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RESEARCH ARTICLE

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The internal crest anatomy of Lambeosaurini (Hadrosauridae: Lambeosaurinae)

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Abstract

The supracranial crests of lambeosaurine hadrosaurids have long been a focus of study due primarily to their extreme morphology. The external anatomy of lambeosaurine crests is understood to be highly variable between species, but variation in their internal anatomy is less well understood. The poor understanding of taxonomic variation in internal anatomy is due in large part to data limitations, where comparisons were historically made using fragmentary specimens, or more recently using CT imaging of primarily immature specimens. Here, we provide a detailed comparison of the internal anatomy of mature individuals of the lambeosaurines *Corythosaurus casuarius*, *Corythosaurus intermedius*, and *Lambeosaurus lambei*, and contrast their morphology with previously described juvenile congeners and mature *Hypacrosaurus altispinus*. The lateral diverticula of *Corythosaurus* spp. and *L. lambei* are large and lobate, with short anterior projections and well-developed posterior projections, lacking the elongated anterior expansions to the diverticula that are unique to *H. altispinus*. The s-loop of the nasal vestibule is highly developed in *L. lambei*, forming exaggerated loops anterior to the orbit. The s-loops of *Corythosaurus* spp. and *L. lambei* curve from lateral to medial within the premaxilla, differing from the direction of curvature of the s-loops in *H. altispinus* that curve from medial to lateral. Very few differences occur between *C. casuarius* and *C. intermedius*, suggesting that there is minimal interspecific variation between these congeneric species. Our results demonstrate that lambeosaurine nasal passages are highly variable between genera, supporting strong internal differences in crest morphology, even in closely related genera within the same tribe.

KEYWORDS

cranial crest, hadrosauridae, lambeosaurinae, nasal anatomy

1 | INTRODUCTION

The cranial anatomy of lambeosaurine hadrosaurids has been a focal point of research within the group since their discovery due to the structure's extreme morphology and dramatic interspecific variation (Abel, 1924; Brown et al., 2023; Dodson, 1975; Evans, 2006; Evans et al., 2009; Gilmore, 1924; Hopson, 1975; Lambe, 1914;

Ostrom, 1961, 1962; Parks, 1922, 1923; Ramírez Velasco et al., 2021; Russell, 1946; Sternberg, 1935; Sullivan & Williamson, 1999; Weishampel, 1981a, 1981b; Wiman, 1931). Lambeosaurines are characterized by possessing prominent supracranial crests formed from expansions of the premaxillae and nasal bones over the skull roof, and are primarily hollow, housing convolutions of the nasal airway (Evans et al., 2009). These crests were initially interpreted to have several potential functions, including defense (Abel, 1924), vocal resonance (Wiman, 1931), tendon or muscle attachments (Parks, 1922; Wilfarth, 1938), trapping air or facilitating snorkeling during underwater feeding (Russell, 1946; Sternberg, 1935, 1939, 1942, 1953, 1964; Wilfarth, 1939), and olfaction or thermoregulation (Ostrom, 1961, 1962), but there is now a general consensus that the primary function was for socio-sexual display, facilitating visual display through their sheer conspicuousness and auditory display through resonant amplification of vocalizations (Brown et al., 2023; Dodson, 1975; Evans et al., 2009; Hopson, 1975; Horner et al., 2004; Sullivan & Williamson, 1999; Weishampel, 1981a, 1997; Wiman, 1931).

These complex nasal passages were first identified as simple u-shaped dorsal expansions of the nasal passages (Lambe, 1914, 1920) but were later described as forming additional s-shaped loops anterior to the orbit and communing into a large midline cavity (=common median chamber; Sternberg, 1935). Subsequent detailed descriptions of fragmentary specimens revealed s-loops are common to *Corythosaurus* and *Lambeosaurus*, along with the identification of “inferior lateral chambers” (=lateral diverticula) that were hypothesized to commune the s-loops with the common median chamber (Ostrom, 1961). The lateral diverticula were later identified as blind cavities that extend laterally from the common median chamber and may be homologous with the circumnarial depression of related hadrosaurines (Hopson, 1975). The s-loops were interpreted as being most developed in *Corythosaurus*, with diverticula being particularly expanded in *Lambeosaurus*, while *Hypacrosaurus* was interpreted as retaining simple narial anatomy, lacking s-loops altogether (Ostrom, 1961; Weishampel, 1981b). Evans et al. (2009) used X-ray CT scanning to describe the internal narial anatomy of a mature *Hypacrosaurus altispinus* and immature specimens of *Corythosaurus casuarius* and *Lambeosaurus* sp., identifying that the previously described convolutions and chambers within the crest were part of the nasal vestibule, distinct from the olfactory chamber. Their results suggest that there is significant taxonomic variation in the complexity of lambeosaurine nasal passages, with *H. altispinus* having more developed s-loops and lateral diverticula than the other taxa.

However, Evans et al. (2009) noted that a significant limitation to their study was the absence of data for mature individuals of *Corythosaurus* and *Lambeosaurus*, and the greater complexity observed in *H. altispinus* may be due in part to ontogenetic variation. Lambeosaurine crest morphology is understood to vary taxonomically in their relative size, shape, and skeletal composition, but at present, ontogenetic and taxonomic variation in their internal anatomy is poorly understood, particularly in adult Lambeosaurini. Here, we describe the internal narial anatomy of mature specimens of *Corythosaurus casuarius*, *C. intermedius*, and *Lambeosaurus lambei* using X-ray CT scanning for the first time and contrast their morphology with the previously described juvenile congeners and mature *H. altispinus* to elucidate ontogenetic and taxonomic variation in their internal anatomy.

2 | MATERIALS AND METHODS

2.1 | Institutional abbreviations

CMN, Canadian Museum of Nature, Ottawa, Ontario, Canada; ROM, Royal Ontario Museum, Toronto, Ontario, Canada; TMP, Tyrrell Museum of Paleontology, Drumheller, Alberta, Canada; UALVP, University of Alberta Laboratory for Vertebrate Paleontology, Edmonton, Alberta, Canada.

2.2 | Anatomical abbreviations

apld, anterior projection of the lateral diverticulum; cmc, common median chamber; dl, dorsal loop; ld, lateral diverticulum; n, nasal; nar, nares; orb, orbit; pm, premaxilla; pm_d, premaxilla posterodorsal process; pm_l, premaxilla posterolateral process; pnf, premaxilla-nasal fontanelle; ppld, posterior projection of the lateral diverticulum; sep, short septum.

