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► **To cite this version:**

Edwin J de Jager, Albert N van Schoor, Jakobus W Hoffman, Anna C Oettlé, C Fonta, et al.. Sulcal pattern variation in extant human endocasts. 2018. <hal-03781536>

HAL Id: hal-03781536

<https://hal.science/hal-03781536v1>

Submitted on 20 Sep 2022

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Automatic detection of cerebral imprints from extant human brain endocasts

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The endocast, described as the replica of the internal table of the bony brain case, constitutes a proxy for reconstructing a timeline and mode of cerebral changes in human evolution (Holloway and Costelareymondie, 1982; Holloway *et al.*, 2004). The identification of cerebral imprints in endocasts of fossil crania are, however, challenging, due to unknown degree of intra- and inter-specific variation and taphonomic processes (Beaudet and Gilissen, 2017; Falk *et al.*, 2018; Zollikofer and León, 2013). Additionally, concerns have been addressed on the coincidence between the gyral and sulcal patterns and the bulges and furrows imprinted on the braincase.

In this context, this study aims to provide an atlas of documented variation in sulcal pattern of endocasts of extant humans, using an automatic method.

This atlas is envisaged for application as a comparative platform for future study of the fossil record.

MATERIALS AND METHODS

Materials - Overall, more than 90 extant human crania from the Pretoria Bone Collection (University of Pretoria, South Africa; L'Abbé *et al.*, 2005) were detailed by X-ray microtomography at a spatial resolution ranging from 94 to 123 μ m at MIXRAD, located at the South African Nuclear Energy Corporation, Pelindaba (South Africa). Individuals with pathologies affecting the inner table were systematically excluded from the study. Finally, 20 adult individuals were selected, including 10 individuals of African and 10 individuals of European ancestry with equal proportions of females and males (Beaudet *et al.*, 2016a).

