Endocast morphology of *Homo naledi* from the Dinaledi Chamber, South Africa

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Contributed by Ralph L. Holloway, April 5, 2018 (sent for review December 1, 2017; reviewed by James K. Rilling and Chet C. Sherwood)

Hominin cranial remains from the Dinaledi Chamber, South Africa, represent multiple individuals of the species *Homo naledi*. This species exhibits a small endocranial volume comparable to *Australopithecus*, combined with several aspects of external cranial anatomy similar to larger-brained species of *Homo* such as *Homo habilis* and *Homo erectus*. Here, we describe the endocast anatomy of this recently discovered species. Despite the small size of the *H. naledi* endocasts, they share several aspects of structure in common with other species of *Homo*, not found in other hominins or great apes, notably in the organization of the inferior frontal and lateral orbital gyri. The presence of such structural innovations in a small-brained hominin may have relevance to behavioral evolution within the genus *Homo*.

**Significance**

The new species *Homo naledi* was discovered in 2013 in a remote cave chamber of the Rising Star cave system, South Africa. This species survived until between 226,000 and 335,000 y ago, placing it in continental Africa at the same time as the early ancestors of modern humans were arising. Yet, *H. naledi* was strikingly primitive in many aspects of its anatomy, including the small size of its brain. Here, we have provided a description of endocast anatomy of this primitive species. Despite its small brain size, *H. naledi* shared some aspects of human brain organization, suggesting that innovations in brain structure were ancestral within the genus *Homo*.

Author contributions: R.L.H., S.D.H., H.M.G., P.T.S., W.B.V., L.R.B., and J.H. designed research, performed research, analyzed data, and wrote the paper.

Reviewers: J.K.R., Emory University; and C.C.S., George Washington University.

Conflict of interest statement: R.L.H. and C.C.S. are coauthors on a 2018 paper published in PNAS.

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2This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1720842115/-/DCSupplemental.

Published online May 14, 2018.
Appendix), resulting in water-displacement volumes of 555 mL for DH1 and 460 mL for DH3, both in good agreement with the virtual reconstructions.

The most notable morphological differences of the frontal lobes between humans and apes involve the inferior frontal and lateral orbital gyri. In apes, this area of the frontal lobes includes the fronto-orbital sulcus, which is usually well preserved on ape endocasts. A fronto-orbital sulcus is also evident on the MH1 endocast of Australopithecus sediba (14) and on some endocasts of Australopithecus afarensis (15, 16). In humans, a fronto-orbital sulcus is not apparent on the external surface of the cortex. Instead, posterior and ventral expansion of the frontal lobes has caused the human inferior frontal and lateral orbital gyri to cover over, or operculate, the anterior area of the insula, forming the frontal opercula; these are divided by the vertical and horizontal rami of the lateral fissure (refs. 17–19, Fig. 3, and SI Appendix, Figs. S6 and S7). Together, these define the borders (SI Appendix, Fig. S8) of the frontal operculum or pars triangularis (associated with Brodmann area 45). Just inferior to the pars triangularis is the orbital operculum or pars orbitalis (associated with Brodmann area 47). Just caudal to both is the fronto-parietal operculum or pars opercularis (associated with Brodmann area 44).

Many endocasts of Plio-Pleistocene Homo lack convolutional detail in this region. A humanlike frontal operculum is clearly visible on some specimens of H. erectus and on endocasts from the Sima de los Huesos, which represent early members of the Neanderthal lineage (3, 4, 20). No evidence of an ancestral fronto-orbital sulcus can be seen on either KNM-ER 1470 (Homo rudolfensis) or OH 16 (H. habilis) (21, 22). KNM-ER 1470 has been argued to have a derived configuration with vertical and horizontal rami of the lateral fissure (21), although this is not visible to us on that endocast.

The DH3 endocast of H. naledi has no fronto-orbital sulcus, similar to Homo and different from apes and Australopithecus. A vertical ramus of the lateral fissure as well as a horizontal branch off this (Fig. 3 and SI Appendix, Figs. S5 and S9) permits a clear identification of a derived frontal operculum in this endocast (23). DH3 displays a Y-shaped pattern of sulcal separation, found in between one-fourth to one-third of modern human hemispheres (17, 24). The inferior portion of the convolution suggests a very pronounced pars orbitalis, while the pars triangularis is slight, similar to the condition Falk (21) suggested for KNM-ER 1470. DH3 is the smallest endocast where this humanlike morphological pattern is clearly preserved. DH3 also has particularly clear middle and inferior frontal sulci that parallel each other. The entire frontal bends sharply in an anterior–inferior direction toward the ventral edge (SI Appendix, Fig. S5), rather than more directly anteriorly toward the frontal pole, which is also a derived trait (18).