2.3 | Materials

Three mature lambeosaurine specimens were included in this study; ROM 1933 (*Corythosaurus casuarius*), UALVP 13 (*C. intermedius*), and TMP 1982.038.0001 (*Lambeosaurus lambei*). These specimens were selected for study because they are large adults of their respective species that possess fully developed supracranial crests and have experienced relatively little crushing, meaning their internal anatomy remains mostly intact and easy to interpret. ROM 1933 was the basis for the reconstruction of *Corythosaurus* nasal passages by Weishampel (1981b), though the skull is slightly damaged, and UALVP 13 is an exquisitely preserved specimen with minimal crushing, but the left side is primarily absent. TMP 1982.038.0001 is plastically compressed anteroposteriorly, but the crest and snout remain otherwise intact. Raw CT data for these specimens are available on Morphosource (https://www.morphosource.org).

2.3.1 | ROM 1933

ROM 1933 is a nearly complete skull of *C. casuarius* with the right facial skeleton and jaws separate, and the rest of the skull in articulation, and is only slightly crushed mediolaterally (Figure 1a). It was collected in 1954 from the Dinosaur Park Formation (then recognized as the

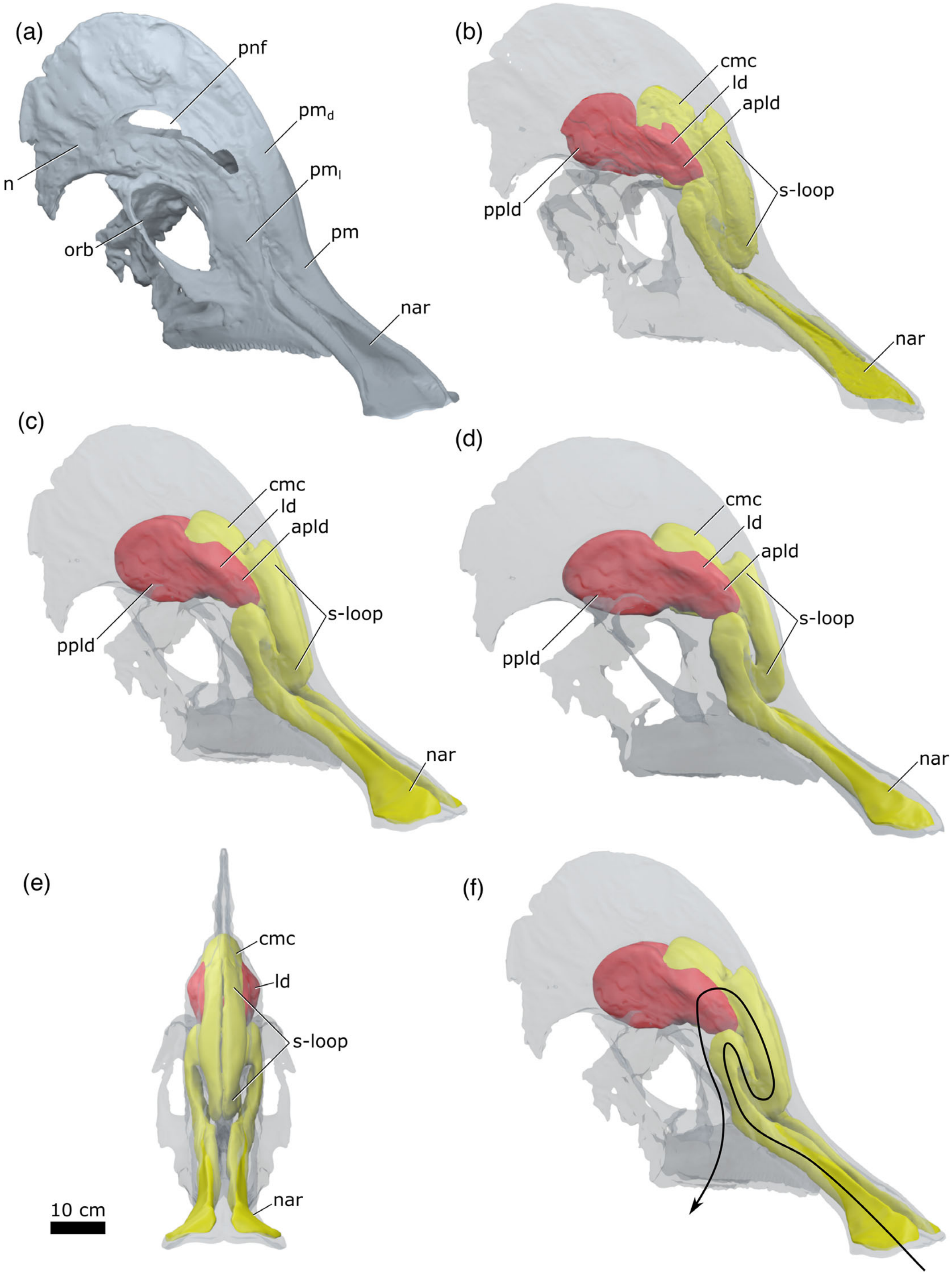

FIGURE 1 Cranial and nasal passage anatomy of *Corythosaurus casuarius* (ROM 1933). Preserved cranial anatomy in right anterolateral view (a), preserved nasal anatomy in right anterolateral view (b), retrodeformed nasal anatomy in right anterolateral view (c), right lateral view (d), anterior view (e), and right anterolateral view indicating the path of inspired air (f, black arrow).

Oldman Formation) of Little Sand Hill Creek, in the vicinity of what is now Dinosaur Provincial Park, Alberta, Canada (Quarry 117; Meridian 4, Township 21, Range 11, Section 4, elevation 673.5 m). ROM 1933 was CT scanned at Spatio-Temporal Targeting and Amplification of Radiation Response (STTARR; https://sttarr.ca/) in Toronto, Canada on October 15, 2021, at 140 kV and 155 mA using the HD bone reconstruction algorithm setting on a GE Revolution Frontier CT scanner, resulting in slice thickness of 0.625 mm and x–y dimensions of 0.976 mm × 0.976 mm. These data were previously published on and retrodeformed for biomechanical analyses, and procedures for CT segmentation can be found therein (Dudgeon & Evans, 2025). The segmented nasal passages were imported into Blender 3.1.2 (Community B.O., 2018) for retrodeformation to reconstruct symmetrical and complete nasal passages for description.

