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TECHNICAL NOTE OPEN ACCESS

Assessing the Impact of Wear on the Recordability of Linear Enamel Hypoplasia: A Quantitative Approach

Sacha Kacki[1,2] | IJk van Hattum[3] | Caroline Laforest[1,4] | Caroline Polet[4] | Frédéric Santos[1] | Sarah Schrader[5] | Sébastien Villotte[6,7]

[1]UMR 5199 PACEA, CNRS, Université de Bordeaux, Ministère de la Culture, Bordeaux, France | [2]Department of Archaeology, Durham University, Durham, UK | [3]Department of Archaeology, Ghent University, Ghent, Belgium | [4]Quaternary Environments & Humans, OD Earth and History of Life, Royal Belgian Institute of Natural Sciences, Brussels, Belgium | [5]Faculty of Archaeology, Leiden University, Leiden, the Netherlands | [6]UMR7206 Éco-Anthropologie, CNRS, MNHN, Université Paris Cité. Musée de l'Homme, Paris, France | [7]Unité de Recherches Art, Archéologie Patrimoine, Université de Liège, Liège, Belgium

Correspondence: Sébastien Villotte (sebastien.villotte@cnrs.fr)

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Keywords: crown height | dental attrition | enamel defects | LEH | methodological standardization | non-specific stress markers | occlusal wear

ABSTRACT

Objectives: This study proposes a standardized, empirically grounded framework for assessing the recordability of linear enamel hypoplasia (LEH) in archeological dental samples. Despite the frequent use of LEH as a skeletal stress indicator, there is no consensus on whether and how to account for dental wear in recording protocols.

Materials and Methods: We analyzed the permanent right teeth of 497 medieval and early modern individuals to assess how dental wear affects the visibility and diagnostic utility of hypoplastic defects across different crown regions. For a given tooth, we assessed if there is a region that tends to be (1) less (or more) recordable than others, (2) less (or more) frequently affected by LEH than others, and (3) less (or more) informative with respect to the presence or absence of LEH than others.

Results: The occlusal third was significantly less recordable and rarely provides additional data beyond the middle and cervical thirds. Excluding the occlusal third has minimal effect on overall LEH prevalence, while omitting the middle or cervical thirds leads to marked underestimation.

Discussion: These results highlight the importance of incorporating wear-based inclusion criteria into LEH recording protocols. We recommend including only teeth with dental wear affecting less than half of the crown. These findings support the development of standardized inclusion criteria based on crown wear to enhance the consistency and comparability of data on enamel hypoplastic defects across studies and populations.

1 | Introduction

Studying skeletal indicators of stress is a central focus of anthropological research aiming to assess the general health status of past populations (e.g., Goodman et al. 1988; Lewis and Roberts 1997; Ribot and Roberts 1996). Among the skeletal and dental indicators that may reflect stress experienced during an individual's life, the most commonly used in anthropology are hypoplastic defects, Harris lines, porous lesions of the cranial vault (porotic hyperostosis) and of the orbital roofs (*cribra orbitalia*), as well as periosteal and endocranial remodeling (for a comprehensive list of skeletal and dental indicators, see Goodman et al. (1988), Table 1).

The study of these stress indicators is not without challenges, including methodological ones. Such limitations significantly hinder data sharing and the comparability of studies—both of which are considered fundamental standards in contemporary scientific research. One of the most fundamental challenges—and frequently a significant source of intra- and inter-observer error (see for instance Villotte and Perréard-Lopreno 2012)—lies in determining whether the area of interest can be analyzed, due to alterations of taphonomic or other origins. It is noteworthy that, despite the extensive body of research on enamel hypoplastic defects (e.g., Boldsen 2007; Chiappa and Schrader 2025; Goodman et al. 1980; Guatelli-Steinberg and Lukacs 1999; Skinner and Goodman 1992; Towle and Irish 2020), there is still no widely accepted standard among biological anthropologists for accounting for dental wear in data recording, despite the fact that dental wear is a universal phenomenon, occurring to varying degrees across all individuals and populations (Mair 1992). In addition to dental attrition, which leads to the loss of portions of the crown that may have displayed enamel hypoplastic defect (Skinner and Goodman 1992; Towle and Irish 2020), a range of physiological, pathological, and taphonomic factors can also hinder the identification of hypoplastic defects. Certain carious lesions can result in the partial or complete destruction of the crown, dental calculus deposits may also cover parts of the tooth, thereby obscuring hypoplastic defects in those areas, while post-mortem alterations can similarly impede identification (Skinner and Goodman 1992). It is therefore essential to consider all of these factors when scoring hypoplastic defects and calculating their prevalence.

