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The effects of diet and beauty products on the uptake and storage of ^{14}C in hair and nails: ramifications for the application of bomb pulse dating to forensic anthropological casework

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ABSTRACT

Radiocarbon dating is a useful tool in the examination of unknown human remains. Recent studies have shown that the analysis of hair and nail samples can provide a highly accurate estimation of the year of death (YOD). However, little research has examined factors that may influence the uptake and storage of ^{14}C in these tissues, such as diet, or the use of beauty products. This study measured the level of ^{14}C in human hair and nail samples collected from living individuals to determine whether diet, and the use of hair dye or nail polish, has a significant impact on the estimation of YOD. The results of this study showed that diet did not appear to impact the radiocarbon content in human hair and nail, and thus should not be considered a limitation when analysing samples obtained from unidentified human remains. The use of nail polish, and in the majority of cases, hair dye, did not significantly impact the ^{14}C concentration in nails and hair. While the results of this study are preliminary, they suggest that in most cases, both hair and nail can be successfully analysed using radiocarbon dating to estimate an individual's YOD. However, best practice should involve the analysis of multiple tissue types, to minimise any error that may be introduced as a result of the decedent's use of beauty products.

1. Introduction

In cases where human remains are discovered skeletonised or partially decomposed, identification is often challenging, particularly when there is no initial identification hypothesis. In forensic medical contexts, the competing question may be whether the remains are in fact of medico-legal significance. Addressing this question may be aided by the application of bomb pulse dating. This form of dating is a derivative of traditional radiocarbon dating, but instead of comparing the ^{14}C level within the biogenic matter to the known half-life of ^{14}C [1], bomb pulse dating analyses levels of ^{14}C in organic matter and directly compares it to atmospheric levels of ^{14}C from 1950 onwards [1]. Bomb pulse dating may indicate that the individual died after 1950 (i.e., is "modern"), and if so, provide information regarding the timing of tissue formation and, depending on the type of tissue available for testing, the year of birth (YOB) and the year of death (YOD) can be estimated.

Increased levels of artificial ^{14}C were produced by above-ground nuclear testing in the 1950–1960 s, which resulted in heightened levels of environmental ^{14}C. Although radiocarbon levels have decreased over the last 60 years since the introduction of the Test Ban Treaty in 1963 [2], as of 2021, they are still above pre-modern levels in the Southern Hemisphere [3–5]. These heightened levels of ^{14}C have been passed along the food chain to humans, and as such can be found, and analyzed, in many human tissues [6–9].

Levels of ^{14}C in the body differ depending on the tissue type (e.g., bone, teeth, hair, nail) and the rate of turnover/formation of that tissue which, in turn is affected by the age of the individual. The analysis of multiple tissue types, with different rates of turnover or growth provides the most accurate information regarding the YOB and the YOD of the unknown remains [6]. When undertaking radiocarbon analysis, human tissues can generally be divided into three groups: tissues with no turnover, tissues with slow turnover and tissues with fast turnover.

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Bone is a tissue with a highly variable turnover [7] and can generally only provide a wide estimate of the YOB or YOD, depending on the age at death of the individual. However, due to its high level of survivability throughout decomposition, bone is typically the preferred tissue to analyze when trying to determine the medico-legal significance of the case.

Biological materials that form early in life, and do not undergo any turnover once formed, such as dental enamel, neurons or the crystalline eye lens [8], are ideal in the estimation of YOB. Teeth are the preferred tissue in forensic anthropological casework, as they are known to survive both decomposition and other destructive forces such as fire, and have known, well documented formation standards [9–11].

The estimation of YOD relies on the analysis of tissues such as muscle, skin, or blood, all of which have a fast turnover time, and will therefore, contain ^{14}C that is closest to the environmental levels at the time of death [12]. Depending on the nature of the case, muscle, skin, or blood are often not available for analysis, due to their rapid rate of decomposition [13]. In contrast, hair and nail, which can survive decomposition for decades [14], may be analyzed to provide an estimate of the YOD, as these tissues both have a rapid rate of growth [15,16].

Previous research has demonstrated that the radiocarbon analysis of both hair and nail is highly accurate and can provide an estimate of YOD within 1–2 years of the actual year of death [5]. However, there has been limited research into the factors that may affect the level of ^{14}C within these tissues, specifically the diet of an individual, and their use of beauty products on their hair and nails.

