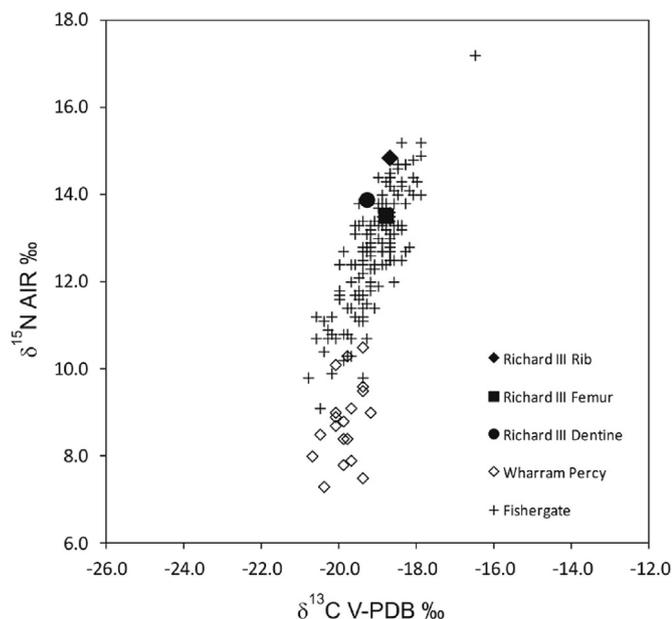
Variations in Richard III's diet can be traced though his life using carbon and nitrogen isotope compositions. Slices of dentine, and the incremental crown dentine samples, provide high-resolution data about Richard's childhood from ~3 to 14 years of age (Fig. 1, Table 1). The general trend through Richard's life is one of increasing  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values (Fig. 1). The earliest  $\delta^{13}\text{C}$  value is  $-18.9\text{‰}$  (~age 3); there is then a considerable drop in  $\delta^{13}\text{C}$  to a value of  $-20.7\text{‰}$ , around the age of 5 years old, and then the values rise back up to a plateau of between  $-18.5$  and  $-19\text{‰}$ . The nitrogen values also show an early dip from  $13.5\text{‰}$  to  $13\text{‰}$  at around the age of 5 and then a systematic increase to  $14.4\text{‰}$  at approximately 14 years of age. The nitrogen isotope values then decrease from the last childhood measurement to the long term average adult value recorded in the femur. Unlike the  $\delta^{13}\text{C}$  data, there is then a large  $\delta^{15}\text{N}$  shift in value between the femur ( $13.5\text{‰}$ ) and the rib ( $14.9\text{‰}$ ) bone. The concurrent decreases in  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  between the ages of 4 and 6 broadly coincide with an increase in  $\delta^{18}\text{O}$  values, and together could suggest that his move away from Northamptonshire was also associated with a major dietary change, to a more cereal-based diet with less meat and fish.

The Late Medieval diet of an aristocrat consisted of bread, ale, meat, fish, wine and spices with a strong correlation between wealth and the relative proportions of these, with more wine and spices and proportionally less ale and cereals with increasing

wealth (Dyer, 1989). The wealthier you were the more variety of meat and fish you consumed. Reconstructing the dietary history of Richard III is unusual as on the one hand we know a fair amount about him as an individual and there are some court records describing the food types he was served. On the other hand, as an isolated skeleton, there are no contemporaneous animal bone samples and thus understanding Richard's dietary history necessitates comparison with isotope data from other contemporaneous humans and their dietary sources. A variety of Late Medieval faunal material, largely from the east of England, is available (Müldner and Richards, 2005; 2007b; Woolgar, 2001; Hamilton and Thomas, 2012) and the isotope ratios are consistent with similar samples from southern England. These demonstrate that there does not seem to be a significant regional variation in faunal isotope data from the period and this adds confidence to our use of these data to aid our interpretations.