The strategies adopted to assess whether a tooth can potentially exhibit evidence of hypoplastic defects, regardless of the method employed (macroscopic or microscopic observation, presence/absence recording, or severity scoring), vary considerably between authors. These strategies are often discussed—sometimes in detail—in relation to tooth wear, the primary factor affecting what will be referred to hereafter as "recordability," defined as the potential to identify enamel hypoplastic defects on a tooth surface given conditions such as wear, breakage, or post-mortem damage.

In a recent article, Towle and Irish (2020) highlight that any methodological choice inherently introduces bias: as dental wear progresses, macroscopic enamel defects become less visible. To minimize bias, all teeth retaining some enamel are included, even though this may result in the omission of worn-away defects. Excluding such teeth, however, would skew the sample toward individuals who died at a younger age. This strategy, adopted by other researchers as well (e.g., Bas et al. 2023; Littleton and Townsend 2005; Miszkiewicz 2015), is not the only approach taken in the literature. In contrast, some studies recommend including only unworn or minimally worn teeth, applying strict criteria for the maximum degree of wear acceptable for inclusion—such as requiring that less than 10% (Cares Henriquez and Oxenham 2020) or less than one-third of the crown be worn (e.g., Chiappa and Schrader 2025; Minozzi et al. 2020). Others employ more specific (and highly variable) criteria, such as: "Where the enamel rim surrounding the dentin was lost at any location, the tooth was excluded from analysis" (Ham et al. 2021, 6), or "Teeth with wear degree 5+ [...] were excluded" (Erkman et al. 2022, 4). Surprisingly, we found no empirical studies in the literature that offer a quantifiable framework for evaluating the impact of factors that limit the recordability of hypoplastic defects. The objective of this technical note is to propose an evaluation of the impact of wear on the recordability of linear enamel defects, to contribute to the larger discussion about which inclusion methods are most appropriate in enamel defect studies. Specifically, this study aims to address three key questions:

1. For a given tooth, is there a region that tends to be less (or more) recordable than others?
2. For a given tooth, is there a region that tends to be less (or more) frequently affected by hypoplastic defects than others?
3. For a given tooth, is there a region that tends to be less (or more) informative with respect to the presence or absence of hypoplastic defects than others?

2 | Material and Methods

The osteological sample analyzed in this study consists of skeletal remains from six European funerary sites dating to the late Middle Ages and early modern period (Table 1). The presence or absence of linear-type hypoplastic defects was recorded for each permanent tooth (in non-adult and adult individuals) of the sample.

The maxillary and mandibular dentitions of all individuals were examined with the naked eye and an ×8 magnification optical loupe, under appropriate lighting and oblique illumination. A hypoplastic defect was considered present when a clearly identifiable depression was observed on the vestibular surface of the tooth. In uncertain cases, confirmation of the defect was made by tactile inspection with a dental probe, following published recommendations in the anthropological literature (Goodman and Armelagos 1985; Molnar and Molnar 1985). In this study, only linear enamel hypoplasia (LEH) was considered, as other morphological types of hypoplastic defects—such as pits and plane-form defects—were extremely rare in the permanent dentition of the analyzed sample. For a detailed presentation of the methods used to record LEH, we refer readers to the Supporting Information provided in Kacki (2017).

In accordance with the recommendations of Goodman and Armelagos (1985), the location of each hypoplastic lesion on the dental crown was recorded by dividing it into three sectors:

TABLE 1 | Sample analyzed (right side only).

Site	Country	Period	*N* individuals with at least one tooth	*N* individuals with at least one unworn tooth	*N* teeth	*N* complete teeth
Notre-Dame de Rouen	France	11th century	130	107	1014	736
Saint-Étienne de Toulouse	France	11–13th century	67	45	261	160
Saint-Pierre de Dreux	France	14th Century	38	29	198	104
Hereford Cathedral	UK	14th Century	90	82	819	674
Les Fédons	France	16th Century	118	102	1202	905
Dendermond/ Termonde	Belgium	16th Century	54	53	525	497
Total			497	418	4019	3096

Note: "*N*": Sample size. "Complete" means that all three crown thirds were scored.