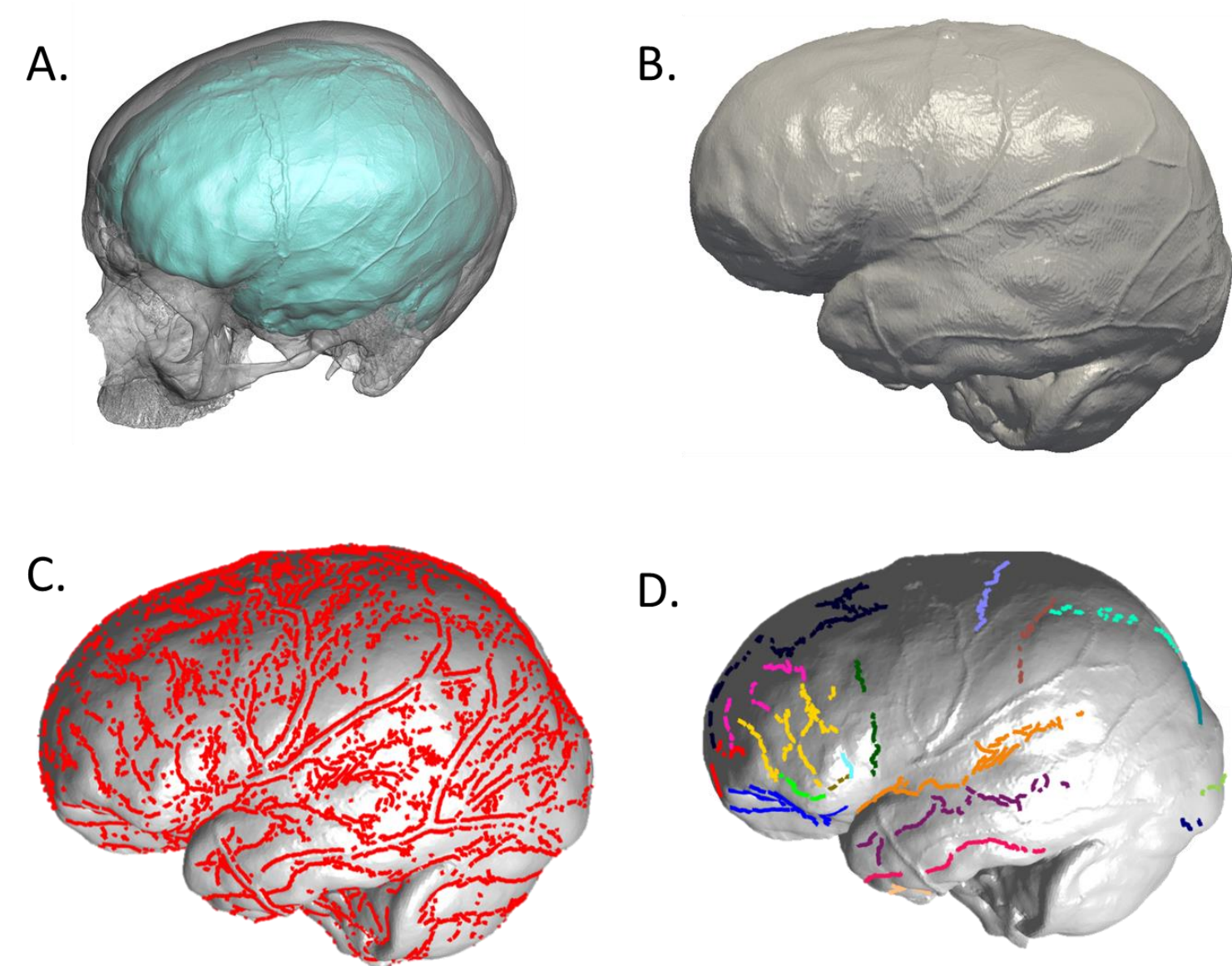


Figure 1: Automatic extraction of endocast from CT-scan of crania using Endex (A). Resulting endocast mesh (B). Crest line detection algorithm is applied (C). Endocast after cleaning and labelling using Matlab (D).

Methods - The virtual extraction and reconstruction of endocasts were performed using the Endex software (Subsol *et al.*, 2010; Fig. 1A; Fig. 1B). Based on previous studies (Subsol, 1995, 1998), an automatic method was used for the identification of neocortical relief in endocasts that includes the algorithm presented by Yoshizawa *et al.* (2007, 2008) for the detection of topographical variations (i.e., crest lines) in 3D meshes (Fig. 1C). The detected structures were corrected manually by removing the non-anatomical features by referring to brain atlases (Connolly, 1950; Ono *et al.*, 1990). Sulci were labelled using a program created with MATLAB R2013a v8.1 (Mathworks) (Beaudet *et al.*, 2016b; Fig. 1D).

