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RESEARCH ARTICLE

Reading between the lines: A study of Harris lines in Middle Holocene foragers of the Cis-Baikal

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Abstract

Harris lines (HLs) are radiographically visible transverse lines of thickened bone that develop from temporary growth cessation during early life. Often attributed to physiological stress during development, HLs are frequently observed in the long bones of adolescents and become less visible over time due to bone remodeling. In recent years, the validity of HL as a sign of stress has been called into question and the methods used in studying HL through X-ray analysis scrutinized. In this study, 80 individuals from the Middle Holocene Cis-Baikal region of Siberia, from the Early Neolithic (EN; 7560–6660 HPD cal. BP) and Late Neolithic (LN; 6060–4970 HPD cal. BP), were studied for the presence and severity of HL. Radiographic analysis employed both the traditional clinical anteroposterior (A–P) orientation and a potentially improved mediolateral (M–L) orientation. EN groups in the Cis-Baikal are known to have experienced higher levels than their LN counterparts; thus, if HL reflect stress experiences, we expected to see more HL in the EN population compared with the LN population. We also expected more visible HL in the M–L orientation due to the suggested improvement in capturing more lines compared with the A–P orientation. While the results support the use of M–L orientation during X-ray capture of HL, there was not a higher number of HL in the EN population as expected. Instead, no significant differences were found in HL severity between the EN and LN populations, and age-at-death resulted in a greater effect on HL counts regardless of mortuary site. The results from this study align not with known stress data from the Middle Holocene Cis-Baikal populations but rather with data pertaining to known growth patterns. We therefore advocate against the use of HL as a sign of physiological stress and instead suggest HL as a reflection of bone growth trajectory.

KEYWORDS

Early Neolithic, growth arrest, Late Neolithic, physiological stress, radiography, transverse lines

1 | INTRODUCTION

In the realm of human osteoarchaeology, physiological stress represents a complex and multi-faceted consideration. In life, any condition, whether internal or external, that alters the homeostatic environment of the body is deemed a stressor (Blackwell et al., 2001; Goodman et al., 1988; Hans Selye, 1973; Selye, 1976). Malnutrition and disease are two such examples that can alter the appearance of the body, including the skeleton, in life (Cameron & Schell, 2012; Harris, 1931; Park, 1964). However, not all stressors that affect the human body are visible on the skeleton, and those that are cannot always be associated with a specific stress event (Roberts & Manchester, 2005). In fact, most stress lesions visible on the skeleton are non-specific, meaning that their causative mechanisms (infectious, nutritional, or other) cannot be identified (Goodman et al., 1984). These lesions are often termed non-specific indicators of physiological stress (Goodman et al., 1988; Roberts & Manchester, 2005; Wells, 1967).

Harris lines (HLs), also known as transverse lines, or lines of arrested growth, are suggested to be one such indicator of stress, but they can only form before an individual reaches skeletal maturity (Mays, 1999). HLs represent an interruption in longitudinal growth of the long bones and the resumption of growth; an individual must sufficiently "recover" from the instigating growth disruptor and resume normal growth for a line to form (Beom et al., 2014; Harris, 1931; Mays, 1985; Miszkiewicz, 2015; Park, 1954; Park & Richter, 1953). Studies of childhood morbidity trends suggest most HL develop after 6 months of age and peak during the first 5 years of life, often coinciding with the average weaning age of a population (Clarke, 1980; Clarke & Gindhart, 1981; Dreizen et al., 1964). Consequently, periods of highest HL frequency are often culturally specific. Although HL may form in any bone that undergoes endochondral ossification, they are most visible in the tibiae, specifically, the distal portion (Garn et al., 1968; Park, 1964; Park & Richter, 1953).