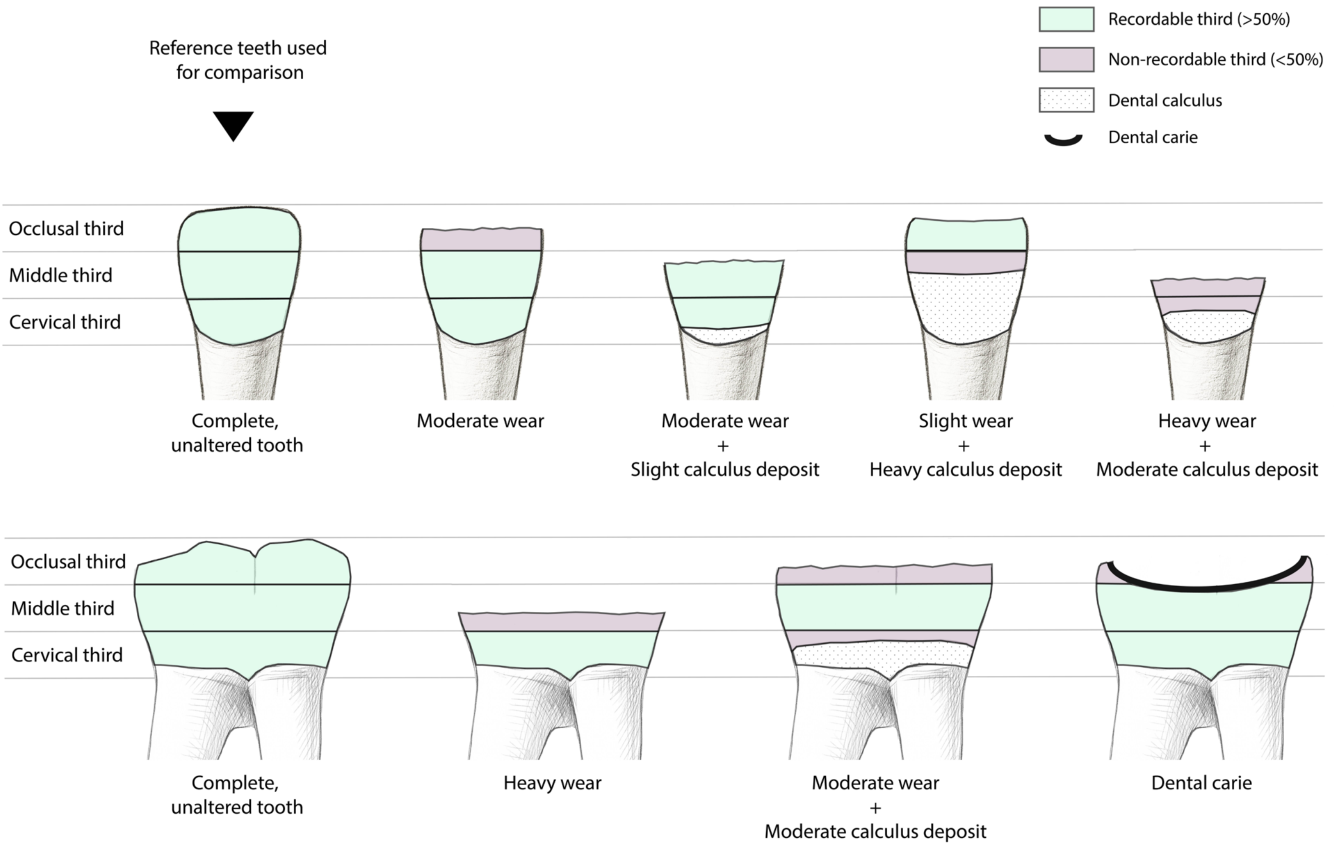

FIGURE 1 | Crown division and recordability criteria: Vestibular surface visibility threshold and exclusion conditions.

occlusal third (also accounting for the "incisal third" of the incisors and canines), middle third, and cervical third. The assignment of LEH to a given third was carried out without the use of metric measurements. This process was facilitated by the comparison of worn teeth to unworn reference teeth from the same collection and by enlarged photographic images of "control" teeth, on which the boundaries of each designated zone had been previously marked. For a third to be considered scorable, at least half of its vestibular surface had to be visible (i.e., not worn, covered by dental calculus, pathologically altered, or taphonomically altered over more than half of its height; see Figure 1).