Mean  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  herbivore values from faunal samples taken from the Late Medieval period around York have values of  $-21.5\text{‰}$  and  $5.5\text{‰}$  respectively (Müldner and Richards, 2007b). Thus, Richard's average skeletal  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values ( $-19.2\text{‰}$  and  $14\text{‰}$ ) are  $>2\text{‰}$  above the herbivore baseline for carbon and  $>8\text{‰}$  for nitrogen and this offset increases through his life (beyond the age of 5–6 years). As the trophic level change for carbon is relatively small ( $\sim 1\text{‰}$ ), this indicates a marine fish component in his diet, especially in adulthood, where the two bone collagen samples are almost  $3\text{‰}$  above the herbivore baseline for carbon. His bone  $\delta^{13}\text{C}$  values are generally higher than comparable UK terrestrial-temperate climate individuals also suggesting a marine component to his diet (Müldner and Richards, 2007a; 2005; Richards et al., 1998; Jay and Richards, 2006; Fuller et al., 2003; Polet and Katzenberg, 2003; Privat et al., 2002).

Taken as a whole, Richard's  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  isotopes are within the higher trophic level area of data from the Late Medieval period (Müldner and Richards, 2007a; 2005; 2007b) and compare favourably to contemporaneous aristocracy and the upper clergy, who as landowners had diets in-line with the wealthiest households. Müldner and Richards (2007a) analysed 155 rib samples from the Gilbertine Priory at Fishergate, York, which included some high-status burials (Fig. 2). The Fishergate group had significantly higher  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values (mean  $-19.1 \pm 0.6\text{‰}$  and  $12.8 \pm 1.3\text{‰}$  respectively) compared to other individuals from earlier time periods in the area, such as those from the rural population of Wharram Percy, Yorkshire (Fuller et al., 2003). The  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values from Richard's skeleton sit at the very top of the high-status Fishergate data set (Fig. 2). The widespread Late Medieval elevation in human bone  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values is caused by a greater consumption of fish protein because of the observance of Christian fasting rituals. These rules required avoidance of 'meat', which was interpreted very specifically to mean terrestrial herbivores, allowing the consumption of a number of other animals, including fish (Barrett et al., 2004). This equated to around a third of the year where no meat could be eaten. This increased demand for fish led to the development of a British commercial fish trade, both marine and freshwater species were eaten, and also imported from Scandinavia. Fish was eaten from a stock of preserved fish (salted or dried) and fresh fish for the richer households, such as herrings, flat-fish, shell-fish and even porpoises and other marine mammals which were permitted on fast days (Dyer, 1989). Cheaper marine



**Fig. 2.** Collagen carbon and nitrogen isotope data from the skeleton of Richard III compared to humans from Fishergate priory, York (Müldner and Richards, 2007b) and Wharram Percy (Fuller et al., 2003).

fish, such as herrings, were regularly available to the poor whereas the wealthy, such as Richard III, would have eaten more expensive freshwater species such as pike (Woolgar, 2001; Serjeantson and Woolgar, 2006), although it is not possible to distinguish marine and freshwater fish intake from the average bone isotope values.

The  $\delta^{15}\text{N}$  and  $\delta^{18}\text{O}$  values in Richard's rib compared to his femur are elevated and this could have several explanations. Elevation in rib isotope composition, compared to the femur, has been noted in other skeletons (Pollard et al., 2012) and could suggest a physiological change. However, a study from Holbæk, Denmark (Jorkov et al., 2007) measured  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  in corresponding rib and femur collagen from 58 individuals from a static community and showed no measurable difference in isotope values. On the basis of this study, they inferred that differences in rib-femur isotope values, outside analytical error, implied dietary variation and although variation is to be expected within a population, an individual with no change of residence or diet, will record  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  isotope values for their rib and femur within analytical error.

Pollard et al. (2012) compared the increases they observed between femur and rib  $\delta^{15}\text{N}$  with the age of the individuals and found no relationship, i.e. the isotope difference was not age related. They suggested that the group may have experienced a major change in lifestyle in the last few years of their life that had a metabolic effect or that they experienced a real dietary change. There are no clear definitions regarding what constitutes a significant  $\Delta^{13}\text{C}$  and  $\Delta^{15}\text{N}$  in regards to dietary change between corresponding human tissues. Chenery et al. (2014) took  $\pm 3\sigma$  of the analytical error for each isotope to constitute a  $\Delta$  significance value and we adopt the same criteria here.