There are many factors that can influence the appearance of HL and even more hypotheses as to how bone growth is sufficiently interrupted to initialize their formation. Two leading hypotheses as to the causative effects behind HL formation can be summarized as follows: (1) HL formation is directly correlated to physiological stress stemming from a multitude of possible insults to the body before skeletal maturity (Buikstra, 1976; Currie et al., 1956; González-Reimers et al., 1993; González-Reimers et al., 2007; Goodman & Clark, 1981; Harris, 1934a; McHenry, 1968; Zapala et al., 2016); and (2) HL does not represent stress events to the body but rather normal stops and starts during bone growth and development (Alfonso Durruty et al., 2006; Alfonso-Durruty, 2011; Larsen, 2015; Papageorgopoulou et al., 2011). In addition to whether or not physiological stress events are responsible for HL formation, critiques also include how HL data are collected and subsequently interpreted. Though it is possible to estimate the age of formation of individual HL, this requires visible HL for analysis (Michał J. Kulus et al., 2024; Michał Jerzy Kulus & Dąbrowski, 2019; Papageorgopoulou et al., 2011). As a living tissue, bone is subject to remodeling throughout life via resorption and formation. Bone remodeling is crucial to overall skeletal health as it adapts bone architecture in response to mechanical loading or strain, repairs micro-damages to the bone surface, and replaces old bone (Frost, 1990; Ruff et al., 2006; Turner, 1998). Because HL can only form during early life (i.e., before skeletal maturity), the natural processes of bone remodeling in the adult years can cause HL to disappear gradually (Garn et al., 1968). As such, the study and integrity of HL are hindered by the potential effects of bone remodeling the older an individual is. To minimize the loss of HL data because of bone remodeling, HLs are theoretically best studied in younger individuals (Roberts & Manchester, 2005). Remodeling has also been shown to affect visibility of HL in standard radiographs (Garn et al., 1968; Scott & Hoppa, 2015). Early discussion by Garn et al. (1968) and a subsequent study by Scott and Hoppa (2015) suggest that HLs are best visualized radiographically when imaged in the mediolateral (M–L) orientation instead of the standard clinical anteroposterior (A–P) orientation because of the direction of normal bone remodeling across the bone shaft. Scott and Hoppa (2015) also suggest that radiograph orientation discrepancies could be contributing the underusage and criticism of HL in osteological research.

The influence of radiographic orientation, inconsistent methods of HL counting by researchers, and the unclear correlation of HL with stress events comprise some of the main criticisms surrounding HL in osteoarchaeological studies (Garn et al., 1968; Goodman & Clark, 1981; Mays, 1995; Papageorgopoulou et al., 2011; Roberts & Manchester, 2005). The objectives of this paper are to address these criticisms through an exploration of HL among the Middle Holocene foragers of Siberia's Cis-Baikal region. The Cis-Baikal forager populations are well suited to test correlations with physiological stress because, over the last several decades, they have been the subjects of extensive osteoarchaeological research, providing an abundance of detailed contextual data. Dating to the Early Neolithic (EN; 7560–6660 HPD cal. BP) and Late Neolithic (LN; 6060–4970 HPD cal. BP; (Weber et al., 2021; Weber & Bettinger, 2010), these populations lie on either side of a unique period of biocultural and climatic transition, the Middle Neolithic, which lacks human osteoarchaeological evidence (Weber et al., 2021). Numerous studies have demonstrated significantly higher levels of physiological stress among the EN through comparative studies of community health and disease (Lieverse, 2010; Lieverse, Link, et al., 2007; Purchase, 2016; Waters-Rist et al., 2016) infant weaning ages (Scharlotta et al., 2018; Waters-Rist et al., 2011), skeletal growth (Osipov et al., 2020; Temple et al., 2014), non-specific infection-induced lesions (Purchase, 2016), and dental indicators of physiological stress (Lieverse, Weber, et al., 2007; Link, 1999; Waters-Rist, 2011). The varying experiences among these two temporally distinct, but spatially connected, populations provide a suitable context for the examination of HL. If HLs are indeed tied to physiological stress experiences during development, then EN individuals should have higher counts than LN individuals. To reduce the effects of bone remodeling, only young (≤25 years) individuals are included, with a further focus on the correlation of HL with age at death. Finally, although osteoarchaeological research is often limited by sample biases and preservation issues, the Middle Holocene Cis-Baikal populations are generally well preserved and include numerous younger individuals from formal graves. Because of the condition of the remains and our subsequent ability to take multiple radiographs, we also explore the association between radiograph orientation and HL visibility. This study has three objectives: (1) to test whether radiographic orientation can impact HL visibility, (2) to test the effect of age-at-death on HL counts, and (3) to test whether HL data reflect previously documented differences in stress experiences between the EN and LN foragers of the Cis-Baikal.

