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Three-Dimensional Maps of the Lenticulostriate Artery Territory

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Abstract

Background and Objectives

Accurate knowledge of the cerebral vascular territories is foundational to stroke care. Yet, precise digital reference maps are not widely accessible, especially for subcortical structures. To address this shortcoming, we constructed 3-dimensional vascular territory maps of the MCA perforators—the lenticulostriate arteries (LSAs).

Methods

Nineteen LSA infarcts were demarcated on DWI scans and then normalized onto a standard 3-dimensional template brain. Normalized infarct volumes were then superimposed to create infarct density maps (heatmaps).

Results

LSA territory heatmaps display the spatial distribution of infarct frequency of the entire territory and highlight its spatially consistent subterritories: medial group, lateral group-*rostral*, and lateral group-*caudal*. The maps show each territory's most commonly affected core, as well as their typical shape, boundary, and variability.

Discussion

The LSA territory maps can be used for education, clinical reference, or research. They can be explored 3-dimensionally on any web browser or downloaded for use. In addition, we present a framework for understanding infarcts within the LSA system based on microvascular architecture.

Introduction

Accurate knowledge of the cerebrovascular territories is foundational to stroke care. Yet, precise digital reference maps are not widely accessible, especially for subcortical structures. To address this, we constructed 3-dimensional vascular territory maps of the MCA perforators—the lenticulostriate arteries (LSAs).

In 1998, Tatu developed the first cerebrovascular atlas designed to be used alongside CT/MRI.[1] The atlas was intended to help clinicians determine which arterial territory was affected, thereby helping establish consistent clinical-anatomical correlations in patients with stroke. An important tool of its day, this standard atlas and such similar maps have not been updated for the current era: they have never been digitized.

In the current era, to establish which arterial territory is affected, most learners and clinicians hunt through online searches. Such searches frequently result in inaccurate images—this undermines both education and clinical practice. When accurate maps are encountered, they are often renditions of the Tatu atlas. These images have limitations. They are 2-dimensional and nonscrollable and thus lack structural precision and clinical applicability. Moreover, the

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subcortical territories are visually difficult to interpret. They show every territory all at once, with many small details that are carefully arranged but difficult to interpret at a glance.[1,2] Typically, territory topography does not visually correspond to the way infarcts actually appear on neuroimaging.

To address this educational and clinical need, we constructed 3-dimensional vascular territory maps of the LSAs by mapping 19 LSA infarcts to a volumetric digital format.

Methods

Nineteen infarcts were used to construct the maps. The LSA territory is comma-shaped in the coronal and axial plane; the medial arterial group supplies the head of the comma and the lateral group supplies the tail of the comma.[3,4] The coronal plane crossing through the foramen of Monro (FM) corresponds to the boundary between the 2 groups.[5]

Inclusion criteria were as follows: (1) Infarcts had to precisely match LSA territory topography based on pathology, microangiography, and imaging research.[2-4,6] (2) Infarcts had to span the entire length of a single LSA or a few penetrating LSAs, extending from the brain's basal surface to the top of the coronal plane.[7] (3) Medial group—infarct anterior to FM, present in the caudate head, anterior limb of the internal capsule (LIC), and rostral putamen.[3,4] (4) Lateral group—infarct posterior to FM, present in the caudal putamen, lateral globus pallidus (GP), *superior* posterior-(LIC), and caudate body.[3,4] *Inferior* posterior-LIC infarcts (below GP upper-border) are within anterior choroidal artery territory and thus were excluded.[2] (5) Vascular imaging findings were used as supportive evidence for classification. Infarcts spanning both medial and lateral groups were excluded, as were ambiguous/variant infarcts.

This resulted in 19 infarcts: 6 medial/13 lateral. The medial and lateral groups further divide into rostral and caudal subgroups.[8] To reflect this, the lateral group infarcts were further subdivided into rostral (6 infarcts) and caudal (7 infarcts).[2,8] Five of 6 medial group infarcts were from proximal MCA occlusions; 6 of 13 lateral group infarcts were from mid-to-distal M1 stenoses/occlusions.

Data Availability

Anonymized data not published within this article will be made available by request from any qualified investigator.

Image Processing

Infarct borders were manually drawn on DWI scans using MRIcroGL software.[9] Subsequently, both the anatomical scan (T1) and the drawn lesion volume were normalized to a standard brain template (MNI-152) with the Clinical Toolbox for SPM software.[10]

After normalization, infarcts were visually inspected to ensure accuracy of registration into common space. Infarcts with major normalization errors were excluded; minor errors (e.g., infarct in ventricle) were manually corrected. The stroke volumes were then superimposed to create infarct density maps (heatmaps) for each territory.