For the sake of clarity, data are illustrated and analyzed for the right side only. Virtually identical results were obtained for the left side. The full dataset used for the analyses is available in Supporting Information (Spreadsheet S1).

Statistical analyses were based on prevalence and odds ratios, computed using R 4.5.0. While the dataset includes multiple observations from the same individuals—introducing a degree of non-independence—odds ratios are non-parametric measures that are comparatively robust to such deviations. Despite this limitation, the patterns observed appear sufficiently pronounced to suggest biologically and functionally meaningful trends.

Odds ratios and their 95% confidence intervals were computed using the "pairwise" package, employing the Woolf method, which incorporates the Haldane–Anscombe correction to address zero-cell counts in contingency tables (Agresti 2002; Lawson 2004).

3 | Results and Discussions

Figure 2 presents data for all right maxillary and mandibular teeth in the sample for which at least one third of the crown was recordable. It shows the percentage of recordable observations for each crown third. A clear pattern emerges: while the presence or absence of LEH could be assessed in 92.7% to 96.5% of cases for the middle third, and in 91.8% to 98.5% for the cervical third, the occlusal third was recordable in only 75.3% to 91.9% of cases. For the whole teeth sample, the recordability of the occlusal third (81.1%) is approximately 14% lower than that of the middle (94.9%) and cervical (95.5%) thirds, which are nearly equivalent. The difference in recordability between the occlusal third and the other two thirds is statistically significant for all teeth except the right upper third molar (Table S1). No significant differences were observed between the middle and cervical thirds, with the exception of the right lower second molar (see Table S1).

These findings provide a clear answer to the first research question: the occlusal third of the crown tends to be systematically and significantly less recordable than the other regions. This discrepancy can be readily attributed to the effects of dental wear, which disproportionately affect the occlusal surface.