2 | MATERIALS AND METHODS

For this study, tibiae of 80 individuals from three Middle Holocene Cis-Baikal cemetery populations were examined radiographically. Two of these date to the EN period (Shamanka II, $n = 34$; Lokomotiv, $n = 22$) and one dates to the LN period (Ust'-Ida I, $n = 24$; Figure 1). To minimize the potential for age-related bone remodeling and subsequent loss of visible HL, only individuals aged 25 years and under at death were included for analysis. Individuals were also placed into four distinct age-at-death groups (0–5, 6–12, 13–20, and 21–25-years-at-death) to facilitate trend analysis of visible HL (Table 1 below). Age and biological sex data used herein represent the combined efforts of several researchers using both morphological (Lieverse, 2005, 2010; Lieverse et al., 2024; Link, 1999) and, in select cases, molecular (de Barros Damgaard et al., 2018; Moussa et al., 2018; Thomson, 2006) analyses.

Digital radiographs were captured using the NOMAD Pro Hand-Held X-ray System (Aribex) and the Dr. Suni Plus Digital Light Sensor (SUNI Medical Imaging Inc.). The NOMAD Pro Hand-Held X-ray System delivers exposure at 60 kVp with a radiographic density of 2.5 mAs and is non-adjustable. However, exposure time can be controlled to avoid overexposure (as was necessary with very young individuals with lower overall bone density and size). Depending on the size of each tibia, exposure time ranged from 0.12 to 0.04 of a second. Owing to the portability of the machine and small size of the sensor's active area (approximately 3 cm × 2 cm), radiographs were taken in

FIGURE 1 A map of the Cis-Baikal region. Cis-Baikal and the locations of the three cemeteries examined in this paper (EN Shamanka II, EN Lokomotiv, and LN Ust'-Ida I; black) and modern towns/cities (red). Map by C. Liepe and used with permission. Topography based on elevation Shuttle Radar Topography Mission (SRTM) v4.1 data (Jarvis et al., 2008). [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Distribution of individuals included for HL capture.

Cemetery	Age group*	Male	Female	Undetermined	Total
Shamanka II (EN) $n = 34$	0–5	0	0	8	8
	6–12	0	0	5	5
	13–20	5	5	0	10
	21–25	6	5	0	11
Lokomotiv (EN) $n = 22$	0–5	1	0	0	1
	6–12	1	0	7	8
	13–20	3	1	0	4
	21–25	3	5	1	9
Ust'-Ida I (LN) $n = 24$	0–5	0	1	3	4
	6–12	5	3	8	16
	13–20	2	1	1	4
	21–25	0	0	0	0
*in years of age at death					80

Abbreviations: EN, Early Neolithic; HL, Harris line; LN, Late Neolithic.

sequential, overlapping increments beginning at the distal end of the bone and ending at the midshaft (overlap measured approximately 0.5 cm). The digital radiographs were then matched up sequentially to form a complete X-ray image for visual analysis in the open-source digital software Fiji (ImageJ). Each tibia deemed to be in acceptable condition, that is, with minimal damage to the distal end trabeculae, was radiographed in both standard clinical A–P and M–L orientations. Though asymmetry has been shown to be minimal when conducting HL analysis in both the A–P orientation (Hughes et al., 1996) and recently in the M–L orientation for adults (Scott & Hoppa, 2015), both the left and right tibiae were radiographed when possible.

A single HL was counted based on the following criteria (Figure 2): (1) the line extended across at least 50% of the bone's diaphyseal breadth, and (2) the line was primarily transverse in orientation (Clark, 1981; Mays, 1985, 1995, 1999). To ensure analysis was unbiased, all individuals were anonymized, scored for HL in the A–P view first, then the M–L view 1 week later. HL counts were then analyzed with consideration for the age at death, site of origin, and biological sex of the individuals included for study.