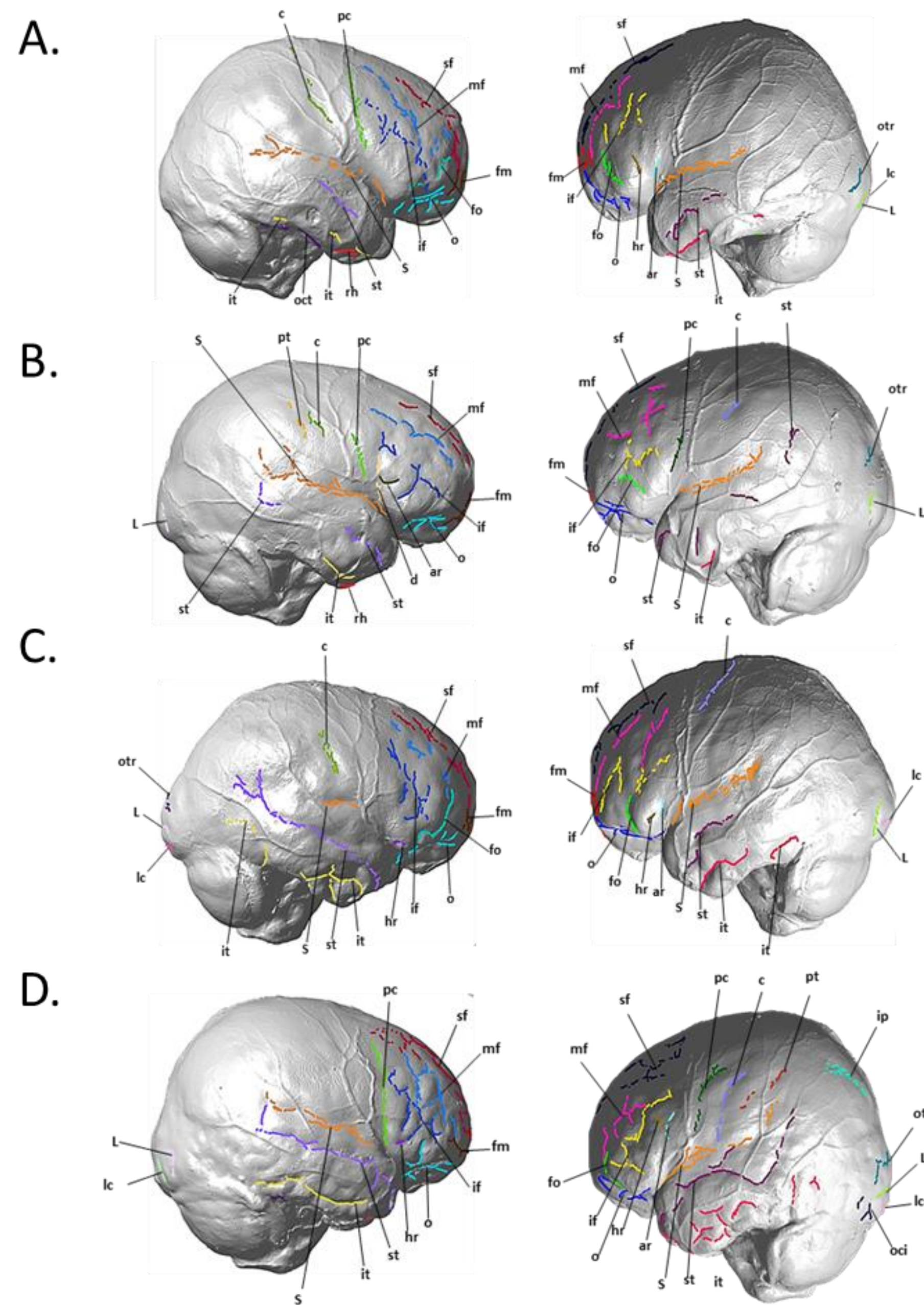


Figure 2: Four examples of lateral right and left views of endocasts with labelled sulcal impressions. African female (A) African male (B) European female (C) European male (D). *Sf*=superior frontal, *mf*=intermediate frontal, *if*=inferior frontal, *fm*=frontomarginal, *fo*=fronto-orbital, *o*=orbital, *pc*=precentral, *c*=central, *pt*=postcentral, *ip*=intraparietal, *otr*=transverse occipital, *L*=Lunate, *oci*=inferior/lateral occipital, *lc*=lateral calcarine, *rc*=retro-calcarine, *S*=Sylvian fissure, *hr*=horizontal ramus, *ar*=ascending ramus, *d*=diagonal, *st*=superior temporal, *it*=inferior temporal, *rh*=rhinal, *oct*=occipitotemporal.