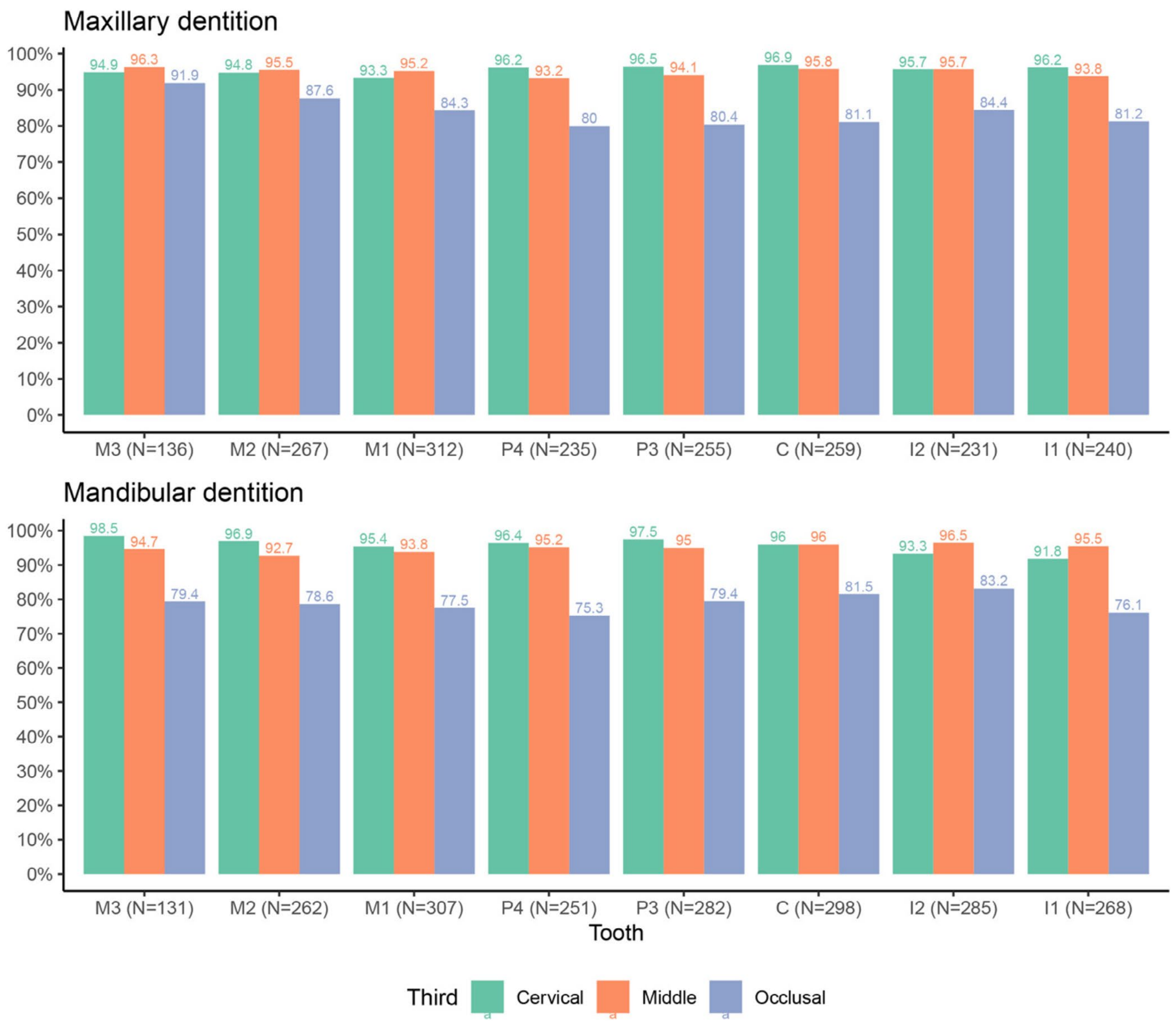

FIGURE 2 | Frequency of crown thirds recorded, for each tooth considered (right side only). *N* indicates the theoretical number of recordable areas.

TABLE 2 | Frequency of LEH per crown third and tooth.

Tooth		Occlusal		Middle		Cervical		Odd ratio		
		n/N	**%**	***n/N***	**%**	***n/N***	**%**	**Occlusal vs. middle**	**Occlusal vs. cervical**	**Middle vs. cervical**
Maxillary	M3	0/125	0.0%	6/131	4.6%	7/129	5.4%	13.00 [0.72–233.23]	15.37 [0.87–271.99]	1.18 [0.40–3.48]
	M2	0/234	0.0%	10/255	3.9%	16/253	6.3%	**20.06 [1.17–344.25]**	**32.58 [1.94–546.24]**	1.62 [0.73–3.59]
	M1	2/263	0.8%	12/297	4.0%	27/291	9.3%	**4.58 [1.17–17.99]**	**10.88 [2.95–40.14]**	**2.37 [1.19–4.73]**
	P4	0/188	0.0%	11/219	5.0%	27/226	11.9%	**20.79 [1.22–355.29]**	**51.97 [3.15–857.98]**	**2.50 [1.22–5.11]**
	P3	6/205	2.9%	23/240	9.6%	41/246	16.7%	**3.32 [1.36–8.07]**	**6.20 [2.65–14.49]**	**1.87 [1.09–3.21]**
	C	17/210	8.1%	91/248	36.7%	91/251	36.3%	**6.42 [3.70–11.17]**	**6.30 [3.63–10.95]**	0.98 [0.68–1.41]
	I2	5/195	2.6%	32/221	14.5%	43/221	19.5%	**5.94 [2.35–14.99]**	**8.44 [3.40–20.97]**	1.42 [0.86–2.34]
	I1	3/195	1.5%	64/225	28.4%	62/231	26.8%	**21.97 [7.34–65.72]**	**20.28 [6.78–60.69]**	0.92 [0.61–1.39]
Mandibular	M3	0/104	0.0%	3/124	2.4%	4/129	3.1%	6.02 [0.31–117.91]	7.49 [0.40–140.80]	1.24 [0.30–5.14]
	M2	2/206	1.0%	10/243	4.1%	12/254	4.7%	3.68 [0.91–14.8]	**4.22 [1.07–16.6]**	1.15 [0.49–2.66]
	M1	2/238	0.8%	11/288	3.8%	10/293	3.4%	3.92 [0.99–15.56]	3.50 [0.87–14.07]	0.89 [0.38–2.10]
	P4	1/189	0.5%	20/239	8.4%	38/242	15.7%	**11.74 [2.21–62.30]**	**23.66 [4.57–122.35]**	**2.02 [1.14–3.56]**
	P3	8/224	3.6%	36/268	13.4%	52/275	18.9%	**4.00 [1.85–8.63]**	**5.98 [2.83–12.65]**	1.50 [0.94–2.37]
	C	24/243	9.9%	106/286	37.1%	115/286	40.2%	**5.29 [3.27–8.55]**	**6.03 [3.74–9.75]**	1.14 [0.82–1.60]
	I2	5/237	2.1%	43/275	15.6%	57/266	21.4%	**7.91 [3.20–19.56]**	**11.60 [4.74–28.38]**	1.47 [0.95–2.27]
	I1	2/204	1.0%	34/256	13.3%	47/246	19.1%	**12.56 [3.43–45.98]**	**19.29 [5.33–69.83]**	1.54 [0.95–2.48]
	All teeth	77/3260	2.4%	512/3815	13.4%	649/3839	16.9%	**6.37 [4.99–8.13]**	**8.36 [6.57–10.64]**	**1.31 [1.16–1.49]**

