

# Paleontological and developmental evidence resolve the homology and dual embryonic origin of a mammalian skull bone, the interparietal

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The homologies of mammalian skull elements are now fairly well established, except for the controversial interparietal bone. A previous experimental study reported an intriguing mixed origin of the interparietal: the medial portion being derived from the neural crest cells, whereas the lateral portion from the mesoderm. The evolutionary history of such mixed origin remains unresolved, and contradictory reports on the presence or absence and developmental patterns of the interparietal among mammals have complicated the question of its homology. Here we provide an alternative perspective on the evolutionary identity of the interparietal, based on a comprehensive study across more than 300 extinct and extant taxa, integrating embryological and paleontological data. Although the interparietal has been regarded as being lost in various lineages, our investigation on embryos demonstrates its presence in all extant mammalian “orders.” The generally accepted paradigm has regarded the interparietal as consisting of two elements that are homologized to the postparietals of basal amniotes. The tabular bones have been postulated as being lost during the rise of modern mammals. However, our results demonstrate that the interparietal consists not of two but of four elements. We propose that the tabulars of basal amniotes are conserved as the lateral interparietal elements, which quickly fuse to the medial elements at the embryonic stage, and that the postparietals are homologous to the medial elements. Hence, the dual developmental origin of the mammalian interparietal can be explained as the evolutionary consequence of the fusion between the crest-derived “postparietals” and the mesoderm-derived “tabulars.”

embryology | morphological evolution | synapsids | fossil | occipital

The evolutionary identity or homology of most mammalian skull elements is now well established (1–3), although many contradictory statements still exist on the interparietal, a dermal skull roof element situated between the parietal and supraoccipital (e.g., 4–8). Several authors have suggested a homology of the paired mammalian interparietals to the paired postparietals in more basal reptiles (6, 9). However, inconsistent patterns reported among mammals (7, 10, 11), and even humans (12), and a unique mixed embryonic origin (1) make the question of the homology of the interparietal an unresolved issue of vertebrate anatomy.

An experimental embryological study in the mouse by Jiang et al. (13) demonstrated a striking dual developmental origin of the interparietal: the median portion is derived from the neural crest cells, whereas the lateral portion is derived from the mesoderm. This report has triggered a renewed interest among developmental biologists in the evolution of the interparietal in amniotes (1, 14, 15). Although integrating fossil record and comparative anatomical data with newly gained experimental findings should provide relevant information for the current discussions on the origin of skull roof bones, it has been hampered by terminological inconsistencies, even within the stem mammal (synapsid) lineage, and unsolved homologies across major living groups (4, 6, 7, 9, 11, 16). In humans, the interparietal develops from two pairs of ossification centers, one medial pair and one lateral pair, eventually fusing seamlessly to the

supraoccipital (17). In contrast to the human pattern, it is generally regarded for mammals that the interparietal arises in development as a pair of bones that soon fuse at the midline to form a single bone (6, 8, 18). However, the absence of the interparietal has been pointed out in marsupials (11, 18), xenarthrans (19), shrews (4), seals (10), hippopotamuses (10), and pangolins (11). The classic work of de Beer (20) reported that the interparietal is lacking in monotremes, bandicoots, armadillos, and pigs.

The paucity of appropriate embryonic material across mammalian species has undoubtedly hindered evaluations as to the primordial anlage, general presence, and variation of the interparietal. As exemplified in humans, the interparietal generally fuses with neighboring bones early in the perinatal period (12). Because the majority of work has been based on mature specimens, previous observers could have been misled by the early fusion of the interparietal with other bones. Here, with the unique availability of wide taxonomic and ontogenetic sampling across all extant mammalian orders and major nonmammalian fossil taxa, we address the issues of variation, patterns, and homology of the interparietal. Our results question the generally accepted homology hypothesis, and we suggest an alternative model that explains the intriguing dual tissue origin of the interparietal. Our integrative study provides a bridge between paleontology and developmental biology and a synthetic understanding of the dermal skull roof of vertebrates.

## Results

Below we present an overview of our findings. A full description of our detailed survey is given in *SI Appendix*. All 51 nonmammalian synapsid species examined possessed the postparietal, which has been posited as homologous to the interparietal (9), either unpaired or paired (*SI Appendix*, Fig. S3 and Table S1). The Jurassic docodont mammal *Haldanodon expectatus* reportedly possesses the interparietal (21), as do the extant monotremes including the platypus *Ornithorhynchus* (22) and the long-beaked echidna *Zaglossus* (23). A small medial membrane bone, a remnant of the interparietal, is found in the short-beaked echidna *Tachyglossus aculeatus* (24). Marsupials reportedly lack the interparietal (11), but we confirmed its presence in various species (*Trichosurus*, *Monodelphis*, *Didelphis*, *Macropus*, and *Sminthopsis*). Contrary to the reported absence of the interparietal in *Monodelphis* (25), in the examined embryonic series of the gray short-tailed opossum *Monodelphis domestica*, both the supraoccipital and interparietal are present. Here, the interparietal was found to be unpaired, paired, tripartite, and quadripartite, depending on the stage (*SI Appendix*, Fig. S4).