2.3.2 | UALVP 13

UALVP 13 consists of an articulated snout, crest, and braincase of *C. intermedius*, and has undergone almost no crushing or distortion, with the exception of slight deformation of the solid dorsal-most aspect of the crest (Figure 2a). The right premaxilla is preserved in its entirety, but only the dorsal-most portion of the left premaxilla is preserved; the rest has fractured away. This specimen was initially designated the holotype of *C. excavatus* (Gilmore, 1923) before the species was synonymized with *C. casuarius* (Currie, 2005; Dodson, 1975), but UALVP 13 is most recently recognized as *C. intermedius* following more detailed biostratigraphic data (Brink et al., 2014; Evans, 2010). The collection of UALVP 13 was problematic; only the skull was collected in 1920 and described by Gilmore (1923), but detailed locality data were not recorded, and the quarry was therefore lost. The excavation site was relocated, and the presumed postcranial skeleton was collected in 2012 and tentatively designated the same specimen number (Bramble et al., 2017). The presumed postcrania was recovered in Bonebed 50 (Bramble et al., 2017), a mixed multitaxic bonebed from the lower to middle Dinosaur Park Formation of Dinosaur Provincial Park, Alberta, Canada (Quarry 259; Meridian 4, Township 21, Range 11, Section 6, elevation 688.5 m; data from TMP database). UALVP 13 was CT scanned at Mazankowski Alberta Heart Institute on April 26, 2016, and the internal cavities of the snout and crest were segmented in 3D Slicer v4.11.20210226 (Fedorov et al., 2012) and imported into Blender 3.1.2 (Community B.O., 2018) for retrodeformation.

2.3.3 | TMP 1982.038.0001

TMP 1982.038.0001 represents a nearly complete skull, jaws, and partial postcrania of *Lambeosaurus lambei* (Figure 3a). It was found in 1982 in what is now the Dinosaur Park Formation (then recognized as the Oldman Formation) of Dinosaur Provincial Park, Alberta, Canada (Quarry 175; Meridian 4, Township 21, Range 11, Section 12, elevation 683.5 m; Currie & Russell, 2005). The skull and jaws are nearly complete but have been crushed and deformed anteroposteriorly. TMP 1982.038.0001 was CT scanned on February 21, 2025, at Calgary Diagnostics in Calgary, Canada, with a slice thickness of 0.625 mm at 120–140 kV. The data were segmented in 3D Slicer v4.11.20210226 (Fedorov et al., 2012) and imported into Blender 3.1.2 (Community B.O., 2018) for retrodeformation.

2.4 | Methods

2.4.1 | Specimen reconstruction and retrodeformation

The three skulls examined in this study preserve the internal narial anatomy in their entirety, but these specimens have undergone varying degrees of taphonomic deformation that altered their shape. We retrodeformed the 3D models produced from the CT scans in Blender 3.1.2 (Community B.O., 2018) to reconstruct undeformed nasal passages for visualization. Retrodeformation was checked by eye, and for transparency, original segmentations prior to retrodeformation are available as Data S1–S8, Supporting Information. ROM 1933 (*Corythosaurus casuarius*) was nearly intact, only having been crushed mediolaterally, particularly the lateral diverticula and common median chamber dorsal to the braincase. This specimen was retrodeformed by plastically deforming the crest laterally, and mirroring the right side onto the left because the left lateral diverticulum was only partially preserved. UALVP 13 (*C. intermedius*) preserves the right nasal passage in its entirety, and this specimen is only slightly plastically deformed along its length. UALVP 13 was retrodeformed by removing mediolateral curvature. TMP 1982.038.0001 (*Lambeosaurus lambei*) is nearly complete but is compressed anteroposteriorly. The crest and nasal passages of this specimen were plastically deformed to match the proportions of ROM 1218, a nearly perfectly preserved skull of *L. lambei* that is approximately equivalent in size. The left side of TMP 1982.038.0001 is more intact than the right, so the left side was mirrored onto the right to create biaxially symmetrical nasal passages for visualization.

The previously described cranial and nasal models of juvenile (ROM 759) and subadult (CMN 34825) *Corythosaurus casuarius*, juvenile *Lambeosaurus* sp. (ROM 758), and mature *Hypacrosaurus altispinus* (ROM 702) from Evans et al. (2009) were imported into Blender 3.1.2 (Community B.O., 2018) for visualization and comparison with the mature specimens included here. These previously reconstructed models were not subjected to any additional retrodeformation by us; only the render properties were modified for consistent visualization across the included specimens.

3 | RESULTS

3.1 | *Corythosaurus casuarius* and *Corythosaurus intermedius*

The nasal passages of mature *Corythosaurus casuarius* (ROM 1933) and *C. intermedius* (UALVP 13) are very similar in morphology, differing only in subtle proportions. The s-loops of both specimens are well developed and formed entirely by the premaxillae. The s-loops extend dorsally to the level of the dorsal margin of the orbit before turning medioventrally and descending approximately 14 cm, and finally turning posterodorsally towards the common median chamber (Figures 1 and 2). In both specimens of *Corythosaurus* examined here, the nasal passages ascend on the lateral margin of the premaxilla and curve medially to form the s-loops. In this way the s-loops can be said to progress from lateral to medial within the premaxillae. The s-loops commune with the common median chamber on its anterior margin, and the common median chamber itself is located completely dorsal to the skull roof and is positioned anterodorsal to the orbits. The chamber itself is mediolaterally narrow between the lateral diverticula and forms the dorsal-most portion of the airway, but is proportionally larger in *C. intermedius* (UALVP 13) than *C. casuarius* (ROM 1933). The lateral diverticula branch laterally from the ventral half of the common median chamber, at the level of the premaxilla-nasal contact, similar to ontogenetically younger specimens of *Corythosaurus* sp. and all other known lambeosaurines (Evans et al., 2009). The lateral diverticula are defined by the posterolateral process of the premaxilla anteriorly and the nasal posteriorly. The diverticula project both anterior and posterior to their apertures with the common median chamber. The apertures between the common median chamber and lateral diverticula are sub-circular in shape, being longer anteroposteriorly than dorsoventrally. The anterior projections of the lateral diverticula from the apertures are relatively short, terminating at the anterior margin of the premaxilla-nasal fontanelle, just dorsal to the s-loops (Figures 1b–d and 2b–d). The posterior projections of the lateral diverticula are lobe-shaped, being mediolaterally narrow but anteroposteriorly and dorsoventrally expanded, extending over the anterior margin of the temporal chamber, and are each larger in dimensions than the common median chamber (Figures 1b–d and 2b–d). The nasopharynx extends ventrally from the common median chamber, expanding into a large unossified cavity that would have extended posteriorly towards the olfactory bulbs of the brain, and ventrally towards the choanae (Evans, 2006).