Hominin endocasts differ from great apes in the extent of frontal and occipital petalial asymmetry (25, 26). None of the endocasts of H. naledi from the Dinaledi Chamber preserve both frontal poles and lateral prefrential surfaces, preventing an assessment of frontopetalial asymmetry. The left frontal pole of DH3 suggests a somewhat greater lateral width. The DH1 occipital shows a left occipital petalia, with the left occipital lobe both markedly larger and more posteriorly projecting than the right (Fig. 1). U.W. 101-200 is a less complete occipital fragment but is consistent with a left occipital petalia equally marked as DH1 (SI Appendix, Fig. S12). This pattern is commonly seen in modern humans and fossil hominins, including both Homo and Australopithecus, although the greater degree of petalial asymmetry seen in H. naledi is most like that seen in modern humans and the larger fossil endocasts of later Homo. Greater variation in asymmetry within the human brain has been suggested to reflect a degree of adaptive plasticity than other living primates (27). In modern humans, left occipital petalia with right frontal petalia is associated with right-handedness (28).

One indicator of the posterior organization of the brain is the position of the lunate sulcus. This sulcus is relatively well-marked in many endocasts of great apes, where its high, transversely extensive and relatively rostral position marks the extent of the primary visual cortex. In living humans, the overall cortex is substantially larger, but the primary visual cortex is relatively less enlarged than the cortex as a whole. The lunate sulcus in humans is variable and less well represented on the cortical surface, but...
when it occurs is less extensive and more posteriorly positioned than in apes. The relatively greater expansion of association cortical areas compared with primary visual cortex is notable in human brain evolution, but the identification of the lunate sulcus in endocasts of fossil hominins is difficult and has been historically controversial (1, 2).

The DH1 endocast bears faint traces of a lateral remnant of the lunate sulcus on the left side and of a dorsal bounding lunate as well (no. 6 in Fig. 1). The right side of this endocast shows a very small groove at the end of the lateral sinus, which could be a remnant of the lunate sulcus. The width from the left lateral lunate impression to the midline is a remnant of the lunate sulcus. The width from the left lateral small groove at the end of the lateral sinus, which could be well (no. 6 in Fig. 1). The right side of this endocast shows a very lunate sulcus on the left side and of a dorsal bounding lunate as well as comparatively reduced. In our assessment, this is comparable with morphology present in endocasts of both Homo and Australopithecus.

Discussion

The endcranial form of H. naledi shares aspects of cortical organization with endocasts of H. habilis, H. rudolfensis, H. floresiensis, and H. erectus. We hypothesize that these shared derived endocast features, particularly in the inferior frontal and lateral orbital gyri, were present in the last common ancestor of Homo. The ancestor of Homo would thus have been different from Au. sediba and Au. africanus in such endocast features (14–16), although Au. sediba (Fig. 3 and SI Appendix, Fig. S7) might have represented an intermediate condition (14, 23).

Despite these similarities of form, species of Homo differ greatly in brain size. H. naledi and H. floresiensis had small volumes within or just above the range of Australopithecus (11, 31). Specimens attributed to H. habilis range from 500 to >700 mL (22, 32), and H. rudolfensis includes two specimens of 752 and 830 mL (33). H. erectus, if it is defined to include both the Dmanisi and Ngandong hominin samples, exhibits a striking range of ECV from 550 to >1,200 mL (33, 34). However, regardless of size, each of these species shares similar frontal lobe morphology, even those with brain size within the range of Australopithecus samples. The form of the frontal lobes was not simply an allometric consequence of larger brain size in Homo. The extensive occipital petalial asymmetry in DH1 is similar to later, larger-brained species of Homo and may likewise suggest that this trait is not merely a consequence of larger brain size.
The morphological characters that distinguish the frontal cortex of *Homo* from known endocasts of *Australopithecus* have been implicated in the evolution of tool use, language, and social behavior. It has been suggested that *pars opercularis* and *pars triangularis*, which involve Brodmann areas 44 and 45, function in the planning of motor sequences underlying Oldowan tool production in addition to the production of speech (35), although the degree to which this is true has been disputed (36). The *pars orbitalis*, which involves Brodmann’s area 47, is associated with language processing (37) and the recognition and production of social emotions, social inhibition, and emotional learning (38); it also differs in organization between hominoids (23). Additionally, a shift toward more extensive occipital petalial asymmetry has been implicated in the evolution of language abilities in the human lineage. The ubiquity of such features within *Homo*, including the small-brained *H. naledi*, suggests that a behavioral niche with serialized communication, planning, and complex action sequences that underlie tool production, as well as increased display of prosocial emotions, may have been the environment for natural selection during the evolution of *Homo*, even for species like *H. naledi* that lack the substantial increases in overall brain size evident in archaic humans and modern *H. sapiens*.