We recorded the presence of dermal interparietal bone in four xenarthran species, including the long-nosed armadillo *Dasyops*

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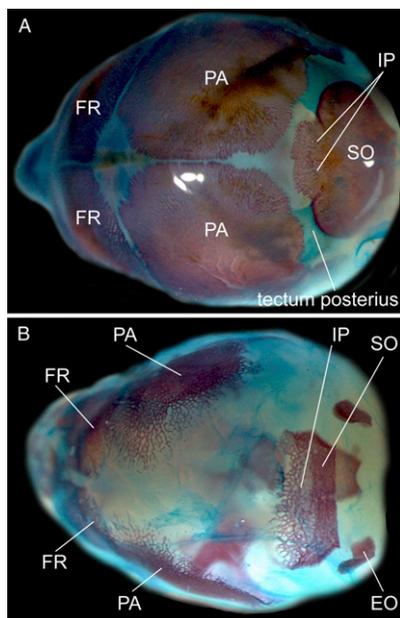
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*hybridus* (Fig. 1A and *SI Appendix, Table S1*). Our investigation confirmed the presence of the interparietal across afrotherians (*SI Appendix, Figs. S5 A and B and S6 and Table S1*). We identified unpaired, paired, and tripartite interparietals in the tree hyrax *Dendrohyrax arboreus*. The interparietal in the rock hyrax *Procavia capensis* was found to be unpaired, paired, tripartite, and quadripartite. In some individuals, the lateral elements fuse earlier to the supraoccipital rather than to the medial elements (*SI Appendix, Fig. S5B*). Tripartite interparietal elements were described for the cape golden mole *Chrysochloris asiatica* (2). In sirenians (*Dugong dugon*, *Trichechus manatus*, and *Trichechus senegalensis*) the interparietal showed a maximum of four elements. Among extinct South American notoungulates, *Toxodon burmeisteri*, *Typotherium cristatum*, *Nesodon imbricatus*, and *Pachyrhynchus* were confirmed to possess the interparietal.

We observed the interparietal universally in Euarchontoglires (Fig. 2 I–J and *SI Appendix, Fig. S9 D–F and Table S1*). In the kangaroo rat *Dipodomys*, the interparietal was essentially formed from four ossification centers (26). One median and two lateral elements were found in various stages of the degu *Octodon degu* (Figs. 3 B and C and 4) and in the Patagonian cavy *Dolichotis patagonum* (Fig. 3 D and E). Among primates, the interparietal was widely found in perinatal individuals (Fig. 2J and *SI Appendix, Table S1*). In humans, the interparietal develops from four elements (12, 27).

Paired interparietals were recorded in lipotyphlans (Figs. 1B and 2A and *SI Appendix, Table S1*). There was no previously published information on the presence of the interparietal in moles. Nevertheless, we found thin paired membranous interparietals, which initiate their ossification from the dorsal tip of the supraoccipital and then grow gradually toward the rostral direction, in both the Iberian mole *Talpa occidentalis* (*SI Appendix, Fig. S10A*) and the European mole *Talpa europaea*. Similarly, we found the developing dermal interparietal in the coast mole *Scapanus orarius* (*SI Appendix, Fig. S10 C and D*) and the Japanese mole *Mogera wogura*. Augier (4) noted that shrews have no interparietal, but we recorded this bone in various shrews (*Sorex araneus*, *Sorex unguiculatus*, and *Crocidura attenuata*) (Fig. 1B).



**Fig. 1.** Dorsal view of cleared and stained embryonic specimens. (A) Specimen of southern long-nosed armadillo (*D. hybridus*). Note the dermal interparietal growing from the anterior tip of the cartilaginous supraoccipital. (B) Specimen of Asian gray shrew (*C. attenuata*). Note the typical reticular appearance of the interparietal seamlessly attached to the anterior tip of the supraoccipital. FR, frontal; IP, interparietal; PA, parietal; SO, supraoccipital.