As ^{14}C enters the body via the food chain, the tissues of individuals with specific diets, such as pescatarians (individuals whose diet includes only fish but no other meat), may have different levels of ^{14}C to those eating a typical omnivorous diet [17]. This is largely due to the marine reservoir effect, which is a well-studied phenomena in traditional radiocarbon dating resulting from an imbalance in the levels of ^{14}C between the atmosphere and marine reservoirs, with the later containing significantly lower levels of ^{14}C [18]. As marine animals absorb ^{14}C from their environment and food, they contain similarly low levels of ^{14}C, which is then passed along the food chain to humans. In individuals who consume a diet high in seafood, this may result in lower levels of ^{14}C than those who eat an omnivorous diet.

The increasing use of beauty products in recent times [19] has also potentially increased the complexity of analysing samples of hair and nail in the estimation of YOD. Hair dye specifically has been shown to decrease the level of ^{14}C within the hair, due to the petrochemicals in the product, resulting in a less actuate estimation of YOD [20].

This study aims to examine the impact that diet and the use of specific beauty products potentially have on the level of ^{14}C within human hair and nail, and how this may impact the estimation of YOD in forensic casework.

2. Methodology

2.1. Sample collection

This study examined the ^{14}C level in samples of hair and nail collected in 2020–2021 from 30 living males and females (Ethics approval EC 4–2019) with different diets. Samples were self-collected by the donor who cut a few strands of their hair close to the scalp and collected fingernail trimmings. Participants completed a questionnaire at the time of providing hair and nail samples: details included county of birth and current country of residence, their diet, whether they had dyed their hair within the last year and if they used nail polish at least once a week over the last year.

2.2. Sample analysis- Australian Nuclear Science and Technology Organisation (ANSTO)

Sample analysis for individuals 1–20 was undertaken at the Centre for Accelerator Science Radiocarbon Dating Laboratory (ANSTO). Hair was washed with 2 M hydrochloric acid (HCL) (60 °C, 20 mins), 1% sodium hydroxide (NaOH) (RT, 20 mins) and 1 M HCl (RT, 10 mins) with rinsing with Milli-Q® water between treatments and washed thoroughly with Milli-Q® water after final treatment, then dried at 40 °C overnight. Nails were cleaned by washing with 10% Decon 90® solution for 20 mins in a sonic bath at 50 °C, rinsed with Milli-Q® water, washed with acetone for 15 mins in sonic bath at 50 °C, rinsed and treated with 2 M HCl (ultrasonic bath, 15 mins, 50 °C). They were washed with Milli-Q® water in ultrasonic bath (15 mins, 50 °C), rinsed twice with Milli-Q® water, then dried at 60 °C for 1 hr.

Hair and nails were combusted in sealed glass tubes and the resulting carbon dioxide (CO_2) graphitised as described by Hua et al. [21]. The accelerator mass spectrometer (AMS) analysis was performed on the Vega NEC 1 MV accelerator [22] with raw measurement results corrected for possible contamination in processing using the standard ANSTO blank correction procedure. $\delta^{13}C$ were measured on the graphite targets using an EA-IRMS and used to correct the measured $^{14}C/^{13}C$ values. Results were reported as percent Modern Carbon (pMC).

2.3. Sample analysis- Australian National University (ANU)

Sample analysis for individuals 21–30 occurred at the ANU Radiocarbon Dating Laboratory. The nail samples were soaked overnight in ultrapure water before being physically cleaned with a scalpel to any traces of dirt or tissue. Hair and nail samples were then defatted in a solution of 2:1 dichloromethane and methanol for 2 h at room temperature. Following this, an acid-base-acid (ABA) pre-treatment was performed, involving 0.1 M HCL (30 m), 0.1 M NaOH (1 hr) and 0.1 M HCL (30 min), at room temperature, rinsing with ultrapure water after each treatment.

Pre-treated samples were placed into quartz tubes containing an oxidation agent (copper oxide (CuO)) and silver, and torch sealed under vacuum, before being combusted for 6 h at 900 °C. The quartz tubes were loaded on a graphite line, the carbon dioxide (CO_2) was cryogenically purified and transferred into an individual reactor. Twice as much hydrogen (H) as CO_2 was added and the graphite produced with iron as a catalyst. The resulting graphite was then measured using AMS following published standard procedures [23]. All data were background subtracted using ^{14}C free coal, corrected for $\delta^{13}C$ and reported as $F^{14}C$ [24]. One sample, H-21 failed to graphitise and was thus excluded from the study.

To ensure differences in sample pre-treatment did not impact the outcome of the AMS analysis, 5 samples were analysed at both the ANU Radiocarbon Dating Laboratory, and the ANSTO. Because the levels of ^{14}C were consistent between the two laboratories, it was assumed that a difference in pre-treatment did not impact the results of the ^{14}C analysis.

2.4. Data analysis

In forensic casework, ideally multiple samples, including bone, would be analysed to determine the placement of the hair/nail result on either the upside or the downside of the curve. In this study samples were taken from living individuals and bone samples were not possible. Consequently, a modified bomb pulse curve (Fig. 1) dating from 1963 to 2021 was utilised to analyse the results [25,26], and minimise the error introduced by the upside of the curve.