The geological age of the Dinaledi Chamber sample of *H. naledi*, between 236,000 and 335,000 y ago (8), prompts the question of whether its small brain size was a retention from the common ancestor of *Homo*, possibly >2 Mya, or whether the small brain size of *H. naledi* may instead have resulted from secondary reduction from a later, larger-brained form of *Homo* (13). In our interpretation, the derived aspects of endocranial morphology in *H. naledi* were likely present in the common ancestor of the genus and do not by themselves provide evidence of close relationship between *H. naledi* and *H. sapiens* or other, larger-brained species within *Homo*. These morphological observations therefore provide no new evidence to test a possible evolutionary reversal or reduction in brain size in this species. To test whether small brain size was retained in *H. naledi* from the common ancestor of *Homo*, or whether instead small brain size evolved secondarily in this lineage, will require better resolution of the phylogenetic tree connecting it to other species of *Homo*. In the case of *H. floresiensis*, a similar question has arisen: Once considered as a possible dwarfed descendant of *H. erectus* (39), recent phylogenetic comparisons suggest that *H. floresiensis* may have branched from a more basal node of the *Homo* phylogeny (40, 41). *H. naledi* does not appear to be closely related to *H. floresiensis*, and the two share different suites of features with more derived species within *Homo* (11), so while these two cases may look similar in presenting small brain size in late-surviving species of *Homo*, we are not prepared to draw any independent conclusion about the relationships or validity of *H. floresiensis* without further study. *H. naledi* adds further evidence that the evolution of brain size in *Homo* was diverse and was not a simple pattern of gradual increase over time.

In recent years, anthropologists have begun to reassess the adaptive importance of brain size. Brain size was once commonly viewed as one of the most important distinguishing features of the genus *Homo* (42). Many hypothesized that the evolution of larger brains was correlated with the evolution of smaller postcanine teeth, as *Homo* pursued a dietary strategy relying upon higher-energy foods and tool use to increase caloric return and fuel a larger brain (43, 44). However, a broader comparison shows that brain size and shape, and postcanine tooth size and shape, were not phylogenetically correlated in hominins (45). Furthermore, *H. naledi*, *H. floresiensis*, and *A. sediba* all exhibit smaller postcanine dentitions and smaller brain sizes than *H. habilis* and *H. erectus* (6, 11, 14, 31, 39). *H. naledi* in particular shares derived hand and wrist morphology, and lower limb and foot morphology, with humans and Neanderthals (many of these features are not represented in known *H. erectus* fossils) that suggest humanlike abilities to manipulate objects and use landscapes (6, 9, 46–49).

As shown here, structural information from endocasts suggests that small and large brains within *Homo* shared many aspects of organization. Behaviors including stone tool manufacture, sociability, and foraging that are shared across the genus *Homo* may have selected for such a pattern of brain organization. Increases in overall brain size occurred in one or more lineages of *Homo* and may reflect specific aspects of adaptive pattern in these lineages. Brain size evolution was not a unitary trend in human ancestry, and we must work to understand a more complex pattern. Future work on the hominin fossil material attributed to *H. naledi* from the Lesedi Chamber (11), including the LES1 cranium, may test these hypotheses and provide additional information about endocast morphology in this species.

**Materials and Methods**

All Dinaledi fossil material is available for study by researchers upon application to the Evolutionary Studies Institute at the University of the Witwatersrand where the material is curated (contact Bernhard Zipfel). Surface scans of the Dinaledi cranial fragments were created by using a NextEngine Desktop laser scanner (model 2020). Between 8 and 12 divisions were used depending on the fragment and were scanned at the highest standard-definition setting. These 8–12 scans were then merged in the accompanying ScanStudio HD Pro software. Two 360-degree scans were completed for each fragment. These 360-degree scans were then aligned and merged in GeoMagic Studio (Version 2014.1.0; Raindrop Geomagic) to create a complete 3D model of the fragment. Dinaledi 3D surface and other digital data are