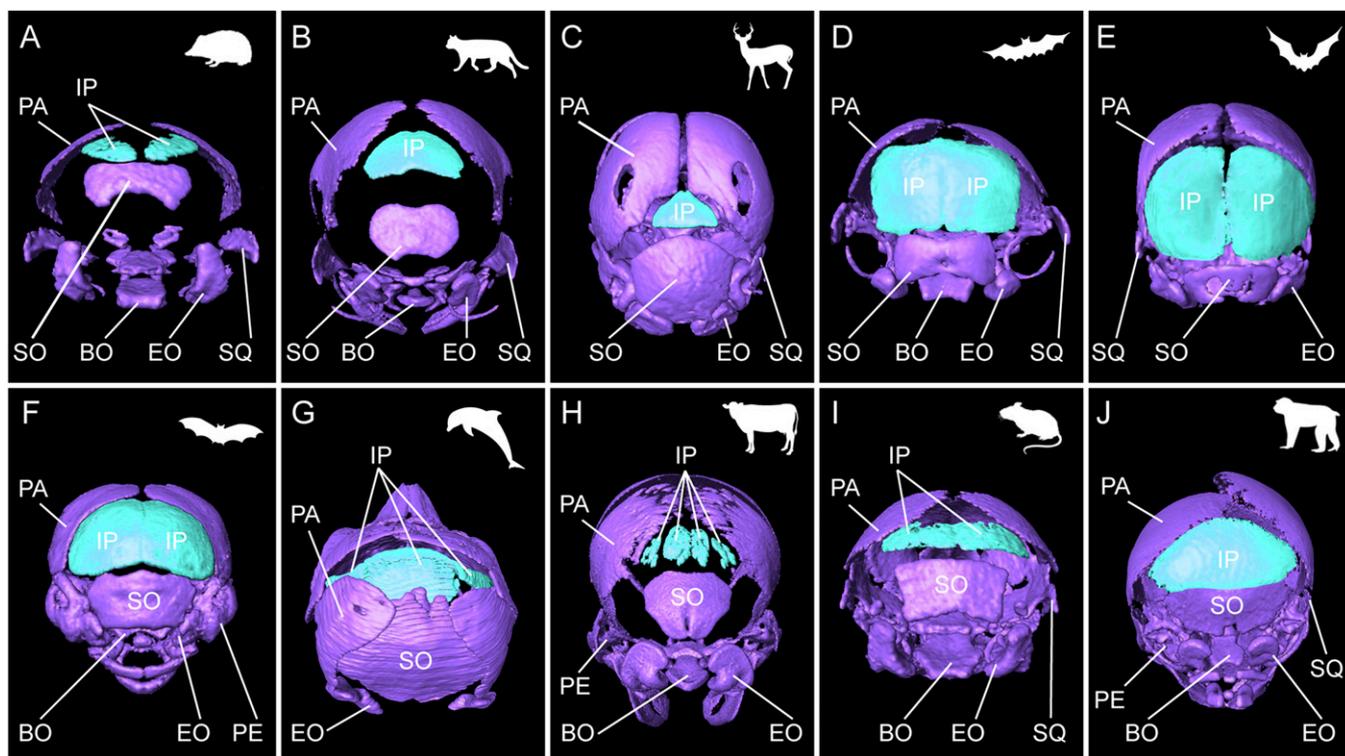
The interparietal is present in artiodactyls, cetaceans, perissodactyls, carnivorans, bats, and pangolins (Fig. 2 B–H and *SI Appendix, Fig. S9 A–C and Table S1*). The bottle-nosed dolphin *Tursiops truncatus* possesses an expanded median and two lateral interparietal elements (Fig. 2G). Eales (28) described the greatly expanded four-element interparietal in the narwhal *Monodon monoceros*. The cow *Bos primigenius* exhibited quadripartite interparietal (Fig. 2H). The tripartite interparietal is reported for the yak *Bos grunniens* (29). Wegner (1960) documented the tripartite interparietal in the jaguar *Panthera onca* and cougar *Puma concolor*. Although Giebel (10) noted that seals lack the interparietal, we observed that prenatal skulls of fur seals *Arctocephalus* (*SI Appendix, Fig. S5G*) and *Callorhinus ursinus* (*SI Appendix, Fig. S8B*) display enlarged interparietals and that the supraoccipital is extremely reduced in size compared with the interparietal, which dominates the caudal portion of the vault. The earless seal *Phoca* is reported to exhibit the lateral interparietal element (2, 25). Gregory (30) reported that pangolins lack the interparietal, but we found its presence in an immature individual of the Chinese pangolin *Manis pentadactyla* (*SI Appendix, Fig. S5E*).