Data were calibrated using OxCal 4.4 [27]. While this study examined samples provided by living individuals, application of results

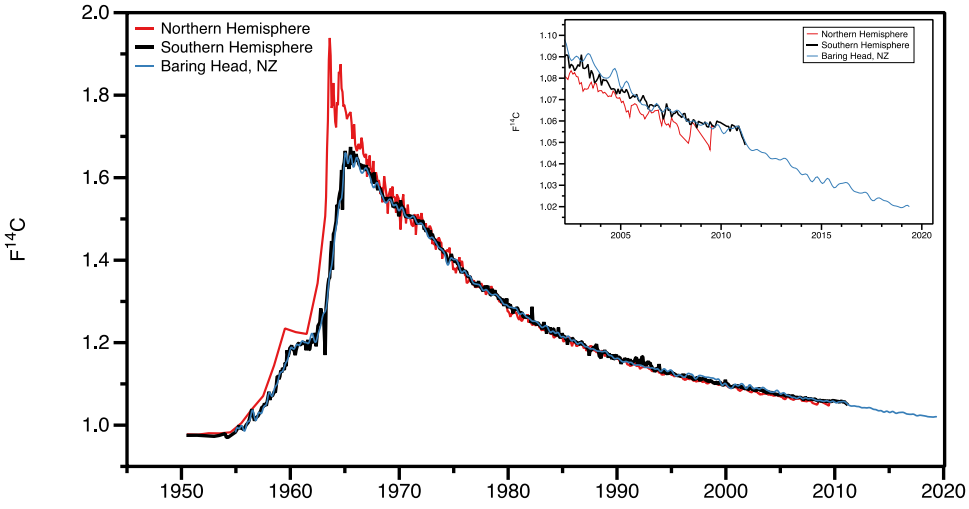

Fig. 1. Bomb Pulse Curve (data extended to 2021).

is intended for forensic casework. Therefore, for the purpose of analysis, the year of collection was known as the 'YOD'.

The equality of average lag times across the hair and nail samples was tested using a paired t-test for diet and a two-sample t-test for beauty products. These tests used an alpha = 0.05 and all tests were performed using Stata Version SE 17 [28].

3. Results

A total of 30 people volunteered samples. The sample groups were comprised of individuals whose diet was omnivorous (n = 16), vegetarian (n = 8) and pescatarian (n = 6). A total of 14 individuals dyed their hair within the last year prior to collection, and 7 individuals used nail polish at least once a week. Tables 1 and 2 show the ^{14}C results of the hair and nail samples respectively. Results are expressed as Fraction Modern ^{14}C ($F^{14}C$) and displayed with the relevant uncertainty (1σ CI). Several samples were excluded from further statistical analysis due to their predicted range, which provided a pre-modern timeline. Overall, the hair samples contained slightly older levels of ^{14}C, with an average of lag time of 1.9 (± 2.5) years, while the nail samples provided an average lag time of 1.3 (± 1.7) years.

Figs. 2 and 3 show the average lag times for the three diet groups, with Fig. 2 displaying the combined hair and nail lag time, and Fig. 3 the individual hair and nail lag times. Overall, relatively minor differences were noted between the diet groups, however, due to the small sample size of the pescatarian group, this could not be statistically quantified.

Table 1
^{14}C results of the hair samples.