Note: Bolded values indicate ORs with 95% confidence intervals that do not include 1, reflecting statistical significance.

Table 2 presents the frequency of LEH for each defined dental region. The results reveal considerable variability in lesion frequency, both between different teeth and among different regions of the same tooth. The higher prevalence of LEH on certain tooth types is a well-documented phenomenon (e.g., Goodman et al. 1980) and will not be discussed in detail here. In contrast, the preferential involvement of specific regions within a tooth remains much less documented and warrants closer attention.

The occlusal third is only rarely affected by LEH, regardless of tooth category, with lesions observed in just 2.4% of all recorded teeth ($N = 3260$). Prevalence across tooth types ranges from 0.0% to a maximum of 9.9%. In contrast, the middle third (overall: 13.4%; range: 2.4%–37.1%) and the cervical third (overall: 16.9%; range: 3.1%–40.2%) are much more frequently affected (Table 2). Most of the statistically significant differences are observed between the occlusal third and one of the other two thirds (25 out

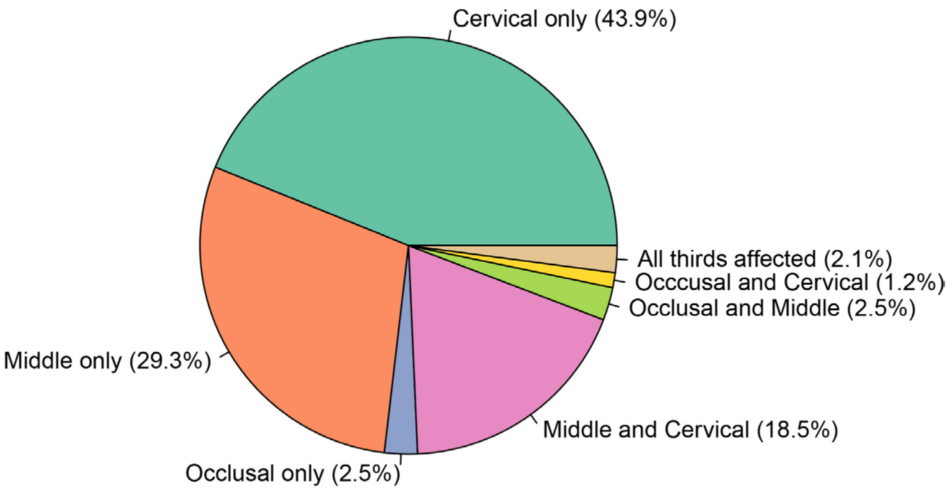

FIGURE 3 | Localization of LEH within the affected complete teeth.

TABLE 3 | Frequency of LEH for fully scored teeth, calculated using all three crown thirds and under hypothetical conditions excluding each third individually (occlusal, middle, or cervical).