## Discussion

**Basic Structure and Evolutionary Patterns of the Interparietal.** The presence of the interparietal is almost universal among extant mammals. Previous reports have noted that there is no interparietal in monotremes (18, 20), marsupials (11, 18), xenarthrans (11, 19, 20), moles and shrews (4), seals (10), and pangolins (30). However, we documented the presence of the interparietal in monotremes (*Ornithorhynchus* and *Tachyglossus*), marsupials (23 species), xenarthrans (*Bradypus*, *Dasybus*, *Tamandua*, and *Cyclopes*), moles (*Talpa*, *Mogera*, and *Scapanus*), shrews (*Crocidura*, *Suncus*, and *Sorex*), seals (*Phoca*, *Arctocephalus*, and *Callorhinus*), and pangolins (*Manis*) (*SI Appendix, Table S1*). Previous studies may have overlooked the presence of the interparietal because of its early fusion to adjacent bones, either the supraoccipital or the parietal. The membranous bone found rostral to the endochondral supraoccipital in these species is interpreted to be the interparietal. The case of some shrews provides an instructive example of the importance of investigating embryonic materials and understanding the topological relationships of calvarial bones. The expansion of the interparietal and the rudimentary presence of the supraoccipital, which was often found in shrews, may have misled anatomists to regard the true interparietal as the supraoccipital and to consider the interparietal to be lacking in shrews (for instance, Fig. 1B). Kuratani (31) observed the expansion of the dermal interparietal bone and the unique case of possible lack of the cartilaginous supraoccipital in the Asian house shrew *Suncus murinus*. In the common shrew *S. araneus* (*SI Appendix, Figs. S7 C and D and S11*) and the long-clawed shrew *S. unguiculatus* (*SI Appendix, Fig. S12*), we observed that the membranous interparietal dorsally covers the cartilaginous supraoccipital, forming a double-layered structure with the supraoccipital. In the Asian gray shrew *C. attenuata*, the presence of the dermal interparietal was obvious (Fig. 1B).

Although the Jurassic docodont *Haldanodon* is reported to possess the interparietal (21), its absence has been noted in other basal mammalian clades, including morganucodontids, multituberculates, *Sinoconodon*, and *Vincelestes* (32). However, as shown in the present study, the “absence” of the interparietal cannot be generalized in these species, because the interparietal may fuse early with other bones or it may be overlooked because of the poor preservation of sutures in fossils. This is especially true for primates, in whom the interparietal fuses with the supraoccipital at very early embryonic stages [cf. Hershkovitz (33), who commented that callitrichid monkeys lack the interparietal].

Generally, the interparietal has been regarded as comprising paired elements that often fuse with each other to form an unpaired bone (8, 9, 11, 18). In contrast, a maximum of four ossification centers were recognized from our survey in artiodactyls (Fig. 2H), cetaceans, rodents, sirenians, hyraxes, platypuses, opossums, and

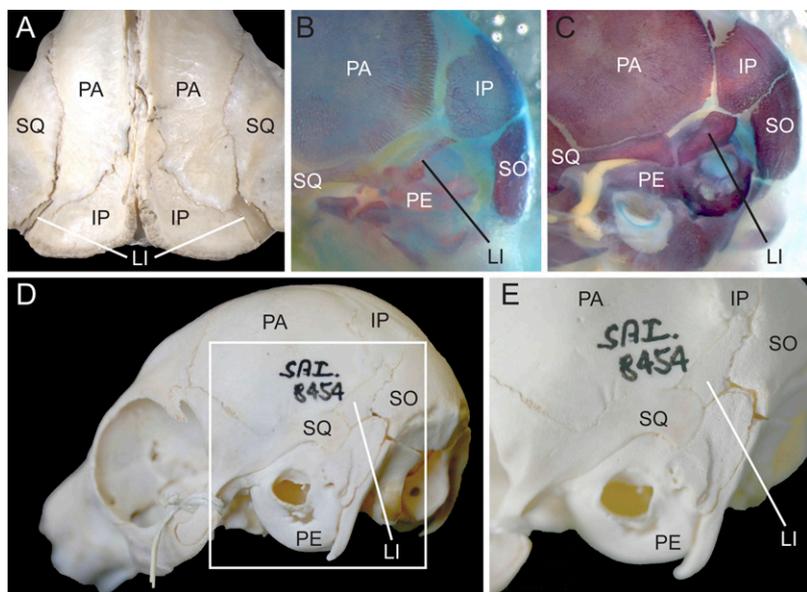


**Fig. 2.** Microtomographic reconstructions of the embryonic skulls in various species (caudal view). (A) Amur hedgehog (*Erinaceus amurensis*). (B) Cat (*Felis catus*). (C) Japanese deer (*Cervus nippon*). (D) Horseshoe bat (*Rhinolopus cornutus*). (E) Hardwicke's woolly bat (*Kerivoula hardwickii*). (F) Blanford's bat (*Hesperoptenus blanfordi*). (G) Bottlenose dolphin (*T. truncatus*). (H) Cow (*B. primigenius*). (I) Large Japanese field mouse (*Apodemus speciosus*). (J) Japanese macaque (*Macaca fuscata*). BO, basioccipital; EO, exoccipital; IP, interparietal; PA, parietal; PE, petrosal; SO, supraoccipital; SQ, squamosal.