ID	Sanu#/ANSTO code	$F^{14}C$	Error	'YOD'	Predicted Range	Predicted median 'YOD'	Lag time (yrs.)	Diet
H-1	OZAD66	0.9878	0.0025	2021	1810–1893	NA	NA	V
H-2	OZAD67	1.009	0.0031	2020	2020	2020	0	O
H-3	OZAD68	1.0266	0.0032	2020	2011–2020	2015.5	4.5	P
H-4 *	OZAD69	1.0133	0.0025	2020	2020	2020	0	O
H-5 *	OZAD70	1.0124	0.0037	2020	2019–2020	2019.5	0.5	O
H-6	OZAD71	1.0097	0.0032	2020	2020	2020	0	V
H-7	OZAD72	1.0252	0.0033	2020	2011–2020	2015.5	4.5	O
H-8 *	OZAD73	1.0237	0.0063	2021	2012–2021	2016.5	4.5	P
H-9	OZAD74	1.0184	0.003	2021	2020–2021	2020.5	0.5	O
H-10	OZAD75	1.0159	0.0031	2020	2020	2020	0	O
H-11 *	OZAD76	1.0074	0.0036	2020	2019–2020	2019.5	0.5	O
H-12 *	OZAD77	1.0308	0.0061	2021	2010–2021	2015.5	5.5	V
H-13	OZAD78	1.0218	0.0032	2021	2020–2021	2020.5	0.5	O
H-14	OZAD79	1.0135	0.003	2021	2020–2021	2020.5	0.5	V
H-15 *	OZAD80	1.0264	0.003	2021	2011–2020	2015.5	5.5	O
H-16	OZAD81	1.0172	0.0027	2021	2020–2021	2020.5	0.5	V
H-17 *	OZAD82	1.0089	0.0027	2021	2020–2021	2020.5	0.5	O
H-18	OZAD83	1.0181	0.0029	2021	2020–2021	2020.5	0.5	P
H-19 *	OZAD84	1.0173	0.0108	2021	2015–2021	2019	2	P
H-20	OZAD85	1.0234	0.0029	2021	2011–2021	2016	5	O
H-22 *	70,426	1.0135	0.0015	2021	2020–2021	2020.5	0.5	P
H-23	70,429	1.0223	0.0015	2021	2011–2021	2016	0.5	P
H-24 *	70,430	0.9897	0.0014	2021	1844–1890	NA	NA	V
H-25	70,431	1.0187	0.0015	2021	2020–2021	2020.5	0.5	V
H-26	70,432	1.0210	0.0017	2021	2020–2021	2020.5	0.5	O
H-27 *	70,614	1.0050	0.0020	2021	1934–1954	NA	NA	O
H-28 *	70,433	1.0160	0.0323	2021	2003–2021	2011.5	9.5	O
H-29 *	70,435	1.0197	0.0015	2021	2020–2021	2020.5	0.5	O
H-30 *	70,436	1.0198	0.0015	2021	2020–2021	2020.5	0.5	O

Note: * Individuals with dyed hair. V = Vegetarian. O = Omnivore. P = Pescatarian.

Table 2
14 C results of the nail samples.

ID	SANU#/ ANSTO code	$F^{14}C$	Error	'YOD'	Predicted Range	Predicted median 'YOD'	Lag time (yrs.)	Diet
N-1	OZAQ26	1.022	0.0023	2021	2012–2021	2016.5	4.5	V
N-2	OZAQ27	1.0212	0.0022	2020	2020–2020	2020	0	O
N-3	OZAQ28	1.0199	0.0028	2020	2020–2020	2020	0	P
N-4	OZAQ29	1.0213	0.0025	2020	2020–2020	2020	0	O
N-5 *	OZAQ30	1.0209	0.0021	2020	2020–2020	2020	0	O
N-6	OZAQ31	1.0233	0.0023	2020	2011–2020	2015.5	4.5	V
N-7	OZAQ32	1.0262	0.0022	2020	2011–2019	2015	5	O
N-8	OZAQ33	1.0173	0.0021	2021	2020–2021	2020.5	0.5	P
N-9	OZAQ34	1.0156	0.0022	2021	2020–2021	2020.5	0.5	O
N-10	OZAQ35	1.0226	0.0028	2020	2012–2020	2016	4	O
N-11	OZAQ36	1.0235	0.0027	2020	2011–2020	2015.5	4.5	O
N-12 *	OZAQ37	1.02	0.0027	2021	2020–2021	2020.5	0.5	V
N-13	OZAQ38	1.0205	0.0026	2021	2020–2021	2020.5	0.5	O
N-14	OZAQ39	1.0193	0.0026	2021	2020–2021	2020.5	0.5	V
N-15	OZAQ40	1.0199	0.0028	2021	2020–2021	2020.5	0.5	O
N-16	OZAQ41	1.0187	0.0025	2021	2020–2021	2020.5	0.5	V
N-17 *	OZAQ42	1.0196	0.0026	2021	2020–2021	2020.5	0.5	O
N-18 *	OZAQ43	1.0233	0.0026	2021	2011–2021	2016	5	P
N-19	OZAQ44	1.0173	0.0028	2021	2020–2021	2020.5	0.5	P
N-20	OZAQ45	1.0219	0.0028	2021	2019–2021	2020	1	O
N-21 *	70,425	1.0150	0.0015	2021	2020–2021	2020.5	0.5	P
N-22	70,427	1.0163	0.0014	2021	2020–2021	2020.5	0.5	P
N-23	70,416	1.0175	0.0013	2021	2020–2021	2020.5	0.5	P
N-24	70,417	1.0186	0.0015	2021	2020–2021	2020.5	0.5	V
N-25	70,418	1.0176	0.0012	2021	2020–2021	2020.5	0.5	V
N-26	70,419	1.0156	0.0012	2021	2020–2021	2020.5	0.5	O
N-27 *	70,616	0.9892	0.0025	2021	1694–1917	NA	NA	O
N-28	70,421	1.0193	0.0013	2021	2020–2021	2020.5	0.5	O
N-29	70,423	1.0194	0.0013	2021	2020–2021	2020.5	0.5	O
N-30 *	70,424	1.0122	0.0014	2021	2020–2021	2020.5	0.5	O

Note: * Individuals who used nail polish weekly. V = Vegetarian. O = Omnivore. P = Pescatarian.