3.2 | *Lambeosaurus lambei*

The nasal passages of *Lambeosaurus lambei* (TMP TMP 1982.038.0001) are similar in overall construction to adult *Corythosaurus* spp. (ROM 1933, UALVP 13), but with notable differences in relative proportions. The s-loops are similarly bounded within the premaxillae, but are extremely developed, looping far posterodorsally within the premaxillae such that their dorsal-most loop is positioned lateral to the lateral diverticula, and forming exaggerated convolutions anterior to the orbit (Figures 3b–f and 4a–c). The portion of the nasal passages communing the s-loops with the common median chamber is expanded anterodorsally to occupy the dorsal-most portion of the crest, creating a dorsal loop that is unique to *L. lambei* among known lambeosaurines. The main airway therefore communes with the common median chamber anterodorsally rather than anteriorly as in *Corythosaurus* spp. The common median chamber is anterodorsally expanded, extending farther dorsal to the lateral diverticula than in *Corythosaurus* spp., and variably preserves a short septum on the anterior-most dorsal surface. The lateral diverticula do not extend anterior to their aperture with the common median chamber, and instead project entirely posteriorly from the aperture with the common median chamber. The apparent absence of anterior projections of the lateral diverticula in *L. lambei* may be due to relative reduction of these structures, or poor ossification, and if present may have extended slightly dorsally along the lateral margins of the dorsal loops (Weishampel, 1981b). The apertures between the common median chamber and lateral diverticula are dorsoventrally narrow and anteroposteriorly elongate. The posterior projections of the lateral diverticula are lobate, but are not as mediolaterally compressed as in *Corythosaurus* spp. The lateral diverticula are formed by the premaxillae anteriorly, and the nasals posteriorly, but the premaxillae contribute significantly more than the nasals

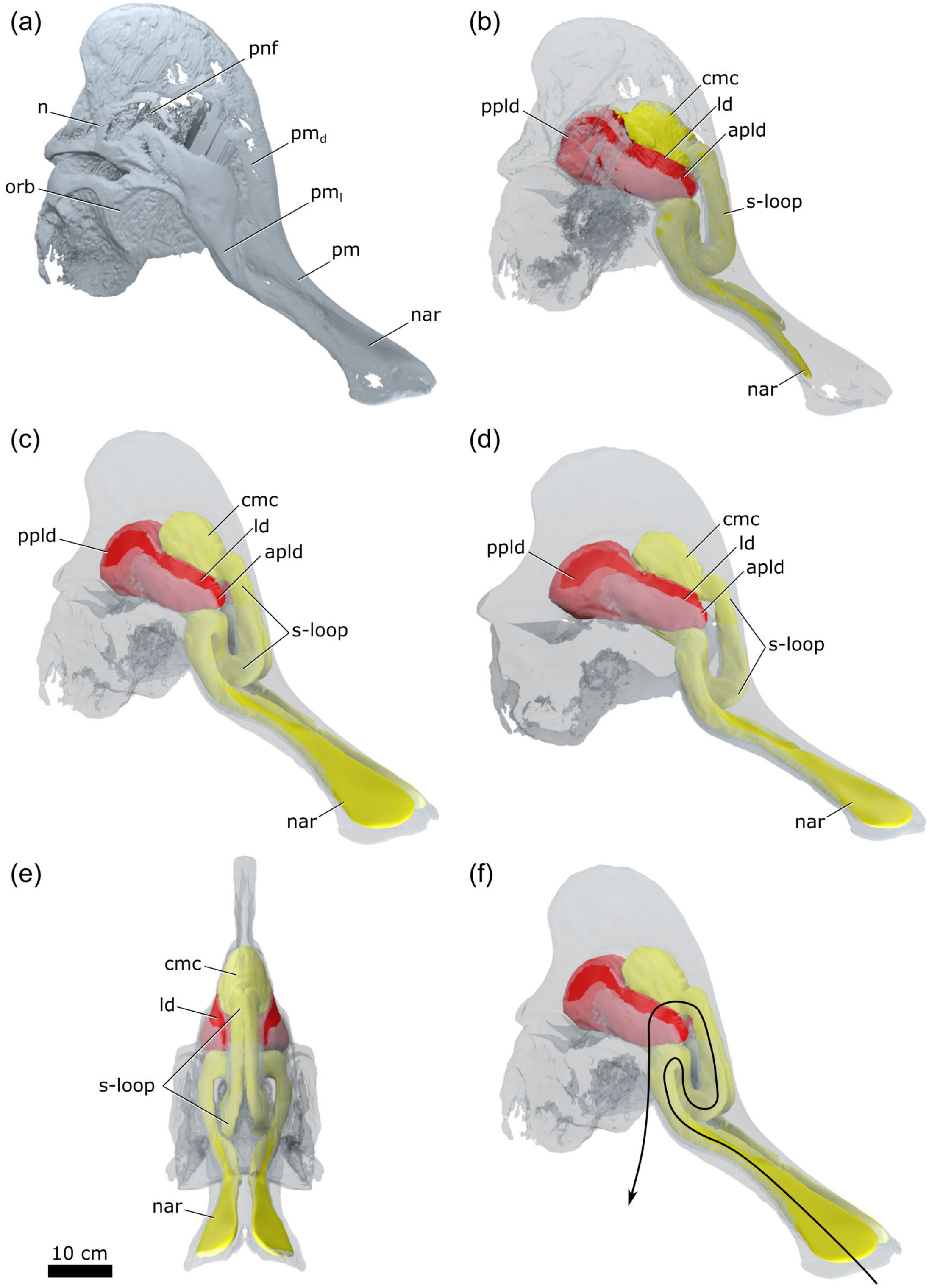

FIGURE 2 Cranial and nasal passage anatomy of *Corythosaurus intermedius* (UALVP 13). Preserved cranial anatomy in right anterolateral view (a), preserved nasal anatomy in right anterolateral view (b), retrodeformed nasal anatomy in right anterolateral view (c), right lateral view (d), anterior view (e), and right anterolateral view indicating the path of inspired air (f, black arrow).

due to the reduction of the latter element in *Lambeosaurus* spp. The nasopharynx extends ventrally from the common median chamber towards the choanae, a morphology that is common to Lambeosaurinae.