Standard Protocol Approvals, Registrations, and Patient Consents

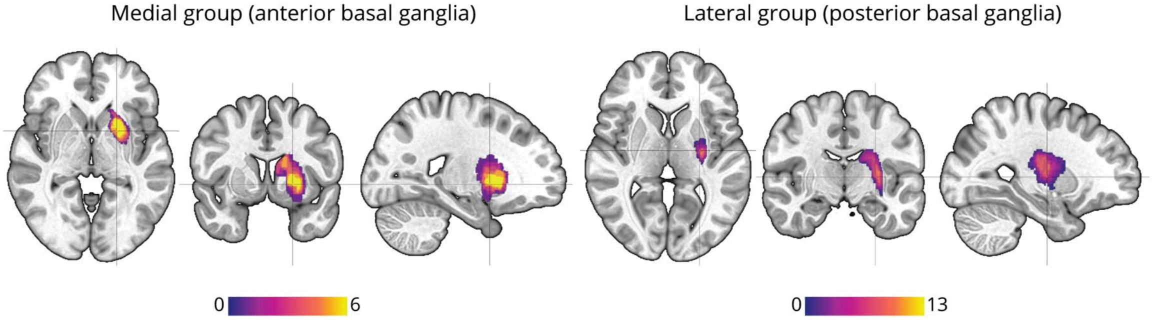
This study was approved by the institutional review board. Participant consent was not required.

Results

Figure 1 displays the infarct density maps in which color denotes the frequency of infarction at each voxel. These heatmaps show the spatial distribution of infarct frequency for the medial and lateral groups. They display each territory's most commonly affected core, as well as their typical shape, boundary, and variability.

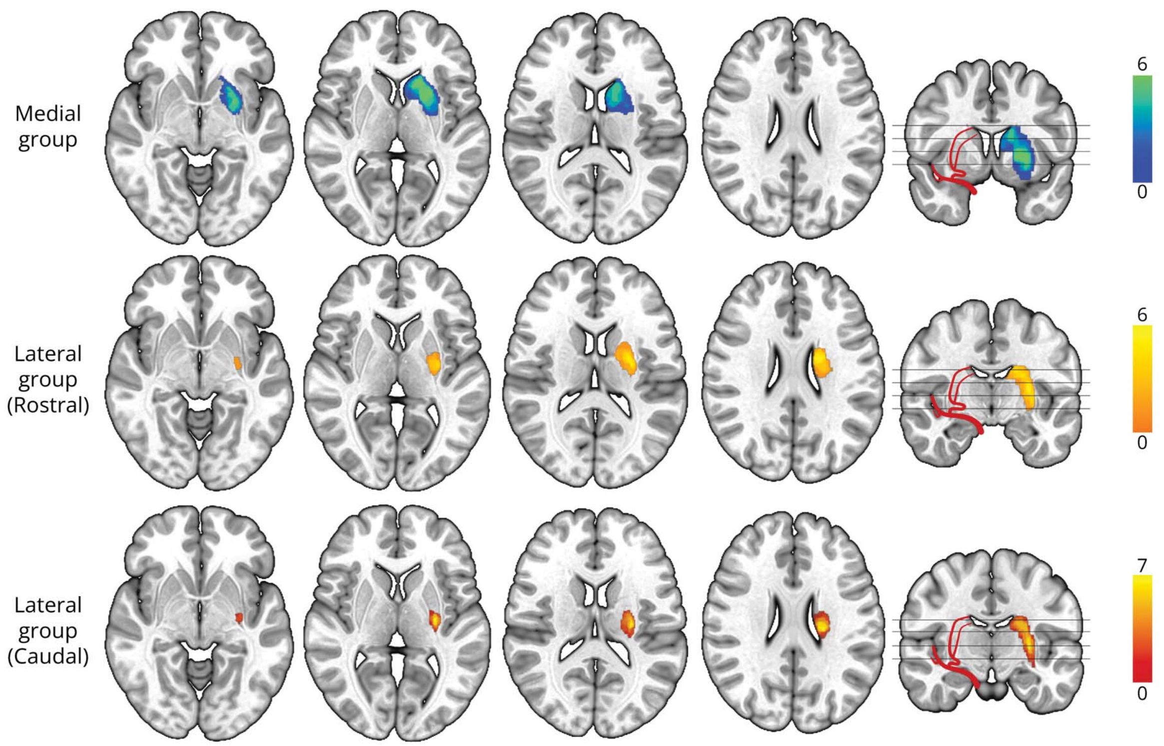
Figure 2 presents the density maps curated to display typical infarct topography: medial group, lateral group-*rostral*, and lateral group-*caudal*.