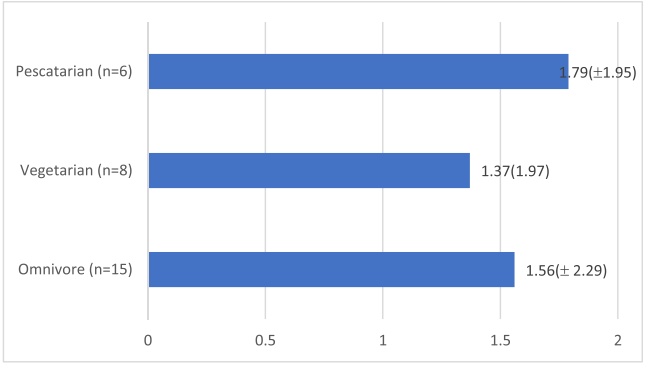

Fig. 2. Average combined lag time (years) of hair and nail samples.

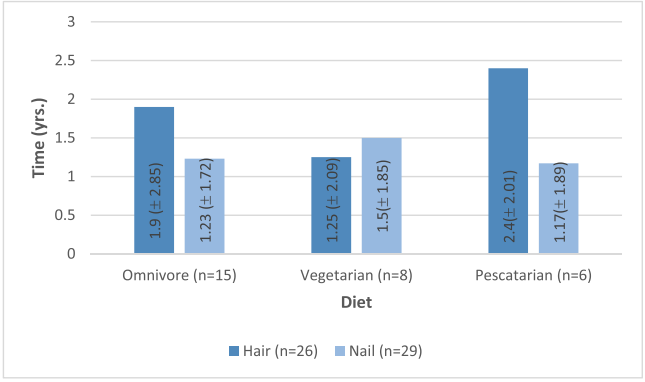

Fig. 3. Average lag time (years) of hair and nail samples.

Table 3
Average $F^{14}C$ content.

	Omnivore (n = 15)	Vegetarian (n = 8)	Pescatarian (n = 6)
Hair (n = 26)	1.02 (+/- 0.006)	1.01 (+/- 0.014)	1.02 (+/−0.004)
Nail (n = 29)	1.02 (+/- 0.003)	1.02 (+/−0.002)	1.02 (+/−0.003)

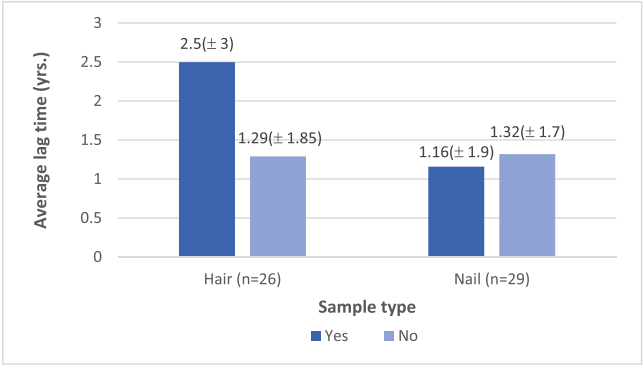

Fig. 4. Average lag time (years) of hair and nail samples of those who did (yes) and did not (no) use beauty products.

When examining the average ^{14}C content in the different diet groups, the differences were negligible (Table 3). All groups had an average $F^{14}C$ content of 1.02, with the exception of the vegetarian hair samples, whose average was 1.01.

The average lag times of those who used hair dye or nail polish compared to those who did not are shown in Fig. 4. The samples of dyed hair, on average provided the highest lag time, while the smallest average lag time was provided by the nail samples of those who used nail polish.

4. Discussion

This study analysed samples of hair and nail donated by 30 individuals to determine their ^{14}C content and examine the accuracy with which these tissues can estimate the YOD. When examining the relationship between the 'YOD' and the 'predicted YOD', an overall combined lag time of 1.6 years was determined when both tissue types were combined. This provides a much-improved YOD timeframe compared to traditional forensic anthropological methods which are based on the visual examination of skeletal weathering and can be highly inaccurate and often span decades due to the high variability of factors such as botanical changes, or environmental factors. This is consistent with previous studies examining the lag time of human hair and nails, which have generally provided an average lag time of around 1 year [5,29].