4 | DISCUSSION

Nasal cavity reconstructions in Lambeosaurini have evolved considerably since the clade's discovery. The

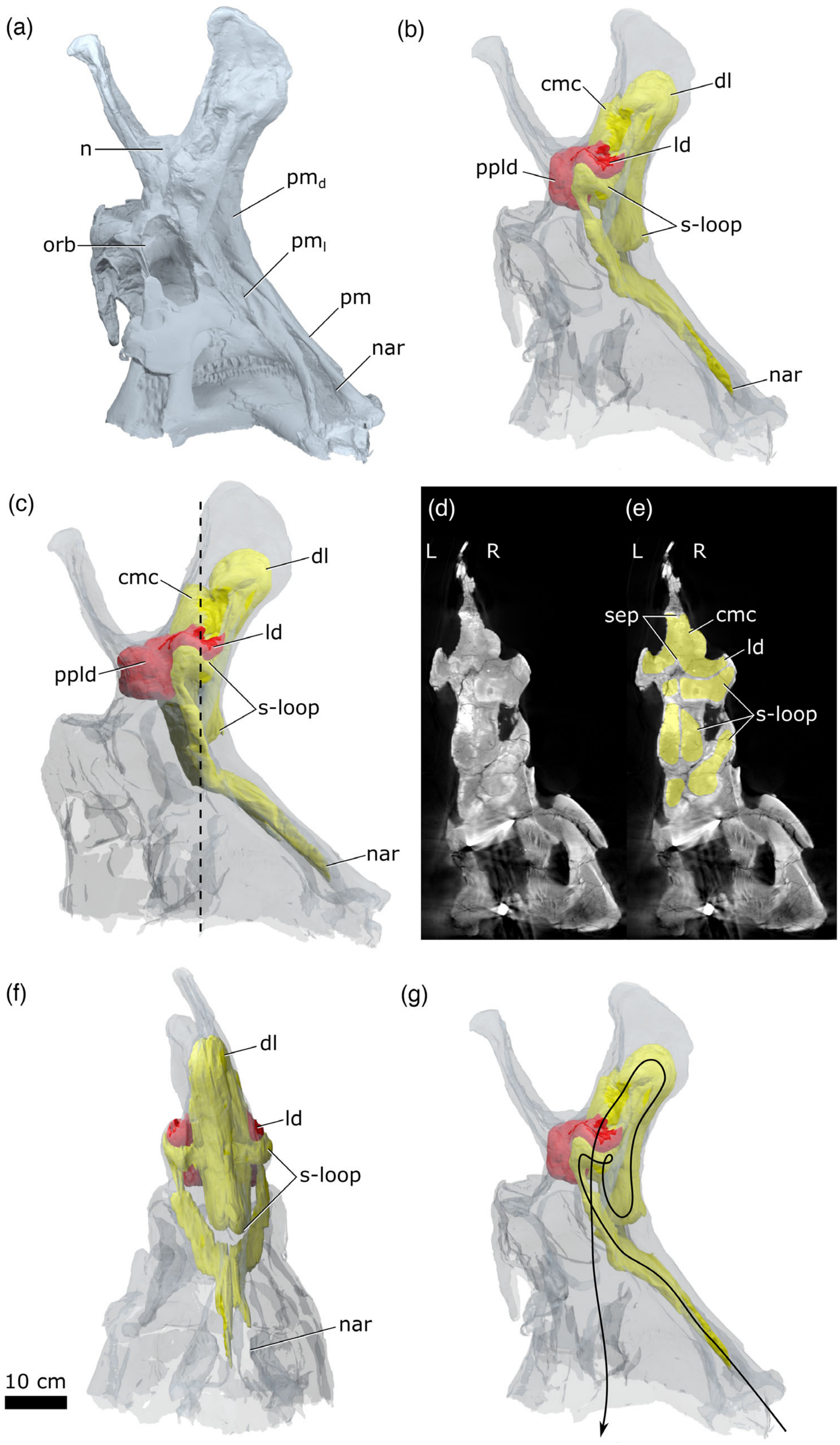

FIGURE 3 Preserved cranial and nasal passage anatomy of *Lambeosaurus lambei* (TMP 1982.038.0001). Skull in right anterolateral view (a), nasal anatomy in right anterolateral view (b), right lateral view (c), coronal cross-section (d, e), anterior view (f), and right anterolateral view indicating the path of inspired air (g, black arrow). Dotted line in (c) indicates the position of coronal cross-section in (d) and (e). Yellow highlighted areas in (e) denote the boundaries of the airway.

nasal passages were first identified in lambeosaurines as relatively simple, with species variably possessing simple u- or s-loops leading into a common median chamber (Lambe, 1914, 1920; Sternberg, 1935). These interpretations were largely supported by subsequent studies of fragmentary and physically dissected specimens of