Could we expect Richard to experience a significant lifestyle change when he was crowned King? His time as King (two years and two months) will be represented by a higher proportion in his rib bone whereas his femur averages at least the last 10–15 years of his life and hence will be dominated by pre-kingship adulthood and will include late adolescence. Using the criteria outlined by Chenery et al. (2014), in the last few years of his life there is a significant ( $> \pm 0.4\text{‰}$ ) increase in  $\delta^{15}\text{N}$  ( $+1.4\text{‰}$ ) from the femur to the rib but no significant ( $> \pm 0.5\text{‰}$ ) change in the  $\delta^{13}\text{C}$  values ( $-0.1\text{‰}$ ) (Table 1). If this change does record a dietary effect, it suggests increased

consumption of high trophic level, terrestrial foods, such as freshwater fish and wildfowl (Müldner and Richards, 2007b); both common delicacies of the privileged (Albarella and Thomas, 2002). The social elite during the 15th Century had diets rich in protein, the amount and variety of which increased in proportion to status (Dyer, 1989). Game birds (swans, herons, pheasants etc.) were exempt from the meat-fasting laws and were relatively expensive to acquire. Like game, freshwater fish was often caught on estates with the larger species sought after as a status symbol of the very rich with demand necessitating royal fishponds to be maintained for the purpose. Wildfowl was very commonly seen at the aristocratic banquet and records from Richard's 1483 Coronation banquet include cygnet, crane, heron and egret, amongst others (Sutton and Hammond, 1983). Eating wild birds was clearly a mark of standing and increased in popularity through the Late Medieval period leading to some species management (swaneries, heronries and doves) (Woolgar, 2001; Albarella and Thomas, 2002). The shift to an increased proportion of freshwater fish and wildfowl in the latter part of his life corresponds to an increase in these "luxury foods" in the last ~2–5 years of his life (ie while he was King) relative to the average last ~10 years of his life.

As with the increase in nitrogen isotope composition, the significant ( $> \pm 0.5\text{‰}$ ) increase in Richard III's oxygen isotope composition ( $+1.5\text{‰}$ ) in the last few years of his life also requires explanation. His rib bone records a  $\delta^{18}\text{O}_\text{p}$  value of  $18.5\text{‰}$  which places him within the British populations residing in high rainfall areas (west coast) during the last ~2–5 years of his life (Evans et al., 2012). If this was an unknown Medieval individual, the data would lead us to suggest that he had migrated to a different area in the last few years of his life. The great advantage of knowing who the skeleton belongs to is we know for certain that this was not the case and thus there must be another explanation. The movements of Richard III from 1483 to 1485 are documented in great detail and do not support domicile outside eastern England (Edwards, 1983). Of the 26 months he was King, he spent 10 months in London and the majority of the remaining time in Yorkshire and the cities of central and eastern England. He made only short visits to the western parts of England; visiting Exeter, Bridgwater and Worcester in the latter half of 1483, each visit lasting for a few days at most. Changes in skeletal  $\delta^{18}\text{O}$  that are not related to a change in drinking water source have been suggested before. The alteration of drinking water  $\delta^{18}\text{O}$  can occur during the cooking process and also through the brewing of beer (Brettell et al., 2012). During the last few years of his life we know Richard was residing predominantly in Eastern England, as his femur composition suggests. Thus we would expect his rib  $\delta^{18}\text{O}$  drinking water value to be  $\sim -8\text{‰}$ , converted to a drinking water value using Daux et al. (2008) and alteration of this value by brewing or stewing could only expect to shift it by  $+1\text{‰}$  (Brettell et al., 2012). Richard's rib  $\delta^{18}\text{O}_\text{PW}$  value of  $-5.2\text{‰}$  is shifted by  $\sim +3\text{‰}$  from what we would expect. The correlation of the increase in rib bone  $\delta^{18}\text{O}$  with an increase in  $\delta^{15}\text{N}$  (rich foods) from the same bone raises another possibility; that he had a change in his fluid composition related to his diet. Wine was certainly a staple only for the very wealthy. For example, it constituted 21% of food expenditure by the Duke of Buckingham's estate in 1452–1453 (Dyer, 1989). Wine was commonly imported from Gascony, northern France and the Rhineland and during the 15th century, sweet wines from the Mediterranean region became increasingly popular (e.g. Malmsey, from Madeira) (Dyer, 1989). As wine is made from grape juice rather than water, there is a significant  $\delta^{18}\text{O}$  water fractionation in the vine. We do not have access to medieval wine to analyse, so in order to determine the likely range of  $\delta^{18}\text{O}$  values we analysed four modern French wines (Table 3) which give an average  $\delta^{18}\text{O}$  value of  $+2.7 \pm 0.9\text{‰}$  (1SD,  $n = 4$ ) and these are in line with the large database of modern Italian wines,