Figure 1 LSA 3-Dimensional Territory Maps



Infarct density maps overlaid on the MNI-152 template brain. Color denotes the frequency of infarction present at each voxel. Six infarcts overlapping in the medial group and 13 infarcts overlapping in the lateral group. LSA = lenticulostriate artery.

Figure 2 LSA Subterritory Maps



Infarct density maps overlaid on the MNI-152 template brain. Color denotes the frequency of infarction present at each voxel. Three representative LSA subterritories: medial group (6 infarcts), lateral group-*rostral* (6 infarcts), and lateral group-*caudal* (7 infarcts). Coronal plane arterial tree is based on Marinkovic.[4] LSA = lenticulostriate artery.

Discussion

We have constructed accurate 3-dimensional maps of the LSA territory that can be used for education, clinical reference, or research. They can be explored 3-dimensionally on any web browser or downloaded for viewing on MRIcroGL at Github.[11]

These maps hold several advantages over the atlases of a generation ago. As a clinical reference tool, the maps display territory topography, which matches the infarct patterns typically seen in practice. The web browser 3-dimensionality allows the user to scroll through the map much like an MRI/CT scan. For the learner, the 3D maps engage multiple perceptual systems simultaneously: vision, movement, and kinesthetic feedback. This promotes multimodal learning and deepens spatial intuition of neuroanatomy.[12]

The vascular territory heatmap approach is one way to overcome the difficulties in dealing with the interindividual variation. The heatmaps show the spatial distribution of infarct frequency, displaying each territory's most commonly affected core, as well as their typical shape, boundary, and variability.