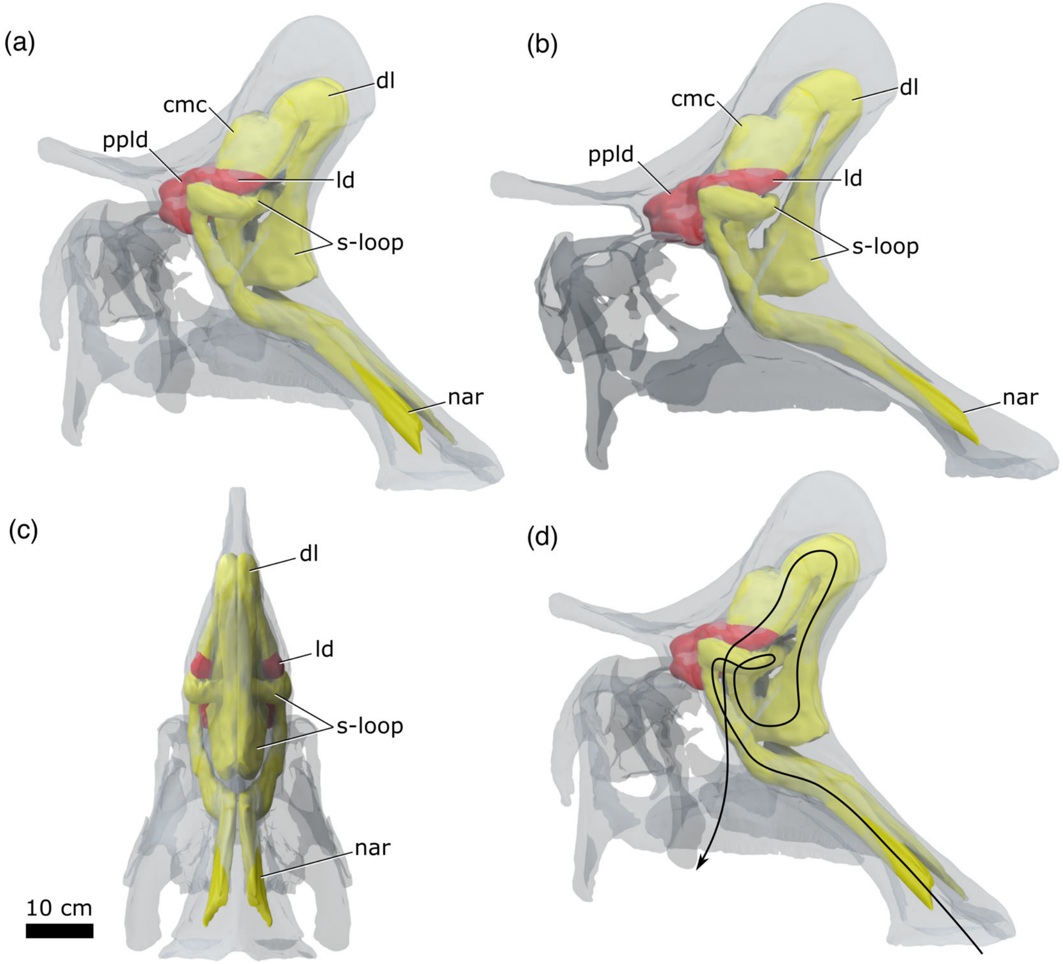

FIGURE 4 Retrodeformed nasal passage anatomy of *Lambeosaurus lambei* (TMP 1982.038.0001). Retrodeformed nasal anatomy in right anterolateral view (a), lateral view (b), anterior view (c), and right anterolateral view indicating the path of inspired air (d, black arrow).

Corythosaurus, but the s-loops of *Lambeosaurus* were interpreted as being far simpler with an additional blind cavity dorsal to them, and variable identification of lateral diverticula anterodorsal to the common median chamber (Ostrom, 1961; Weishampel, 1981b). Subsequent analyses of immature specimens found the nasal anatomy of these two genera to largely conform to each other, forming an s-loop leading to the common median chamber and with lateral diverticula branching laterally from it (Evans et al., 2009). The analysis of mature individuals of *Corythosaurus casuarius*, *C. intermedius*, and *Lambeosaurus lambei* presented here demonstrates that the s-loops of these taxa are more convoluted than previously appreciated in adults. Most significantly, the s-loops of *L. lambei* are highly convoluted within the premaxilla, representing the most extreme development of this structure currently known among lambeosaurines. *Lambeosaurus lambei* is further derived in the development of a dorsal loop within the premaxillae, between the s-loop distally and the common median chamber proximally. The lateral diverticula of *Corythosaurus* spp. and *L. lambei* are both lobate and primarily project posterior to their apertures with the common median chamber, differing from the anteriorly projecting diverticula of mature *Hypacrosaurus altispinus* (Evans et al., 2009). The revised model of mature nasal anatomy in Lambeosaurini provides several key insights into their phylogenetics, and supracranial crest function in these taxa more generally.

4.1 | Interspecific variation

The internal anatomy of the crests of mature *Corythosaurus* spp. and *Lambeosaurus lambei* conform to the typical lambeosaurine morphology overall but exhibit distinct taxonomic differences. *Corythosaurus casuarius* and *C. intermedius* have few differences in internal anatomy, but *L. lambei* exhibits more exaggerated features, including larger s-loops and the addition of a dorsal loop anterodorsal to the common median chamber. The internal anatomy of the taxa described here contrasts markedly with that of adult *Hypacrosaurus altispinus* (Figure 5) (Evans et al., 2009), the most notable differences being the direction of curvature of the s-loops and the proportions of the projections of the lateral diverticula. The s-loops of *Corythosaurus* spp. and *L. lambei*