Tooth		*n/N*	3 thirds	W/O Occlusal		W/O Cervical		W/O Middle	
			%	%	OR	%	OR	%	OR
Maxillary	M3	13/118	11.0%	11.0%	1.00 [0.45–2.23]	5.1%	2.21 [0.84–5.86]	5.9%	1.90 [0.75–4.83]
	M2	24/221	10.9%	10.9%	1.00 [0.55–1.81]	4.5%	**2.50 [1.18–5.28]**	7.2%	1.54 [0.80–2.97]
	M1	35/243	14.4%	14.4%	1.00 [0.60–1.65]	4.5%	**3.44 [1.73–6.87]**	10.7%	1.40 [0.82–2.39]
	P4	30/180	16.7%	16.7%	1.00 [0.58–1.73]	5.6%	**3.29 [1.58–6.86]**	12.8%	1.36 [0.76–2.43]
	P3	49/197	24.9%	24.9%	1.00 [0.63–1.58]	11.7%	**2.48 [1.45–4.24]**	18.3%	1.47 [0.91–2.39]
	C	125/204	61.3%	57.8%	1.15 [0.78–1.71]	43.1%	**2.08 [1.40–3.08]**	44.1%	**2.00 [1.35–2.96]**
	I2	60/185	32.4%	30.8%	1.08 [0.70–1.67]	17.8%	**2.19 [1.35–3.56]**	22.7%	**1.63 [1.03–2.58]**
	I1	78/185	42.2%	41.6%	1.02 [0.68–1.54]	30.3%	**1.67 [1.09–2.57]**	28.6%	**1.81 [1.18–2.78]**
Mandibular	M3	6/102	5.9%	5.9%	1.00 [0.33–3.07]	2.9%	1.91 [0.51–7.23]	3.9%	1.47 [0.43–5.07]
	M2	18/198	9.1%	8.6%	1.06 [0.54–2.11]	5.6%	1.67 [0.78–3.59]	6.1%	1.53 [0.73–3.23]
	M1	20/224	8.9%	8.9%	1.00 [0.53–1.90]	4.9%	1.86 [0.88–3.93]	5.4%	1.70 [0.82–3.53]
	P4	44/182	24.2%	24.2%	1.00 [0.62–1.61]	9.9%	**2.86 [1.59–5.14]**	17.6%	1.49 [0.90–2.47]
	P3	77/218	35.3%	34.4%	1.04 [0.70–1.54]	17.0%	**2.65 [1.69–4.15]**	24.3%	**1.69 [1.12–2.56]**
	C	158/232	68.1%	65.5%	1.12 [0.76–1.65]	45.7%	**2.53 [1.73–3.68]**	48.7%	**2.24 [1.54–3.26]**
	I2	72/220	32.7%	31.8%	1.04 [0.70–1.55]	16.4%	**2.47 [1.57–3.88]**	23.2%	**1.61 [1.06–2.44]**
	I1	54/187	28.9%	28.9%	1.00 [0.64–1.56]	13.4%	**2.60 [1.54–4.39]**	21.4%	1.49 [0.93–2.38]
	All teeth	863/3096	27.9%	27.2%	1.04 [0.93–1.16]	15.6%	**2.08 [1.84–2.36]**	19.7%	**1.57 [1.40–1.77]**

Note: Bolded values indicate ORs with 95% confidence intervals that do not include 1, reflecting statistical significance.

of 32 pairwise comparisons), whereas differences between the middle and cervical thirds are comparatively rare (4 out of 16 comparisons).

Overall, the occlusal third appears to exhibit LEH far less frequently than the middle and cervical thirds across all tooth types, with statistically significant differences observed in the majority of cases. Our results offer a definitive response to the second research question (for a given tooth, is there a region that tends to be less (or more) frequently affected by hypoplastic defect than others?). It is also noteworthy that the cervical third, although more sporadically, tends—when all teeth are considered together—to display slightly but significantly higher prevalence of LEH than the middle third. Our results are consistent with previous studies (e.g., King et al. 2005; Littleton and Townsend 2005; Nakayama 2016), which reported a relatively low frequency of linear enamel hypoplasia (LEH) on the occlusal third compared to other parts of the tooth.

Finally, a subsample of 3096 teeth for which all three crown thirds were scored was analyzed (Table 1). A tooth was considered affected if LEH was present on at least one of the three subsections, resulting in a prevalence of 27.9% within this subsample. Among the 864 affected teeth, only 2.5% exhibited LEH exclusively on the occlusal third (Figure 3).