When comparing the two tissue types in this study, nail samples were found to contain the most recent ^{14}C content and provided a more precise YOD estimation than hair samples, with a slightly lower average lag time: 1.3 years and 1.9 years respectively. Consequently, both sample types could provide relevant information in forensic anthropological casework. These results support previous research which has shown nails to provide a more accurate estimation of YOD than hair [5,20].

The influence that diet may have on the ^{14}C content of the hair and nail samples was also examined in this study. While previous research by Johnstone-Belford et al. [5] demonstrated that the analysis of both nail and hair samples can assist with the determination of YOD, providing a YOD estimate within 1 or 2 years of the actual YOD respectively, little research has examined the factors that may influence this estimation. To determine the impact that diet has on the uptake of ^{14}C, this pilot study examined a cohort that included omnivores, vegetarians and pescatarians. The lag times (Fig. 2) suggest that diet may not impact the level of ^{14}C within hair and nail samples. When separating the diet groups into hair and nail samples (Fig. 3), the nail samples provided a smaller lag time in both the omnivorous and pescatarian groups. The hair was slightly more accurate than the nails in the vegetarian group, with a lag time of 1.3 years vs 1.5 years respectively. Although it appears that the hair samples collected from the pescatarian group have a marginally higher average lag time than the samples from the other diet groups, it is a relatively small increase, and again, due to the small sample size of the pescatarian group, cannot be statistically quantified.

Previous research has shown that the marine reservoir effect may impact the level of ^{14}C within a sample [30,31], but these studies are largely based on the traditional radiocarbon dating of marine samples. Unlike in our study, recent mathematic modelling by Georgiadou and Stenstrom has suggested that diet may significantly impact the level of ^{14}C within a sample [17]. The difference to our study may be due to the limited sample size in the pescatarian group compared to the omnivorous group and may not be representative of the broader pescatarian community. It is also possible that the similarity between the diet groups may be due to the modern, globalised diet. This includes a significant increase in the consumption of processed foods, but may also impacted by modern farming techniques which use greenhouses with high CO_2 levels, resulting in produce with a lower ^{14}C than that grown in a natural environment [32,33]. Although the intake of protein type differs between the three diet groups, the supplemental dietary intake of the donors is unknown, which may be a balancing factor in the ^{14}C content in these tissues. This study suggests that diet may not have a substantial impact on the level of ^{14}C within human tissues and should not be considered a limiting factor in forensic casework.

Similarly, the use of beauty products did not impact on the content of ^{14}C within the hair and nail samples. The average lag time for nail samples was found to be marginally lower in those that did use nail polish regularly compared to those who did not (1.2 years vs 1.3 years) (Fig. 4). However, this difference was not found to be significant suggesting that the regular use of nail polish did not impact the level of ^{14}C within the nail. The results of one sample (N-27) contradicted this trend, providing a calibrated age range between 1694 and 1917 AD. This result may be due to nail polish contamination, suggesting that care must be taken with chemical pre-treatment, and that nail samples may all benefit from an acetone wash prior to an ABA treatment to remove any traces of nail polish. However, the corresponding hair sample from this individual (H-27) also contained low levels of ^{14}C, that corresponded to a pre-modern (1934–1954) time. This suggests that the ^{14}C levels in this individuals hair and nails may have been impacted by something other than beauty products, such as vitamin supplements, or amino acids, both of which can be sources of ^{14}C free carbon [34].

The average lag time for the hair samples of those who had dyed their hair within the last year of the sample being collected was marginally higher, at 2.5 years, than those who had not dyed their hair within the last year, who had an average lag time of 1.3 years (Fig. 4). While the higher average lag time seen in the samples with hair dye may suggest that the use of hair dye can lower the ^{14}C content in human hair, the difference was not found to be statistically significant. Further research, utilising a larger sample size may provide clarity regarding the impact that hair dye has on ^{14}C levels in human hair.

Two samples of dyed hair (H-27 and H-24), however, did contain significantly lower levels of $F^{14}C$ (0.99 and 1.0050), dating the hair to pre-modern (pre-1950) times. Both individuals' hair had been dyed within the last year, although the specific type of dye was unknown. Due to the pre-modern level of ^{14}C, these samples were removed from all analysis, as to not introduce extra error.

Santos et al. [35], examined the impact of hair dye on the level of ^{14}C, by comparing the ^{14}C in dyed head hair, body hair and a nail from one individual and found substantial differences between the ^{14}C content of all three samples. However, the overall results of this pilot study did not support this hypothesis, suggesting that a specific type of hair dye may be the cause of ^{14}C contamination. The results of sample H-1 should also be noted, as although this individual did not dye their hair, the ^{14}C result was significantly older than the actual hair age. While it is not possible to know exactly why this sample contained such a low ^{14}C level, one possible explanation is that another form of hair treatment (other than hair dye), such as a long-lasting keratin treatment, or a perm treatment, may have contaminated the ^{14}C within the sample. Further research may benefit from including a variety of long-lasting hair treatments to determine their effect on stored ^{14}C. Alternatively, the low level of ^{14}C in this sample may be due to technical error, as it was noted that there was machine instability when running this sample.