To ascertain the risk of intra-observer error, 35 individuals from the entire sample were randomly selected, scored for HL in both A–P and M–L orientation, then scored again 3 weeks later by the primary author. Twenty-one of the 35 individuals had both tibiae in acceptable condition for imaging; thus, a total of 56 tibiae were included. Intraobserver error was then calculated using a correlation coefficient for both orientations in Excel.

As an additional precaution, asymmetry was also tested in individuals from the total sample population that had both left and right tibiae in acceptable condition for imaging. This included 66 individuals (132 tibiae) and was done using a Mann Whitney *U* test in SPSS.

To determine whether A–P or M–L radiograph capture was more effective, raw counts of identified HL in both orientations were compared using a Wilcoxon signed test in SPSS. In total, 170 tibiae were imaged from across the three mortuary populations included in this study. This included both left and right when available, and others from the skeletal collection aged 25 years or younger at death in sufficient condition for imaging that did not belong to the EN or LN.

A non-parametric ranked analysis of variance (ANOVA) was conducted in SPSS to test the individual effects of both the four age-at-death categories (0–5, 5–12, 13–20, and 21–25 years) and three cemetery populations (Shamanka II, Lokomotiv, and Ust'-Ida I) against HL counts. As an additional measure, two-way ANOVA was also conducted as a parametric test to examine the interactive effects of age and site on overall HL counts. A Tukey post hoc test was then conducted to determine if any of the four age groupings had a significant effect on mean HL counts for the total sample without consideration for individual sites.

As seen above (Table 1), the 6–12 age group is over-represented in Ust-Ida I (LN) but under-represented in Shamanka II (EN). To control for this uneven distribution and ensure that it did not significantly impact the mean HL counts in the LN population or bias the results, a non-parametric alternative to the *t* test, the Mann–Whitney *U* test, was done to compare HL counts from only those individuals aged 6–12-years-at-death from the EN (Shamanka II and Lokomotiv pooled; $n = 13$) and the LN (UID; $n = 16$).

3 | RESULTS

3.1 | Intra-observer and asymmetry analyses

The intra-observer correlation coefficient showed a very high positive linear correlation between the initial and follow-up HL counts in both orientations (A–P: $r = 0.9773$; M–L: $r = 0.9797$). This means intra-observer reliability between the initial HL count and the following count 3 weeks later is very strong.

As with intra-observer error testing, both X-ray orientations were analyzed separately for asymmetry. The results of a Mann–Whitney