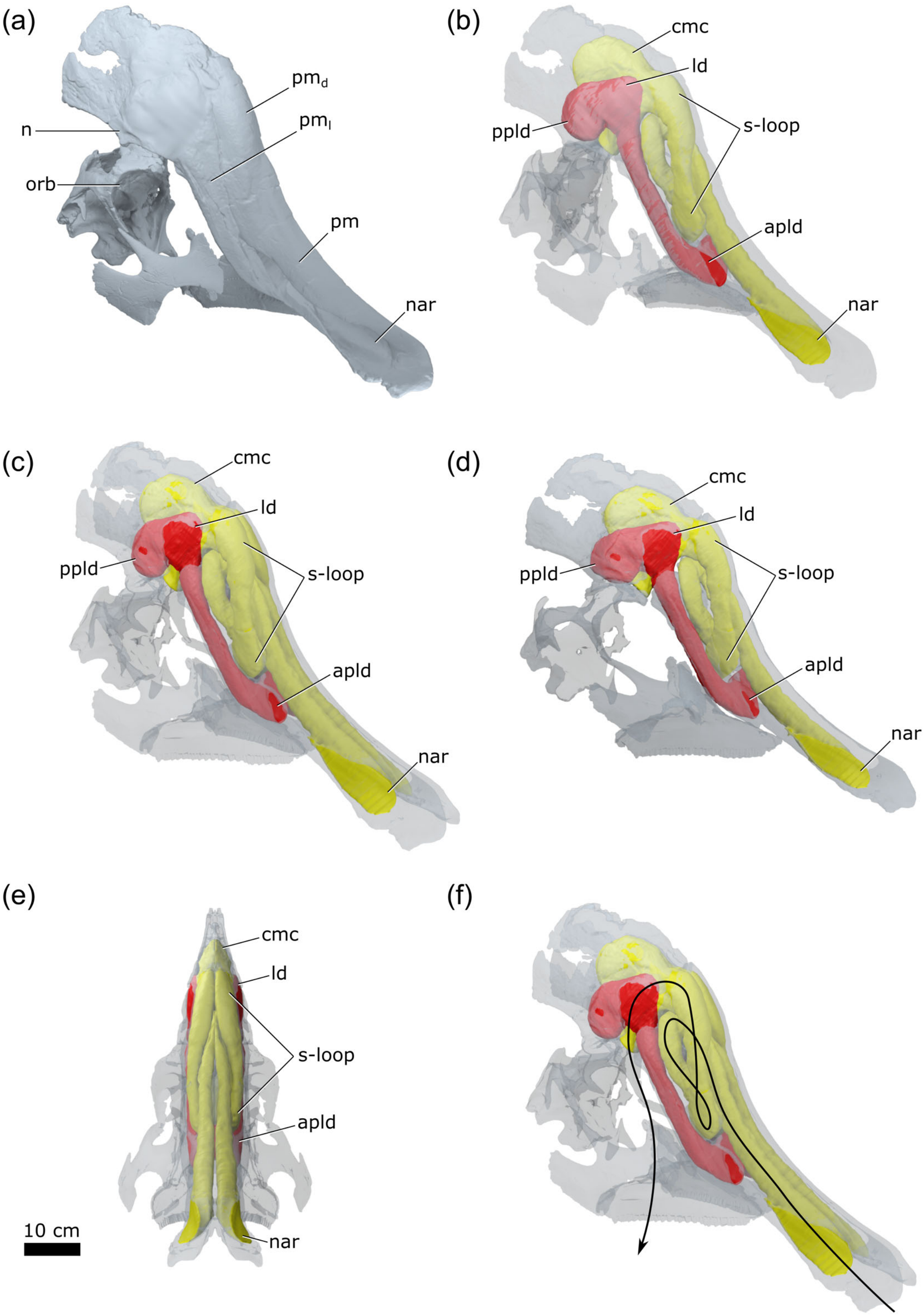

FIGURE 5 Cranial and nasal passage anatomy of *Hypacrosaurus altispinus* (ROM 702; modified for rendering from Evans et al., 2009). Preserved cranial anatomy in right anterolateral view (a), preserved nasal anatomy in right anterolateral view (b), retrodeformed nasal anatomy in right anterolateral view (c), right lateral view (d), anterior view (e), and right anterolateral view indicating the path of inspired air (f, black arrow).

progress from lateral to medial within the premaxilla (Figures 1–4), whereas the s-loops of *H. altispinus* progress from medial to lateral (Figure 5) (Evans et al., 2009). Although variable in overall size, the relative proportions of the anterior and posterior projections of the lateral diverticula are consistent among *Corythosaurus* spp. and *L. lambei*, where the posterior projections are significantly larger than the anterior projections, and the posterior projections are lobate. The lateral diverticula of *H. altispinus* have relatively small posterior projections, though they remain mediolaterally compressed as in *Corythosaurus* spp., but the anterior projections are extremely developed, extending anteroventrally within the premaxillae to the level of the ventral margin of the s-loops (Figure 5). In this way, the lateral diverticula are the most divergent structures between the three genera.

The direction of curvature of the s-loops and morphology of the lateral diverticula in these taxa are significant in the context of their hypothesized evolutionary relationships. While there is some disagreement (Dalman et al., 2025; Prieto-Marquez, 2010; Ramírez Velasco et al., 2021), most phylogenies find *Corythosaurus* spp. and *Hypacrosaurus altispinus* to be more closely related to each other than either is to *Lambeosaurus* spp. (Evans, 2010; Evans & Reisz, 2007; Gates et al., 2021; Godefroit et al., 2003; Godefroit et al., 2004; Godefroit et al., 2012; Kobayashi et al., 2021; Longrich et al., 2021; Prieto-Marquez et al., 2016; Xing et al., 2017). If the majority of phylogenies are correct, then the combination of a lateral-to-medial curvature in the s-loops and a small anterior projection of the lateral diverticula is likely ancestral for Lambeosaurini, and *H. altispinus* is derived in reversing the curvature of the s-loops and possessing a longer anterior projection to the diverticula. These data presented here support the hypothesis of Evans et al. (2009), who suggested there were significant evolutionary modifications to the nasal passages in the lineage leading to *H. altispinus* that were independent of external crest anatomy. We recommend that future phylogenies of lambeosaurine hadrosaurids incorporate characters on the internal anatomy of the crest to better elucidate the interrelationships within this group and more completely capture the morphological variation in crest anatomy. The homologies of these structures in the related corythosaurian *Parasaurolophus* are presently unclear (Gates et al., 2021; Ostrom, 1961; Weishampel, 1981b), and detailed internal descriptions of the genus using CT data are needed to better evaluate internal narial evolution in Lambeosaurinae more broadly.

4.2 | Ontogenetic variation

The data presented here support previous hypotheses suggesting significant ontogenetic variation in the internal anatomy of lambeosaurine supracranial crests. Juvenile *C. casuarius* have more developed anterior projections of the lateral diverticula than subadult *C. casuarius*, and the anterior projections are most reduced in the adult *C. casuarius* described here (Figure 6a–c) (Evans et al., 2009). The ontogenetic reduction of the anterior projections coincides with the posterodorsal expansion of the s-loops (Figure 6a–c), and the reduction of the lateral diverticula in this taxon may be due to spatial constraints within the premaxillae. This shortening of the anterior projections through ontogeny may either be due to their absolute reduction in size, or simply due to differential growth where the other components of the airway outpace the growth of the anterior projections.

Comparisons between the juvenile *Lambeosaurus* sp. described by Evans et al. (2009) and the mature *L. lambei* described here suggest a similar ontogenetic trend to *Corythosaurus*. The s-loops are initially simple early in ontogeny, and the lateral diverticula are anteriorly expanded, but the adult *L. lambei* has remarkably well-developed s-loops that extend anterolateral to the lateral diverticula, which themselves lack anterior projections (Figure 6e,f). *Lambeosaurus lambei* may have experienced similar spatial constraints within the premaxillae to *Corythosaurus* spp., reducing the relative size of the anterior projections of the lateral diverticula to facilitate the posterolateral expansion of the s-loops. It is therefore possible that the unique medial-to-lateral curvature of the s-loops in *H. altispinus* is an adaptation to facilitate anterior expansion of the lateral diverticula, but a more complete ontogenetic series of this species is needed to evaluate the development of the different regions of the nasal passages. The extreme ontogenetic change in development of the s-loops in *L. lambei* is surprising given previous reconstructions for the taxon, and supports previous hypotheses that dramatically different selection pressures acted on the internal and external crest anatomy in lambeosaurines (Evans et al., 2009).