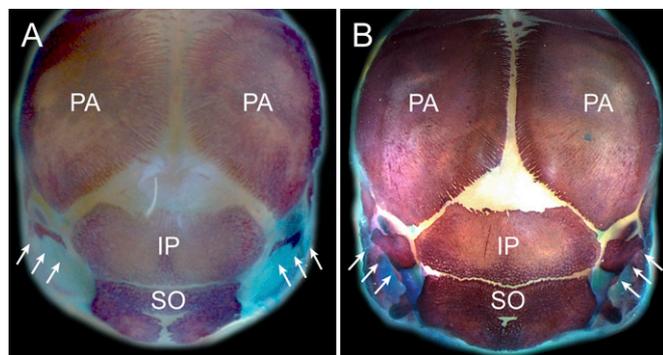
humans (*SI Appendix, Table S1*). The four elements fusing with one another become paired or unpaired, depending on the species or developmental stage. The fact that the lateral elements fuse to the medial elements at the embryonic stage in many taxa makes it critically difficult to identify the lateral portions of the interparietal. Tripartite interparietals were found in opossums (Fig. 3*A*), rodents (Figs. 3*B–E* and 4), cetaceans (Fig. 2*G*), felids, seals, yaks, manatees, tenrecs, hyracoids, golden moles, and humans. In these taxa, the median bone is an enlarged element formed by the fusion of two

medial elements, and the lateral elements are separated from this median bone. Similarly, extinct notoungulates also exhibit tripartite interparietals.

The facts presented above indicate that the interparietal consists of four basic elements: one medial pair and one lateral pair (see Fig. 5*B*). In most living mammals, the lateral element fuses first with the medial element, forming paired interparietals, and later in ontogeny, the fusion occurs between the two composites, forming an unpaired interparietal. Nevertheless, in some species



**Fig. 3.** Lateral view of skulls of opossum and rodents. (A) Dorsal view of a white-eared opossum (*Didelphis albiventris*). (B and C) Degu (*O. degu*) skulls of different stages. (D) Perinatal skull of Patagonian cavy (*D. patagonum*). Note the lateral interparietal element (LI). (E) Close-up image of *D.* IP, interparietal; LI, lateral interparietal element; PA, parietal; PE, petrosal; SO, supraoccipital; SQ, squamosal.



**Fig. 4.** Dorsal view of embryonic skulls of degu (*O. degu*). (A) Note the lateral interparietal elements (arrows) lying lateral to the median interparietal (IP). (B) A more advanced individual of degu. Note the lateral interparietal elements (arrows). IP, interparietal; PA, parietal; SO, supraoccipital.

(rodents, cetaceans, tenrecs, hyracoids, felids, seals, manatees, yaks, golden moles, and humans), the medial elements initially fuse with each other, whereas the lateral elements remain separate from the medial element, producing a tripartite interparietal (Fig. 4). Such a condition is comparable to that in most nonmammalian synsids, in whom paired tabulars are present but are separated from the median postparietal (e.g., see *Titanophoneus* in Fig. 5A).

**Homology of the Mammalian Interparietal.** Both the postparietal and the tabular are widely present in various tetrapods, including lissamphibians, diapsids, and nonmammalian synsids [the terminology of the postparietal has been variable depending on the authors, such as “retroparietal” (34), “dermosupraoccipital” (35), “dermooccipital” (16), and “parieto-extrascapular” (36)] (SI Appendix, Table S1). The stem condition of lissamphibians, as illustrated by some dissorophids, exhibits paired postparietals and tabulars (37). Although modern lissamphibians were previously suggested to have lost the postparietals (38), they are present in some living anurans such as the spadefoot toad *Pelobates* (39) and fire-bellied toad *Bombina* (40). Basal amniotes exhibit paired postparietals and tabulars (41) (SI Appendix, Fig. S1). In contrast, no extant sauropsid reportedly possesses the postparietals, with the exception of the American alligator *Alligator mississippiensis* (42). Extant chelonians (turtles, tortoises, and terrapins) (37), squamates (18, 37, 43–45), and birds (46) lack the postparietals. However, the presence of paired postparietals is common among fossil diapsids (37, 41) (SI Appendix, Figs. S1 and S2).