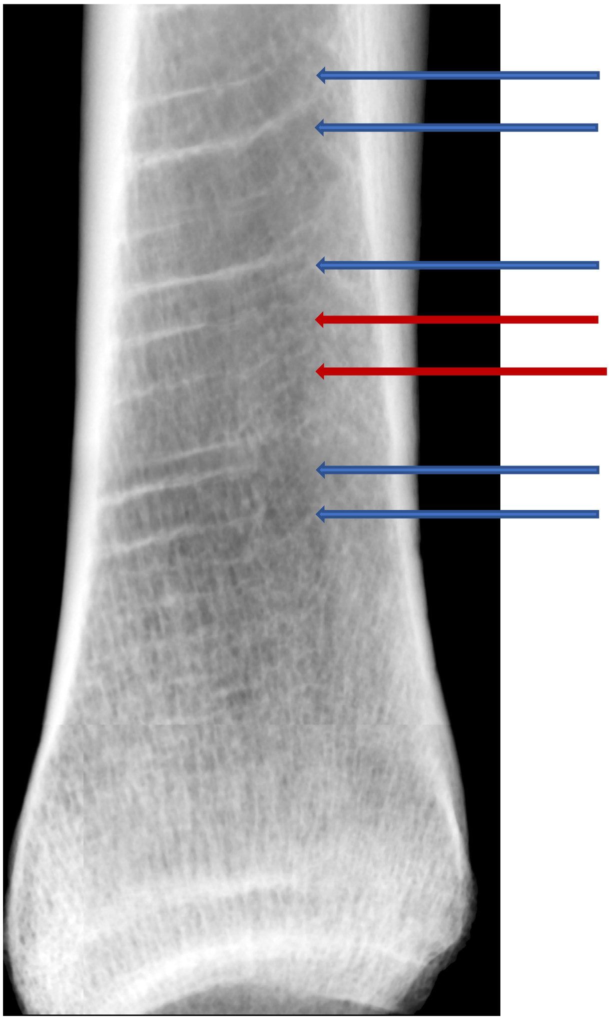

FIGURE 2 Radiograph (ML orientation) of Harris line (HL) in the distal tibia. Left tibia with 5 HL extending across 50% or more of the shaft (blue arrows). Note the two clearly visible partial HLs that do not extend across 50% or more of the shaft (red arrows), suggesting remodeling. (SHA_2003.025.01, Female. Age group 21–25). [Colour figure can be viewed at wileyonlinelibrary.com]

U test showed no statistically significant differences between left and right HL counts in either orientation ($P < 0.05$; AP: $P = 0.883$; M–L: $P = 0.901$). Results were consistent with previous studies of asymmetry (e.g., Hughes et al., 1996; Scott & Hoppa, 2015), so HL counts on left and right tibiae were used interchangeably for further analyses. In rare cases (A–P, $N = 3$; M–L, $N = 4$) where bilateral counts did not align for an individual, the higher of the two values was used.

3.2 | Anteroposterior versus mediolateral radiograph orientation

Once the preliminary analyses of intra-observer error and asymmetry were completed, statistical testing was then possible for the effect of A–P versus M–L orientation on HL counts. M–L orientation in this study resulted in a statistically significantly higher number of identifiable HL compared with A–P orientation as determined by a Wilcoxon signed test ($P < 0.001$; Table 2). As suggested by Garn et al. (1968) and shown by Scott and Hoppa (2015), M–L orientation results in higher (mean HL counts: A–P = 0.82 HL; M–L = 1.40 HL) and arguably more accurate counts of HL than does the standard clinical A–P imaging approach. Based on these results, further statistical analyses on the correlation of HL with site (Shamanka II and Lokomotiv, EN; Ust'-Ida I, LN) and age-at-death used HL counts from the M–L orientation alone.

3.3 | Correlation of HL with site and age-at-death

Statistical analyses for the interaction effects of the four age-at-death categories on mean HL counts by site found no significant interaction between age and site ($P = 0.405$). Site alone also showed no significant effect on HL counts. Instead, age alone had a significant effect on HL counts, regardless of site (Table 3).

Further analysis on the effect of age through a Tukey post hoc test found that the 6- to 12-year category, regardless of site, had the highest mean HL count of any of the four age groups. This average was also significantly higher than the 13- to 20-year group (mean difference of 1.40 HL), which coincides with a sharp decline in HL counts for all three sites (Figure 3). The results of this analysis therefore suggest that age-at-death is the only factor correlated with HL counts among the Cis-Baikal foragers with neither archaeological period (EN. vs. LN) nor, by extension, cemetery sample (Shamanka II and Lokomotiv, EN; Ust'-Ida I, LN) playing a significant role.

The results of a Mann–Whitney *U* test showed no statistically significant effect on mean HL counts for individuals aged 6–12-years-at-death despite being overrepresented in the LN population of Ust'-Ida I (Table 4). As such, the overall higher number of HL in the 6–12 age group does not appear to reflect overrepresentation from the LN site of Ust'-Ida I, nor does the higher number of individuals aged 6–12 from this site unduly bias our results.

4 | DISCUSSION

4.1 | Limitations to the study

There are three limitations to this study acknowledged by the authors that include the equipment used in X-ray image capture, the age distribution of the sample population, and the assumptions tied to the use of non-specific indicators of physiological stress, including HL, in osteoarchaeology.