**Table 3**  
Analysed  $\delta^{18}\text{O}$  values of modern French wines with errors  $\pm 0.05$  per mil.

Wine	$\delta^{18}\text{O}_{\text{V-SMOW2}} \text{‰}$
Burgundy (white)	+1.87
Chardonnay (white)	+3.81
Beaujolais (red)	+2.09
Claret (red)	+2.94

produced between 2000 and 2010, which range in  $\delta^{18}\text{O}$  composition between  $-1.3$  and  $+8.9\text{‰}$  ( $n = 4,000$ , 95%) (Dordevic et al., 2013). A simple mixing equation model constructed between drinking water typical of eastern England ( $-8\text{‰}$ ) and the French wine average value ( $+2.7\text{‰}$ ) suggests that Richard's  $\delta^{18}\text{O}_{\text{DW}}$  value of  $-5.2\text{‰}$  could be achieved by deriving  $\sim 26\%$  of his oxygen from wine, and the rest from local water. It should be noted that in converting phosphate oxygen data to drinking water values results in considerable uncertainty:  $1\text{‰}$ – $3.5\text{‰}$  as discussed in Pollard et al. (2011). However, there is still a significant increase in the raw  $\delta^{18}\text{O}_{\text{p}}$  values between the femur and rib that requires explanation. Uncertainty about rib turnover rates and the drinking water conversion means that this value is a crude approximation, however it does serve to give some sense of the possible quantities of wine involved. This contrasts with the  $\delta^{18}\text{O}_{\text{p}}$  composition of his femur, which predominantly represents the time before he was King, and gives a local  $\delta^{18}\text{O}_{\text{DW}}$  equivalent value of  $-8.2\text{‰}$ , typical of eastern England groundwater values.

Should we expect to see a significant change in diet when Richard was crowned King? Evidence remaining from coronation banquets throughout the Medieval period suggests that during the 15th Century, the coronation banquet was on average 25% larger in size than previous centuries and Richard III's banquet was noted for being particularly long and elaborate (Sutton and Hammond, 1983). As Richard's reign was short, such excesses are likely to have persisted and following his coronation in 1483, Richard went on Royal progress, during which he is likely to have been treated to elaborate banquets at each accommodating household. Thus it is not unexpected that his consumption of wine and rich foods increased over the last few years of his life.

#### 4. Conclusions

The recent discovery of the remains of King Richard III, one of the most controversial characters in British history, provides an opportunity to use scientific methods to assess conflicting historical and literary descriptions of his life. Our data comprise isotope results from different parts of the skeleton in order to reconstruct a life history of his diet, exposure to pollution and geographical movements. Most significantly, we demonstrate a substantial shift in his bone isotope values towards the end of his life. As we are dealing with an individual with known provenance and with, in parts, a detailed documentation of his diet and location we can test and extend our interpretations of skeletal isotope analysis. The isotope changes evident between Richard's femur and rib bones, when assessed against historical documentations, suggest a significant increase in feasting and wine consumption in his later years. This is the first example where the intake of wine has been suggested as having an impact on the oxygen isotope composition of an individual and thus has wider implications for isotope-based archaeology.

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#### Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jas.2014.06.021>.

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