Here, we hypothesize that the medial interparietal ossification centers and lateral ossification centers of mammals are homologous to the postparietals and the tabulars, respectively, of ancestral forms (Fig. 5A). The spatial arrangements of these bones, the number of elements, and the intramembranous nature of these bones lend support to this postulate. The topological correspondence of the posttemporal canal in nonmammalian synsids and in primitive mammals also gives support to this hypothesis. In nonmammalian synsids, the tabular generally forms an arch or roof over the posttemporal canal (SI Appendix, Fig. S3 B, D, and F) (see also ref. 47). This canal is located at the junction of the tabular, squamosal, and mastoid in *Morganucodon* (48). The posttemporal canal is found in monotremes, opossums, and armadillos (49). For example, in opossums this canal is located at the junction of the lateral interparietal, squamosal, and mastoid as in *Morganucodon* (SI Appendix, Fig. S4) (see also refs. 50 and 51).

Frequent fusions between the tabular and postparietal in nonmammalian synsids suggest the strong coupling trend of these bones. Across the observed nonmammalian synsids, 33 species exhibited one median postparietal and two tabulars (e.g., *Titanophoneus* in Fig. 5A), whereas 17 species showed only the median “postparietal” (SI Appendix, Fig. S3 and Table S1). In the later ones, the tabular is not lost but is fused to the postparietal.

Given the presence and shape of the tabular and postparietal in juveniles of *Cistecephalus microrhinus*, a Late Permian anomodont therapsid, the tabular is fused to the true postparietal to form an enlarged median “postparietal” in mature individuals of this species (52–54), which resembles the single interparietal of various extant mammals (Fig. 2 B, C, and J).

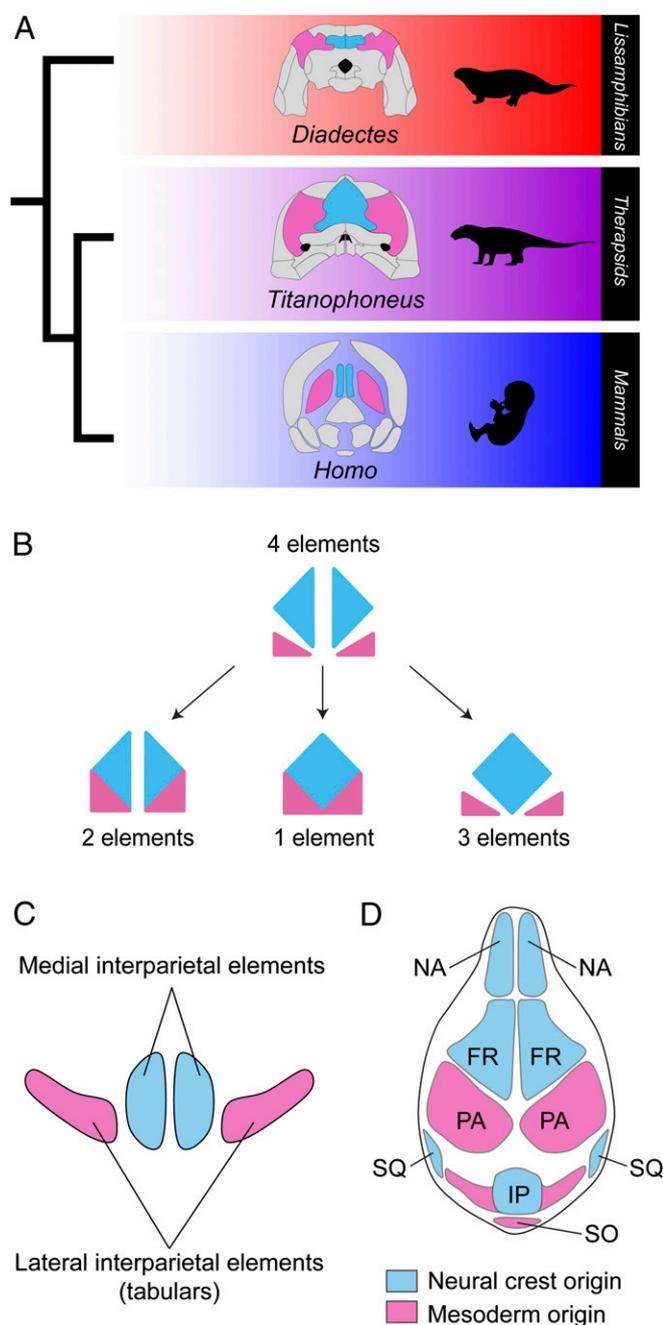
The interparietal has been regarded as an intramembranous bone formed dorsally to the tectum posterius, generally developing as a pair (7). Goodrich (9) suggested that the origin of the mammalian skull from a reptilian-like condition was brought about by the evolutionary loss of the prefrontal, postfrontal, postorbital, and quadratojugal. In his view, the postparietal pair has remained as the interparietal pair. Similarly, Gross and Hanken (1) and Morriss-Kay (3) have noted that the mammalian interparietal is homologous to the postparietal bone of “archaic reptiles.” In contrast, our investigation demonstrates that the interparietal is constituted of four rather than just two elements. Such a developmental pattern of the modern mammalian interparietal from four dermal ossification centers is not fully explained, and thus this generally accepted paradigm on the homology of the interparietal (6, 8, 9, 18, 20) cannot be supported. Furthermore, the “interparietal” frequently documented in nonmammalian synsids (e.g., refs. 41 and 53) is inconsistent. In cases where the bone labeled “interparietal” is isolated from the tabular, calling it the “postparietal” or “medial interparietal” would be appropriate.