First, the radiographic equipment used for the purpose of this research, though convenient in its transportability, is not capable of capturing the entire shaft of a tibia due to the small surface area of the sensor. As such, it was necessary to stitch together multiple images to form a complete image of the distal tibia portion for analysis. Each image captured was overlapped with the subsequent one

TABLE 2 Differences in the number of HL observed in A–P orientation versus M–L orientation.

Wilcoxon signed test							
Orientation	N	Mean	Q1	Median	Q3	SD	Sig. (M–L – A–P P value)
A–P	170	0.82	0.00	0.00	1.00	1.453	<0.001*
M–L	170	1.40	0.00	0.00	2.00	2.174	

Abbreviation: HL, Harris line.
*Significant at the $P < 0.05$ level. There is a significant difference in HL counts when comparing A–P to M–L orientation. Note that most in most cases, HL counts were zero. As such, the first quartile and median reflect this.

TABLE 3 Two-way ANOVA test for main interaction effects of age at death and site on mean counts of HL.

Dependent variable: HL			
Source	DF	F	Significance (P value)
Age	3	3.421	0.022*
Site	2	0.367	0.694
Site* Age	5	1.034	0.405
Total		80	

Abbreviation: HL, Harris line.
*Significant at the $P < 0.05$ level. Test of between-subjects effects for age at death (0–5, 5–12, 13–20, and 21–25 years) and site (EN Shamanka II, EN Lokomotiv, and LN Ust'-Ida I on the total sample population, $n = 80$) shows no significant effect ($P = 0.403$) on the total sample mean when age and site are combined. Site also has no significant effect on mean HL counts ($P = 0.694$). Age, however, does have a significant effect on mean HL counts ($P = 0.022$).

TABLE 4 Mann–Whitney *U* results for HL counts of EN and LN individuals aged 6–12-years-at-death.

Site	Sum of ranks	Count (N)	U statistic
EN	220	13	129
LN	215	16	79
Critical value ($P \leq 0.05$)			59
Z score			−1.0744
P value			0.28462*

Abbreviations: EN, Early Neolithic; HL, Harris line; LN, Late Neolithic.
*Not significant at the $P \leq 0.05$ level. A critical value of 59 (for sample sizes of $n = 13$ and $n = 16$; P value ≤ 0.05) is below the lowest *U* statistic (79). The null hypothesis cannot be rejected, and there is no significant effect of EN versus LN on HL.

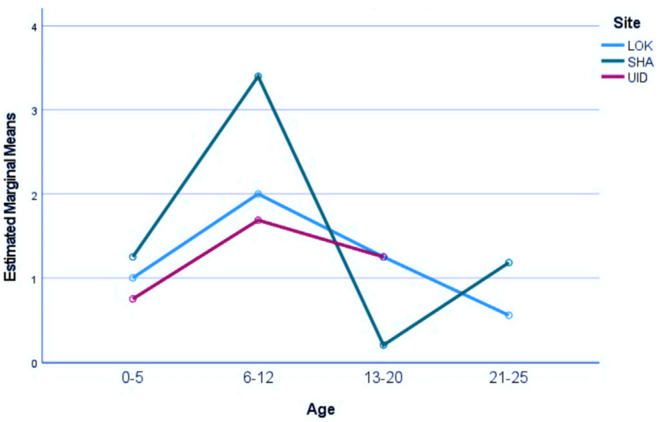

FIGURE 3 Mean Harris line (HL) counts by age. Mean HL counts by age for each cemetery. Note the highest mean for the age category 6–12 years old for all three sites. The UID cemetery age category 21–25 years is not plotted given that there are no individuals in that age category. SHA, Shamanka II (EN); LOK, Lokomotiv (EN); UID, Ust'-Ida I (LN). [Colour figure can be viewed at wileyonlinelibrary.com]

during X-ray capture to match up landmarks and form a complete image of the distal tibia. Figure 2 (above) was created in this way. Though non-handheld X-ray equipment is ideal for HL research, this study demonstrated that handheld equipment can be made suitable for small areas of interest, as required in HL image capture.