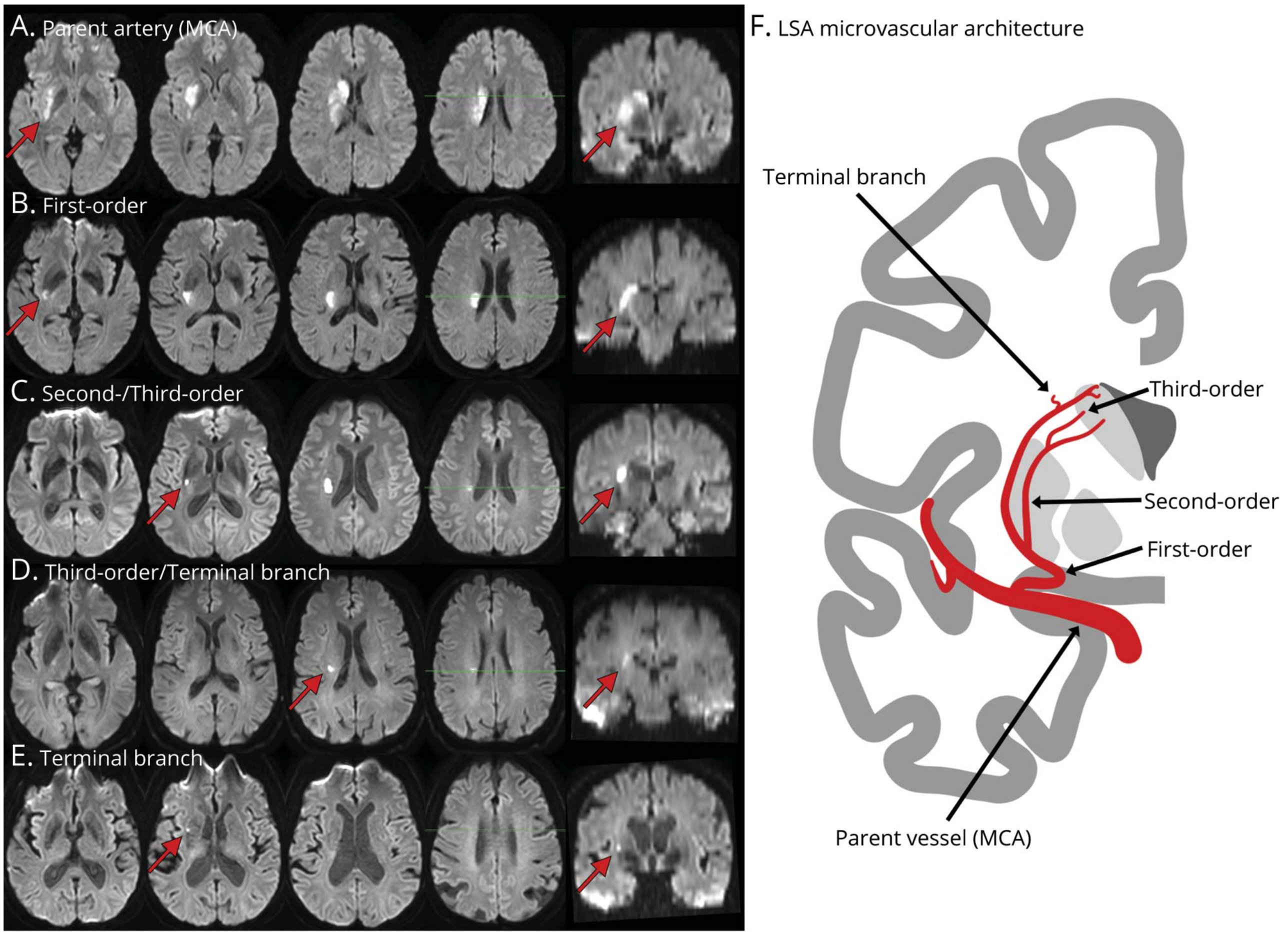
LSA Infarct Interpretation

The LSAs are variable and complex. Figure 3 shows a visual aid for LSA infarct interpretation based on microvascular architecture. The LSAs arise from the MCA, averaging approximately 10 first-order arterial trunks that arise from proximal M1 to distal M1/proximal M2.[2,13] There are 2 well-defined arterial groups, the medial and lateral, named for where they arise off the MCA not for where they supply, which is the anterior and posterior basal ganglia, respectively.[3,4]

Each arterial group contains several first-order arterial trunks, which give rise to second-order and third-order branches of variable length.[6] Arising from these branches are numerous short arterioles leading to spheroidal terminal capillary beds.[6] These branching patterns account structurally for the morphology of LSA territory infarcts.[6] Our 3-dimensional maps are a composite summation of all the branches, short arterioles, and terminal vessels, which form the large-scale territory of a single trunk to a few first-order trunks (Figure 2).

Figure 3 shows how infarct topography can be used to infer the probable site of vascular occlusion within the LSA tree. Familiarity with this topography fosters pattern recognition, leading to improved diagnostic accuracy. Occlusion of the parent MCA may lead to occlusion of several contiguous first-order trunks or all of them (Figure 3A). These large "striatocapsular" infarcts often span both medial and lateral groups.[7] Gray matter may infarct before white, especially when occlusion has recanalized.

Figure 3 Guide to LSA Infarct Interpretation



Exemplar LSA infarcts. Red arrows show the inferior start point of the infarct. Green line shows the location of the coronal slice displayed. (A) Parent (MCA) occlusion may lead to occlusion of several contiguous first-order trunks or all of them, producing large "striatocapsular" infarcts that may span both medial and lateral groups. (B) Occlusion of a single penetrating first-order trunk produces a comma-shaped infarct (coronal view) beginning at the basal surface. (C and D) Occlusion of second-order or third-order vessels produces variable branch-shaped infarcts that do not extend to the basal surface. (D and E) Third-order, terminal branch or side branch occlusions produce spheroid-shaped infarcts, reflecting the shape of their capillary beds. (F) Exemplar LSA microvascular tree, based on Marinkovic.[4] Occlusions from second-order vessels and beyond cannot be visualized on conventional imaging but can be probabilistically inferred based on the microvascular architecture provided in this framework.[6,14] LSA = lenticulostriate artery.

Occlusion of a single penetrating first-order trunk produces a comma-shaped infarct, best seen in the coronal plane (Figure 3B).[3] Infarct extends from the brain's basal surface and outlines the shape of the vascular tree: narrow at the bottom (trunk) and wide at the top (arborization of the branches), with a concavity in the middle.

Occlusions of second-order or third-order vessels produce variable branch-shaped infarcts that do not extend to the basal surface (Figure 3, C and D).[6,14] This reflects the variable course, caliber, length, and arborization of these vessels.[13] Third-order, terminal branch or side branch occlusions produce spheroid-shaped infarcts, reflecting the shape of their capillary beds (Figure 3, D and E); these are classic lacunes.[4,6] Occlusions from second-order vessels and beyond cannot be visualized on conventional imaging but can be probabilistically inferred based on the microvascular architecture provided in this framework.[6,14]

This framework is applicable to most patients as approximately 80% of LSAs arise as a single first-order trunk or as a stem giving rise to 2–5 first-order trunks.[15] However, 7.0%–14.5% of patients show extreme LSA variation and would not be expected to have the same infarct topography as our maps.[4,15]

Author Contributions

D. Antoniello: drafting/revision of the manuscript for content, including medical writing for content; major role in the acquisition of data; study concept or design; analysis or interpretation of data. S.S. Ladsaria: major role in the acquisition of data. R. Bhatia: major role in the acquisition of data.

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Disclosure

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