Although a limitation of this pilot study was the small sample size, this study provides a framework for future investigations into the factors that may affect the uptake and storage of ^{14}C within human tissues, and possible reasons for how they affect the applicability of bomb pulse dating to forensic casework.

5. Conclusion

This study examined factors that may affect the content of ^{14}C in both human hair and nails. The radiocarbon analysis of hair or nail samples in forensic anthropological casework may provide vital information regarding the YOD, and the time since death. Both the hair and nail samples in this study were found to provide satisfactory estimates of YOD, in keeping with previous literature, with an average lag time of 1.9 years and 1.3 years respectively. Differences in diet did not appear to impact the content of ^{14}C in either hair or nails, suggesting that the diet of the decedent will not impact the YOD estimation. Similarly, the regular use of nail polish did not impact the ^{14}C content in nails and should not be considered a limiting factor when analysing nail samples, if sample preparation

removes all traces of polish. Hair dye however, while not significantly impacting the ^{14}C level in most hair samples, may have lowered the ^{14}C content in two samples. Consequently, the analysis of multiple samples is recommended where possible to provide the most precise estimate of YOD.

CRediT authorship contribution statement

Eden Johnstone-Belford: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Stewart J Fallon:** Methodology, Validation, Formal analysis, Investigation, Resources, Writing – review & editing, Supervision. **Geraldine Jacobsen:** Methodology, Validation, Formal analysis, Investigation, Resources, Writing – review & editing, Supervision. **Joanna F Dipnall:** Validation, Formal analysis, Data curation, Writing – review & editing. **Soren Blau:** Conceptualization, Methodology, Validation, Writing – review & editing, Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] G.W.L. Hodgins, Measuring atomic bomb-derived 14C levels in human remains to determine year of birth and/or year of death, US Dep. Justice, Natl. Inst. Justice: Wash. DC (2009) 98.
[2] I. Levin, et al., Observations and modelling of the global distribution and long-term trend of atmospheric 14CO2, Tellus Ser. B, Chem. Phys. Meteorol. 62 (1) (2010) 26–46.
[3] K. Stenstrom, et al., Local variations in C-14 - How is bomb-pulse dating of human tissues and cells affected? Nucl. Instrum. Methods Phys. Res. Sect. B-Beam Interact. Mater. At. 268 (7–8) (2010) 1299–1302.
[4] Q. Hua, M. Barbetti, Review of tropospheric bomb 14C data for carbon cycle modeling and age calibration purposes, Radiocarbon 46 (3) (2004) 1273–1298.
[5] E. Johnstone-Belford, et al., Examining the use of different sample types following decomposition to estimate year of death using bomb pulse dating, J. Forensic Leg. Med 85 (2022) 102275-102275.
[6] R.A. O'Reilly, A. Ruffell, P.J. Reimer, Suspect graveyard burial (South Armagh, N. Ireland): combined search, forensic anthropology and radiocarbon dating, Sci. Justice 63 (1) (2023) 1–8.
[7] E. Johnstone-Belford, et al., The importance of bone sample selection when using radiocarbon analysis in cases of unidentified human remains, Forensic Sci. Int. 341 (2022) 111480-111480.
[8] N. Lynnerup, et al., Radiocarbon dating of the human eye lens crystallines reveal proteins without carbon turnover throughout life (radiocarbon dating eye lenses), PLoS ONE 3 (1) (2008) e1529.
[9] S.J. Flood, et al., A comparison of Demirjian's four dental development methods for forensic age estimation in South Australian sub-adults, J. Forensic Leg. Med. 20 (7) (2013) 875–883.
[10] S. Karkhanis, P. Mack, D. Franklin, Dental age estimation standards for a Western Australian population, Forensic Sci. Int. 257 (2015) 509.e1–509.e9.
[11] M. Kondo-Nakamura, et al., Single tooth tells us the date of birth, Int. J. Leg. Med. 125 (6) (2011) 873–877.