Second, the sample populations in this study are limited in their overall age distribution. Despite the large number of individuals from each of the three mortuary sites, the age distribution is not equal across the four age categories (0–5, 6–12, 13–20, and 21–25-years-at-death) nor within each site. Ust'-Ida I, as discussed, features a disproportionate number of individuals in the 6–12-years-at-death category ($n = 16$), whereas Shamanka II has very few ($n = 5$). Ust'-Ida I also has no individuals in the 21–25-years-at-death category. Nonetheless, the inferences made in this paper are supported statistically, and the benefit of studying HL in non-adult and young adult individuals is clear. Future studies may benefit from further reducing the age-at-death categories and more closely monitoring for the effects noted here in the 6- to 12-year group.

Finally, HLs are, by definition, a *non-specific* indicator of physiological stress. Though they can be analyzed in conjunction with other indicators of overall health, growth, stress, and nutrition, they are still debated in their connection to any specific type of growth insult during early life. As discussed above, HLs also require a period of recovery to form, which means they may be a sign of resiliency rather than morbidity. The substantial breadth of available data in relation to stress in the Middle Holocene Cis-Baikal forager populations included in this study presented an ideal chance to test the nature of HL formation in relation to known periods of physiological stress; however, the aetiological mechanisms behind HL formation are still not fully understood. This study purports that it is not possible here to determine whether HL formed as a response to physiological stress or to natural disruptions in growth.

4.2 | Radiographic orientation

Based on our analysis, M–L radiographic orientation results in significantly higher HL counts than the standard clinical A–P orientation. Though the results of this study concur with their findings, Scott and Hoppa (2015) were unable to determine a statistically significant difference between the two views in their examined sample of non-adults. This study was able to do so despite a broader age range (≤25 years) and larger sample size across the three cemeteries. Overall, this study both affirms the need to re-evaluate procedures for HL image capture and successfully demonstrates the efficacy of M–L orientation regardless of age of the individual.

It is important to note that, although M–L orientation resulted in higher HL counts among the Cis-Baikal populations, the goal of improving HL imaging techniques is to obtain more accurate, rather than higher, HL counts. Imaging techniques should best facilitate our ability to view the highest *consistent* count of HL. The results of this study and other comparisons of radiograph orientation not only demonstrate the importance of using M–L orientation for HL imaging but also support the theoretical concepts behind it.

There are many factors that can alter the appearance of HL, with normal bone remodeling being chief among them. During remodeling, bone is slowly removed along the transverse (M–L) plane (Garn et al., 1968). If we consider HL from a 2-dimensional perspective, a singular HL in the process of being remodeled is made smaller when viewed from the anterior or posterior. Bone modeling does not occur at an equal rate around the perimeter of a long bone; on the contrary, bone modeling occurs on the transverse plane meaning that, as bone is removed, new bone is equally deposited on that same plane (Garn et al., 1968; Scott & Hoppa, 2015). When radiographed from the medial or lateral side, a line will still extend across the entire shaft for a longer period of remodeling than in the A–P plane, at least until remodeling has reached the midline of the bone shaft. Nonetheless, controlled age profiles for a given sample population are suggested to be the best defense against loss of HL to remodeling (Scott & Hoppa, 2015).

4.3 | Physiological stress and age at death

Comparative studies of infant weaning ages (Scharlotta et al., 2018; Waters-Rist et al., 2011), skeletal growth rates (Osipov et al., 2020; Temple et al., 2014, 2021), non-specific infection-induced skeletal lesions (Purchase, 2016), and dental indicators of physiological stress including linear enamel hypoplasia (Lieverse, Link, et al., 2007; Link, 1999; Waters-Rist, 2011) and periodontitis (Lieverse, Link, et al., 2007) found that EN foragers experienced more severe and more frequent episodes of physiological stress than their LN counterparts. Studies within the EN alone also found that skeletal morphological indicators of activity including osteoarthritis and entheseal changes revealed unequal stress experiences between the EN populations of Shamanka II and Lokomotiv (Lieverse et al., 2009, 2013, 2016; Lieverse, Weber, et al., 2007). Contrarily, this study found no significant differences in HL counts among the EN and LN cemetery populations and no significant differences between the two EN cemetery populations. Instead, age-at-death significantly impacted HL counts for individuals across the entire sample. In fact, for all three sites, the highest HL counts were observed in individuals aged 6–12 years.