5 | CONCLUSIONS

The internal crest anatomy of mature individuals of *Corythosaurus casuarius* and *C. intermedius* largely correspond to previous anatomical reconstructions, but *Lambeosaurus lambei* possesses much more complex narial anatomy than has previously been recognized. Although these taxa share the same overall anatomy, including s-loops and lateral diverticula branching from the common median chamber, there are significant differences in the proportions of these sections of the vestibule, and mature *L. lambei* is apparently unique in the addition of a dorsal loop. The internal anatomy of

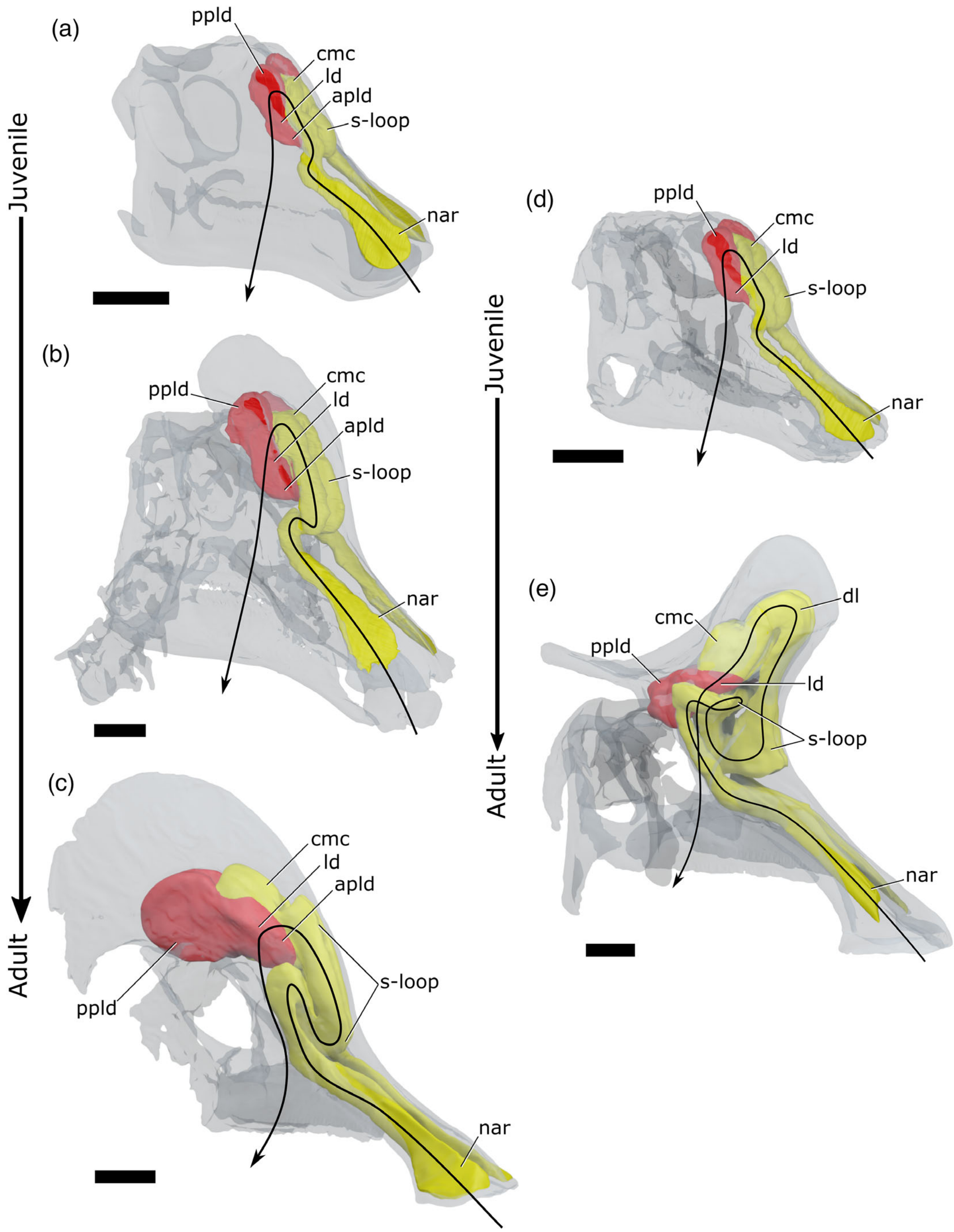

FIGURE 6 Nasal passage anatomy of juvenile (a; ROM 759), subadult (b; CMN 34825), and adult (c; ROM 1933) *Corythosaurus casuarius*, and juvenile (d; ROM 758), and adult (e; TMP, 1982.38.0001) *Lambeosaurus lambei* in right anterolateral view (a, b, d are modified from Evans et al., 2009). Black arrows within the crania indicate paths of inspired air. Scale bars represent 10 cm.

H. altispinus is most different from *Corythosaurus* spp. and *L. lambei* in reversing the direction of curvature of the s-loop and expanding the lateral diverticula anteriorly, supporting hypotheses that *H. altispinus* exhibits derived narial anatomy among lambeosaurines. Altogether, the reported differences in internal narial anatomy are just as divergent between genera as the external bony crests, providing new opportunities for the formation of phylogenetic characters. CT scanning lambeosaurines is therefore critical to future phylogenetic reconstructions by providing characters in crest anatomy that are not inherently obvious from their external structure.

Lastly, the updated narial models for mature Lambeosaurini presented here have broader implications for behavioral interpretations in these taxa. Lambeosaurine supracranial crests are generally considered to have facilitated resonant amplifications of vocalizations, and the strong divergences in internal crest anatomy between genera suggest differences in their potential resonant function and sound production. The extreme convolutions and correspondingly lengthened nasal passages of *L. lambei* indicate the potential for lower frequency sound production than in *Corythosaurus* spp., a significant interpretation given that these genera were partially contemporaneous with each other and the tube-crested corythosaurian *Parasaurolophus walkeri* in the Dinosaur Park Formation (Mallon et al., 2012). Significant taxonomic variation in internal crest anatomy of coeval genera may represent selection for differing vocalizations and suggest a potentially broad prehistoric soundscape. More detailed anatomical reconstructions of other lambeosaurine taxa are needed to fully understand crest homology and potential behavioral variation.

AUTHOR CONTRIBUTIONS

Thomas W. Dudgeon: Conceptualization; data curation; formal analysis; visualization; writing – review and editing; writing – original draft; funding acquisition; methodology; investigation; validation. **Courtney Brown:** Conceptualization; formal analysis; writing – review and editing; methodology; investigation; validation. **David C. Evans:** Conceptualization; supervision; writing – review and editing; funding acquisition; investigation; validation.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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