The ectocranial surfaces of each fragment 3D model was manually deleted to reveal the "positive" model of the endocranial surface that corresponds with cortical morphology. Different orientations, object colors, lighting, reflectivity settings, and curvature maps were then used within GeoMagic Studio to better illustrate the endocranial features. This was done consistently within each image; in this regard, no area was digitally enhanced compared with the others. Endocranial descriptions were based on these digital models as well as physical models created from them with a Zortrax model M200 3D printer and/or with silicon molding material (Dentsply and Equinox) used on the endocranial surfaces of the 3D prints. These models were then compared with 35 chimpanzee endocasts, 10 chimpanzee brain casts, 5 fixed chimpanzee brains, a digital brain model averaged from 29 chimpanzee MRIs, 14 human hemisphere endocasts, 5 fixed human brains, and a digital brain model averaged from 152 human MRIs.

The 3D surface data of the MH1 endocast (14) were acquired from the Evolutionary Studies Institute at the University of the Witwatersrand. The 3D surface data of the "Bria" (SIS 6167) chimpanzee brain (27) were acquired from the National Chimpanzee Brain Resource (www.chimpanzeebrain.org). The 3D surface data of the 29-subject averaged chimpanzee brain were acquired from the Van Essen laboratory at Washington University in St. Louis. The 3D surface data of the MNI 152 averaged human brain were acquired from the Montreal Neurological Institute (www.mccgiil.ca/neuro). While we have atlases of human and chimpanzee cortical morphology, there are no atlases for their last common ancestor or for early hominins. Consequently, our identifications were based on both modern ape and modern human cortical maps and available cytoarchitectonic maps (18, 19, 50–52).

In the original report (6), two ECVs were provided by using virtual cross-sections of the DH3/DH4 and DH1/DH2 fragments. Missing portions and the cranial bases were closed virtually by using a "Fill by Curvature" hole-filling function. The resultant ECV values were 465 cm³ (DH3/DH4) and 560 cm³ (DH1/DH2). When the basal endocranial portion of STS 19 Au. africanaus specimen was scaled to fit the smaller DH3/DH4 composite to better simulate the cranial base form, the ECV estimate did not change significantly.

In this study, we 3D-printed original composite models (without the missing basal portions) and made manual endocast reconstructions, using the endocasts to provide the missing basal portions (rostral poles, clivus, cerebellar lobes, and foramen magnum) on the 3D prints. To do so, the basal portions of the 3D prints were flattened by the printing process and were cut away to the edges of the actual endocranial portions, exposing the honeycomb matrix formed during the printing process. These were filled with plaster so that the reconstructions would not float during water immersion for volume estimation. Plastine was modeled to effect reasonable imitations of the missing portions, based on comparative specimens. The models were then immersed in water, and the water displacement was documented as the volume. The smaller ECV value was 460 mL, and the larger ECV value was 555 mL, each being the average of three measurements. These reconstructions (SI Appendix, Fig. 513) were within 5 mL of the original estimates, thus confirming the ECVs originally published.

ACKNOWLEDGMENTS. The specimens of H. naledi described in this study are curated in the Evolutionary Studies Institute at the University of the Witwatersrand. The 3D surface data of the Dinaledi fossil material are available from MorphoSource.org. The 3D surface data of the MH1 endocast are curated in the Evolutionary Studies Institute at the University of the Witwatersrand. The 3D surface data of the "Bria" (SIS 6167) chimpanzee brain are courtesy of Ada Gomez Robles and Chem Herwood and are curated at the National Chimpanzee Brain Resource (supported by NIH Grant NS092988). The 3D surface data of the 29-subject averaged chimpanzee brain were acquired from the Van Essen laboratory at Washington University. This work and are courtesy of Matthew G. Gardner and David Van Essen of Washington University in St. Louis and James Rilling and Todd Preuss of Emory University. The 3D surface data of the MNI 152 averaged human brain were courtesy of the Montreal Neurological Institute. This work was supported by the National Geographic Society, the National Research Foundation of South Africa, the Lyda Hill Foundation, the Fullbright Scholar Program, the Vilas Trust, and the Wisconsin Alumni Research Foundation. P.T.S. was supported by Grant S2935 from the John Templeton Foundation titled "What Drives Human Cognitive Evolution?" (N. Toth, K. Schick, C. Allen, P. T Todd, and P.T.S., coprincipal investigators).

5. Dart RA (1929) Australopithecus africanus; and His Place in Human Origins (University of Witwatersrand Archives, Johannesburg).