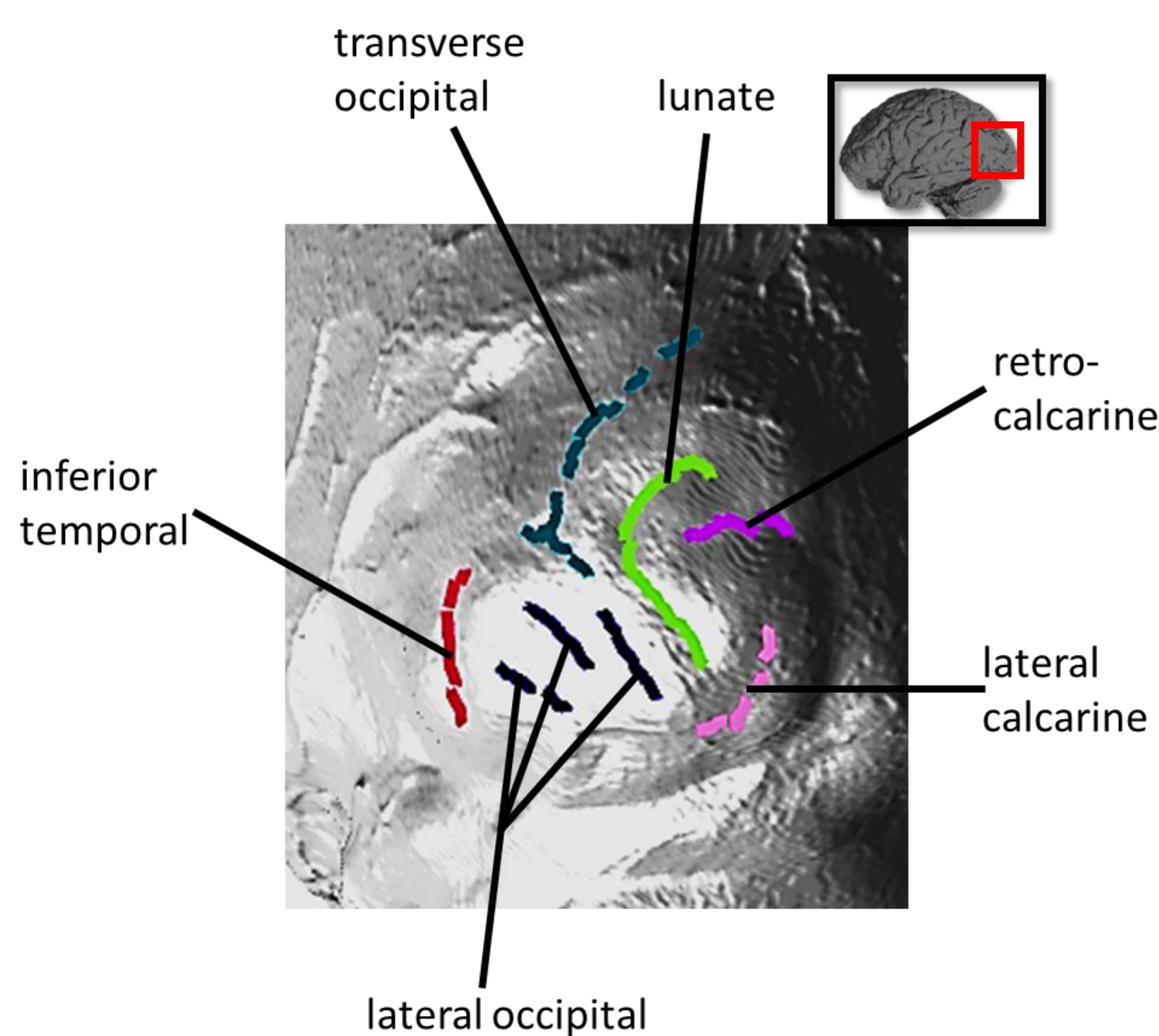


Figure 3: Occipital view showing the lunate sulcus impression in one selected individual.

RESULTS

The frequency of identifiable sulci are listed in Table 1 from highest to lowest on the left (L) and the right (R) hemispheres (Fig. 2).

Table 1: Frequency of sulci observed for left and right hemispheres.

| Sulcus | Left | Sulcus | Right |
|---------------------------|------|---------------------------|-------|
| orbital sulci | 100% | orbital sulci | 100% |
| inferior temporal | 100% | frontomarginal | 100% |
| superior frontal | 95% | inferior temporal | 95% |
| sylvian fissure | 95% | superior frontal | 90% |
| intermediate frontal | 90% | inferior frontal | 90% |
| frontomarginal | 85% | superior temporal | 90% |
| inferior frontal | 85% | sylvian fissure | 85% |
| lunate | 80% | intermediate frontal | 75% |
| fronto-orbital | 75% | lunate | 70% |
| superior temporal | 75% | fronto-orbital | 60% |
| transverse occipital | 70% | rhinal | 60% |
| central | 55% | lateral occipital | 60% |
| lateral calcarine | 55% | transverse occipital | 55% |
| lateral occipital | 50% | central | 50% |
| anterior horizontal ramus | 40% | occipitotemporal | 45% |
| ascending ramus | 40% | precentral | 40% |
| precentral | 35% | anterior horizontal ramus | 20% |
| occipitotemporal | 35% | ascending ramus | 20% |
| intraparietal | 30% | lateral calcarine | 20% |
| rhinal | 25% | postcentral | 15% |
| collateral | 25% | intraparietal | 15% |
| postcentral | 20% | retro-calcarine | 10% |
| retro-calcarine | 20% | collateral | 0% |

DISCUSSION

Through this semi-automatic sulci detection approach, we were able to identify sulci involved in crucial functions and long-standing debates in paleoanthropology. Indeed, the sulci of the frontal lobe were visible in almost all the individuals; an example of such being the presence of the inferior frontal sulcus, which marks the superior boundary of the Broca's area in extant humans (Standing and Borley, 2008). The borders of Broca's area (i.e., the horizontal and the ascending rami) were identified in 40% of the specimens considered in this study in the left hemisphere.

Similarly, the borders of the visual association and auditory areas, namely the superior temporal sulcus (L=75%; R=90%) and inferior temporal sulcus (L=100%; R=95%), respectively, were clearly identified on the left and right hemispheres. Interestingly, the lunate sulcus was identified in 80% (while 27.3% in Allen *et al.*, 2006; and 60% in Ono *et al.*, 1990) of the specimens on the right hemisphere; a significant finding due to its shift in location throughout the hominin lineage (Falk, 2014; Fig. 3).

CONCLUSIVE REMARKS

Newly developed imaging techniques are beneficial in documenting the detailed cortical variation in extant human endocasts, and may contribute towards a reliable comparative database for the study of endocasts in the hominin lineage.

Our atlas will subsequently be used for the construction of a statistical model for documenting the extant human sulcal variation, and, ultimately, for the development of a protocol for the automatic recognition of cerebral imprints in fossil hominin endocasts. This protocol would be critical for improving the accuracy of future investigations pertaining to cortical evolution in the fossil record (Beaudet, 2017).

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Acknowledgements: We thank G. Krüger (Univ. Pretoria) for collection access; F. de Beer and L. Bam (Necsa) for data acquisition; J. Dumoncel (AMIS – UMR5288) for technical support. Supported by the National Research Foundation of South Africa (Grant Number: 112186); and we are grateful to the Erasmus Mundus program AESOP+. A. Beaudet is funded by the Centre of Excellence in Palaeosciences, the Claude Leon Foundation and the French Institute of South Africa. *Ethical clearance was obtained from the Main Research Ethics committee of the Faculty of Health Science, University of Pretoria August 2017 (No:339/2017).*