[12] E.C. Johnstone-Belford, S. Blau, A review of bomb pulse dating and its use in the investigation of unidentified human remains, J. Forensic Sci. (2019).
[13] E.M.J. Schotsmans, N. Márquez-Grant, S.L. Forbes (Eds.), Taphonomy of Human Remains: Forensic Analysis of the Dead and the Depositional Environment, John Wiley & Sons, Incorporated, New York, 2017.
[14] L. Biehler-Gomez, et al., Frequency of biological non-skeletal materials in dry bone scenarios, J. Forensic Leg. Med 78 (2021) 102125-102125.
[15] S. Yaemsiri, et al., Growth rate of human fingernails and toenails in healthy American young adults, J. Eur. Acad. Dermatol. Venereol. 24 (4) (2010) 420–423.
[16] D.A. Whitting, U. Blume-Peytavi, A. Tosti, R.M. Trüeb (Eds.), Hair Growth and Disorders, Springer Berlin Heidelberg, Berlin, Heidelberg: Berlin, Heidelberg, 2008.
[17] E. Georgiadou, K. Stenstrom, Bomb-pulse dating of human material: modeling the influence of diet, Radiocarbon 52 (2) (2010) 800–807.
[18] L. Ortlieb, G. Vargas, J.-F. Saliège, Marine radiocarbon reservoir effect along the northern Chile–southern Peru coast (14–24°S) throughout the Holocene, Quat. Res 75 (1) (2011) 91–103.
[19] Y. Ma, K.H. Kwon, Changes in purchasing patterns in the beauty market due to Post–COVID-19: Literature review, J. Cosmet. Dermatol. 20 (10) (2021) 3074–3079.
[20] G.M. Santos, et al., Improved radiocarbon analyses of modern human hair to determine the year-of-death by cross-flow nanofiltered amino acids: common contaminants, implications for isotopic analysis, and recommendations, Rapid Commun. Mass Spectrom. 29 (19) (2015) 1765–1773.
[21] Q. Hua, et al., Progress in radiocarbon target preparation at the ANTARES AMS centre, Radiocarbon 43 (2001) 275–282.
[22] K.M. Wilcken, et al., From carbon to actinides: A new universal 1MV accelerator mass spectrometer at ANSTO, Nucl. Instrum. Methods Phys. Res. Sect. B: Beam Interact. Mater. At. (2015).
[23] S.J. Fallon, L.K. Fifield, J.M. Chappell, The next chapter in radiocarbon dating at the Australian National University: status report on the single stage AMS, Nucl. Instrum. Methods Phys. Res. Sect. B, Beam Interact. Mater. At. 268 (7) (2010) 898–901.
[24] P.J. Reimer, T.A. Brown, R.W. Reimer, Discussion: reporting and calibration of post-bomb 14C data, Radiocarbon 46 (3) (2004).
[25] J.C. Turnbull, S.E. Mikaloff Fletcher, I. Ansell, G.W. Brailsford, R.C. Moss, M.W. Norris, K. Steinkamp, Sixty years of radiocarbon dioxide measurements at Wellington, New Zealand: 1954–2014, Atmos. Chem. Phys. 17 (2017) 14771–14784.
[26] Q. Hua, et al., Atmospheric radiocarbon for the period 1950–2019, Radiocarbon 64 (4) (2022) 723–745.
[27] C. Bronk Ramsey, Bayesian analysis of radiocarbon dates, Radiocarbon 51 (1) (2009) 337–360.
[28] StataCorp, Stata Statistical Software: Release 16, StataCorp LLC, College Station, TX, 2021.
[29] W.S. Broecker, A. Schulert, E.A. Olsen, Bomb carbon-14 in human beings, Science 130 (3371) (1959) 331–332.
[30] J.E. Gordon, D.D. Harkness, Magnitude and geographic variation of the radiocarbon content in Antarctic marine life: Implications for reservoir corrections in radiocarbon dating, Quat. Sci. Rev. 11 (7–8) (1992) 697–708.
[31] A.S. Commendador, et al., Radiocarbon dating human skeletal material on rapa nui: evaluating the effect of uncertainty in marine-derived carbon, Radiocarbon 56 (1) (2014) 277–294.
[32] S. Jew, S.S. AbuMweis, P.J.H. Jones, Evolution of the human diet: linking our ancestral diet to modern functional foods as a means of chronic disease prevention, J. Med Food 12 (5) (2009) 925–934.
[33] J. van der Plicht, J.P. Beijers, Radiocarbon in food: a non-problem of health effects, Environ. Chem. Lett. 9 (2) (2011) 167–168.
[34] K. Ivanov, et al., Biotechnology in the production of pharmaceutical industry ingredients: amino acids, Biotechnol. Biotechnol. Equip. 27 (2014) 3620–3626.
[35] G.M. Santos, et al., Improved radiocarbon analyses of modern human hair to determine the year-of-death by cross-flow nanofiltered amino acids: common contaminants, implications for isotopic analysis, and recommendations, Rapid Commun. Mass Spectrom. 29 (19) (2015) 1765–1773.