Although the tabular is fused to the medial interparietal in some species of Dicynodontia (e.g., *Dicynodon*, *Diictodon*, and *Emydops*), it is clearly present and proportionally large in many other nonmammalian synsids (SI Appendix, Table S1). Among extinct basal mammals, the tabular is present in *Morganucodon*, but its relative size is much reduced compared with those in nonmammalian synsids (48). *Haldanodon* shows an unpaired interparietal. The interparietal is not reported in multituberculates, but we assume their interparietal is fused to the supraoccipital. Thus, it seems that in crown-group mammals the tabular became reduced in size and fused to the medial interparietal.

According to Sidor (55), who studied the variation and evolution of cranial elements in synsids leading to the living mammal crown group, there are, surprisingly, no fossil species that lack the tabular, whereas the extant lineage studied (*Ornithorhynchus*, *Didelphis*, and *Homo*) were reported to lack this bone. Nonetheless, as in the case of *Homo*, the lateral interparietal pair, which we hypothesize to be homologous to the tabulars, is identifiable in embryos (SI Appendix, Fig. S13) (12, 27). Although the “simplification trend” of the mammalian skull (55) still holds, the general assumption that the tabular is lost in the modern mammalian lineage (18, 21, 55) is questionable. Broom (35) and von Huene (56) noted that the postparietal found in fossil amphibian-like land vertebrate *Diadectes* (Fig. 5A) should be considered homologous to the postparietal of the stegocephalians. Furthermore, Jarvik (57) proposed that the postparietal and tabular of basal tetrapods are homologous to the medial and lateral extrascapulars, respectively, of osteolepiform fishes. If these scenarios are to be supported, the medial and lateral extrascapulars of osteolepiforms should be regarded as conserved in mammals as the four basic elements constituting the interparietal.

As noted earlier, dual origin of the interparietal has been reported in the mouse, the medial portion being derived from the neural crest cells and the lateral portion from the mesoderm (Fig. 5D) (13). At least four segments are necessary to account for such mixed arrangements (Fig. 5C). We found (see also ref. 26) that the rodent interparietal originates from four ossification centers. Therefore, the two medial interparietal elements may correspond to the neural crest cell-derived portion and the lateral elements to the mesoderm-derived portion. Thus, the dual origin found for the interparietal (13) could be regarded as the evolutionary consequence of the fusion between the crest-derived “postparietals” and the mesoderm-derived “tabulars.”

Gross and Hanken (1) noted that the location of the interparietal in the mouse corresponds to that of the “parietal” in the avian skull, a bone for which a controversy exists on its neural crest (58) or mesodermal origin (59). From embryological (i.e.,



**Fig. 5.** Evolutionary and development pattern of the interparietal. (A) Cladogram and caudal view of skulls of Early Permian lissamphibian *Diadectes*, Late Permian therapsid *Titanophoneus*, and human fetus. The medial interparietal (postparietal) are shown in blue, and the lateral interparietal (tabular) is shown in pink. (B) Diversity of the interparietal elements. Single, paired, or tripartite interparietal is consequently produced, depending on the fusion pattern of the four elements. (C) Suggested basic structure of the interparietal. The interparietal is suggested to consist of two medial elements and two lateral elements. (D) Tissue origins of the mouse skull vault [after Jiang et al. (13)]. The interparietal has dual origins, the median portion derived from the neural crest and the lateral part from the mesoderm. FR, frontal; IP, interparietal; NA, nasal; PA, parietal; SO, supraoccipital; SQ, squamosal.

dual mesenchymal origin) and topographical (or anatomical) grounds, Noden and Schneider (59) proposed that the bone conventionally labeled “parietal” in the chick would more appropriately be termed “interparietal” and “frontal” as “fronto-parietal.” In the chick, the boundary between frontal and parietal

overlies the otic capsule, whereas in the mouse, this boundary occurs over the orbit (59). Although the developmental origin of the avian “parietal” [the “interparietal” of Noden and Schneider (59)] is controversially reported to be exclusively derived from the mesoderm (59) or exclusively from the neural crest cells (58), no studies have been conducted to test the dual embryonic origin for the avian “parietal” (1). If the avian “parietal” is validated to be derived from both the neural crest cells and the mesoderm, it will indicate that the mammalian interparietal is homologous to the avian “parietal.”