Researchers have known about the impact of bone remodeling on HL visibility for some time (Garn et al., 1968; McHenry, 1968), a limitation that can be at least partially mitigated by controlling for age-at-death and imaging orientation (as demonstrated here). However, the issue of HL resorption is not the only critique voiced by osteoarchaeologists. HL gained early popularity in anthropological studies (Buikstra & Cook, 1980), but its inconsistent correlation with other non-specific indicators of physiological stress presented points of contention (Papageorgopoulou et al., 2011). In some cases, HLs have been shown to have good correlation to episodes of physiological stress (Buikstra, 1976; González-Reimers et al., 2007, 1993; Goodman & Clark, 1981; Harris, 1931, 1934b; McHenry, 1968; Zapala et al., 2016). In other cases, HL frequency has been shown to *decrease* over time among populations displaying gradual *increases* in other osteological signs of physiological stress and reduced health outcomes (Cassidy, 1984; Goodman & Clark, 1981; Perzigian et al., 1984; Rose et al., 1984).

In response to its unclear association with physiological stress, critics purport that HL often occurs only because of normal stops and starts in natural bone growth (Alfonso Durruty et al., 2006; Alfonso-Durruty, 2011; Larsen, 2015; Papageorgopoulou et al., 2011). In fact, a previous study of these same Cis-Baikal foragers found a significant delay in bone maturation for non-adult individuals (Temple et al., 2021). Results found that non-adult Cis-Baikal foragers underwent epiphyseal and apophyseal fusion of the tibiae and femora between 17 and 22 years; on average, fusion happens between 14 and 17 years in females and 16–18 in males (Schaefer et al., 2009). Given that HL can continue to form until epiphyseal fusion is complete, this may have affected HL counts in Cis-Baikal individuals as they continued to experience stops and starts in growth for longer than the average population. HL may be overrepresented in the 6–12 age group (regardless of site) because those individuals underwent substantial periods of bone growth with little chance for bone remodeling prior to death compared with older individuals included in the study (i.e., the 13- to 20- and 21- to 25-year groups). As argued by Mays (1985, 1995) and supported by additional studies (Arnay-de-la Rosa et al., 1994; Danforth et al., 1994; Magennis, 1990; Pfeiffer et al., 1986; Ribot & Roberts, 1996), growth resumption after complete cessation can occur in three different ways: normal, catch-up, or expedited. More HL development during periods of accelerated growth (i.e., between 6 and 12 years) could have resulted from expedited growth following sufficient recovery from growth interruption or delays during early childhood (0–6 years).

The narrow window for HL formation in the Cis-Baikal foragers is further supported by a sharp decline in mean HL counts in the next age category (13–20 years; Figure 3). As such, HL may better reflect the typical bone growth patterns of young individuals during the

Middle Holocene, rather than physiological stress events. HLs in this study do not reflect known differences in stress experiences between EN and LN individuals in the Cis-Baikal.

5 | CONCLUSIONS

In the case of testing A–P and M–L orientation, the results were as expected and support a re-evaluation of the methods used to image and examine HL moving forward. In the case of whether HLs coincide with known stress experiences during life, at least in Cis-Baikal foragers, the results were not as expected. Though several independent lines of evidence consistently indicate that EN individuals experienced higher levels of physiological stress during life than LN individuals, there were no significant differences in HL counts between them. Given that this study could examine trends in four specific age categories (0–5, 5–12, 13–20, and 21–25-years-at-death), the results instead suggest HL may be useful when examining growth trends in an archaeological population. Though this does require large sample sizes of young individuals, the results of this analysis do not support using HL as a marker of physiological stress. Instead, as with other critics of studying stress events through HL, this study suggests HLs are best reflective of age-specific growth experiences in Cis-Baikal foragers, regardless of their cultural or temporal period of origin.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data used herein are available by reasonable request through the primary author.

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