Table 3 presents the frequency of LEH per tooth, calculated both with all three thirds included and in hypothetical scenarios where one third was excluded. Excluding the occlusal third has virtually no impact on overall LEH prevalence, whether at the level of individual teeth or across the entire sample, as indicated by odds ratios equal to or very close to 1, with no statistically significant differences observed. In contrast, removing the cervical third leads to a significant decrease in LEH frequency for most teeth. Excluding the middle third also results in a reduction in prevalence—significant when all teeth are considered together—although the effect is less pronounced than that observed for the cervical third. These findings address our third research question, demonstrating that the occlusal third contributes minimally to the detection of LEH and is therefore substantially less informative than the middle or cervical thirds.

4 | Conclusions

In an extensive medieval and early modern archeological sample of approximately 500 individuals, our analyses demonstrate that the occlusal third of dental crowns is consistently less recordable than the middle and cervical thirds, primarily due to the effects of dental wear. This reduced recordability significantly limits the potential to identify LEH in the occlusal region. Furthermore, LEH is barely observed on the occlusal third, and even less without being accompanied by lesions on the middle and/or cervical thirds, indicating that the occlusal third rarely provides unique or additional information about the presence of LEH. The fact that most hypoplastic defects are located on the cervical and middle thirds of permanent teeth has already been reported by various authors (e.g., King et al. 2005; Nakayama 2016). This pattern has been associated with tooth geometry (regardless of tooth type), which makes defects in the occlusal regions shallower and less identifiable than those in the mid-crown and cervical regions (Hillson and Bond 1997).

Importantly, excluding the occlusal third from analyses has a negligible impact on the overall prevalence of LEH per tooth. In contrast, the cervical and middle thirds play a critical role in detecting hypoplastic defects, as their exclusion leads to a significant underestimation of LEH frequency across the sample. It should be noted that since our study focused exclusively on LEH in permanent teeth, caution is warranted before generalizing these findings to other types of enamel defects, such as pits or plane-form hypoplastic defects (cf. Littleton and Townsend 2005), or to deciduous teeth (cf. López-Lázaro et al. 2022).

The descriptive statistics suggest that moderate abrasion of the dental crown—primarily affecting the occlusal third—results in only limited data loss, whereas wear or damage affecting the middle and cervical thirds significantly compromises the ability to detect LEH. Based on these findings, we recommend that future studies aiming to produce comparable and shareable data on LEH restrict their analyses to teeth with sufficiently preserved middle and cervical thirds. Specifically, since this study required at least half of a crown third to be visible for reliable assessment, we suggest including only teeth with less than half of their crown worn away—equivalent to losing no more than one-third of the entire crown plus half of one third—to ensure data reliability. By adopting such standardized criteria for recordability based on crown wear, researchers can minimize bias introduced by dental attrition and improve the consistency and comparability of hypoplastic defect prevalence estimates across populations and studies.

Given that dental wear is strongly correlated with age, the proposed exclusion method is likely to disproportionately remove older individuals from the analysis. This may introduce representation bias and limit the ability to assess LEH frequency across age groups. To mitigate such bias, two complementary strategies can be considered. The first involves reporting dual prevalence estimates: (1) the unadjusted prevalence, based on all teeth regardless of wear, and (2) a corrected prevalence, calculated using the proposed exclusion criteria. Presenting both values alongside the proportion of teeth excluded due to wear would enable more nuanced comparisons across samples or age cohorts with differing wear patterns. The second strategy, intended to improve the inclusion of older individuals in comparative analyses, entails assessing LEH prevalence by dental thirds rather than by whole tooth. Although this approach increases analytical complexity by requiring multiple observations per tooth, it offers a more age-inclusive framework for evaluating LEH frequency.

Author Contributions

Sacha Kacki: funding acquisition, writing – review and editing, investigation, data curation, conceptualization, methodology. **IJk van Hattum:** writing – review and editing, investigation. **Caroline Laforest:** investigation, writing – review and editing. **Caroline Polet:** investigation, writing – review and editing. **Frédéric Santos:** formal analysis, writing – review and editing, validation. **Sarah Schrader:** investigation, writing – review and editing. **Sébastien Villotte:** conceptualization, writing – original

draft, writing – review and editing, project administration, funding acquisition, formal analysis, investigation, methodology.

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Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study is available in the Supporting Information of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information. Table S1. **Data S2:** Spreadsheet S1. Raw data analyzed in this study.