The early ontogenetic fusion of the lateral and medial interparietal elements in living mammals may have been acquired in the synapsid lineage with encephalization and changes in molecular signaling. There is now good evidence that calvarial suture closures are associated with the expression of TGF- $\beta$  receptor genes (*Tgfr1* and *Tgfr2*) and FGF receptor genes (*Fgfr1* and *Fgfr2*) (60). Mutations in these molecules and the increased signaling of TGF- $\beta$  or FGF provokes early suture closure in humans—the so-called craniosynostosis syndrome (60, 61). However, inactivation of *Tgfr2* in the mouse leads to the absence of the interparietal and parietal (62), suggesting the critical role of TGF- $\beta$  signaling in the dermal skull roof development (see also ref. 63). In addition, recent findings demonstrate that *Tgfr2* activity is required for axon formation and neuronal migration in the developing mammalian neocortex (64) and that expression of *Fgfr1* and *Fgfr2* determines brain size (65, 66). Richtsmeier et al. (67) have pointed out the analogy between human craniosynostosis and the simplification trend of cranial bone elements in synapsid evolution. Given the phenotypic integration of brain and neurocranium growth, they suggested the possible shared genetic pathways for brain development and skull tissue growth. It is quite intriguing to recognize that humans, which exhibit the most aberrant case of encephalization in vertebrate evolution (68) are, at the same time, the species that shows one of the most complete and accelerated fusions of the interparietal among mammals. Investigators may profit from testing whether encephalization and suture fusions in the skull roof are pleiotropically caused by changes in TGF- $\beta$  and/or FGF signaling.

In conclusion, the discovery of the four-element nature of the interparietal (Fig. 5B) provides a synthetic understanding of the dermal skull roof of mammals. The “three-element interparietal” can be interpreted as consisting of one median bone, produced by the fusion of the medial interparietal elements, and two lateral interparietal elements. The “two-element interparietal” consists of a right and a left bone, each of which is the fusion of the medial and lateral interparietal elements. The “one-element interparietal” is interpreted as the fusion of all four elements (two medial and two lateral interparietal elements) into one median bone. However, it must be noted that the lateral interparietal elements may be fused earlier to the supraoccipital or to the parietal than to the medial interparietal in some cases (e.g., hyraxes). In terms of homology (Fig. 5A), the lateral interparietal elements derived from the mesoderm and the medial elements derived from the neural crest cells seem to correspond to the tabular and postparietal elements, respectively, of basal tetrapods. If future experimental studies on species other than the mouse similarly confirm the dual origin of the interparietal, our hypothesis shall be further supported.

Lastly, it is worth noting that wormian bones are rarely found anterior to the true interparietal in hyraxes, horses, cows, and primates (*SI Appendix*, Fig. S14). This anomalous dermal bone has been referred to as “os Incae” in humans (12) and “preinterparietal” in other mammals (7). Whether the preinterparietal is a simple developmental anomaly or a trait obtained de novo in some mammals remains uncertain. Future investigations on developmental and evolutionary patterns of the preinterparietal are needed to further understand the anatomy of the mammalian skull.

## Methods

We investigated more than 3,000 skulls of 318 species in the context of studies on ossification sequences and sutural fusion in mammals (69, 70) and

conducted a comprehensive review on literature describing amniote skulls (S/ Appendix, Table S1). Fetal or perinatal stages were studied to document whether the interparietal was recognizable and to record the number of interparietal ossification centers and contacts. Following de Beer (20) and Wegner (7), we defined the interparietal as an intramembranous bone that is formed dorsally to the tectum posterius and posteriorly to the parietal. Documentation was based on macerated skulls and cleared and stained specimens, as well as on microtomographic scans (Anthropological Institute, University of Zurich,  $\mu$ CT80, SCANCO Medical). Three-dimensional visualization was conducted in Amira 5.3 (Visage Imaging). A missing distinctive interparietal could be due to real loss or primordial fusion with one of the adjacent bones. Therefore, we restricted our observations to the recording of

interparietals and omitted any speculation based on the “absence” of clear signs of this element.

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