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From Carotid Lumen Segmentation to Stenosis Quantification in CTA

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Introduction. Cardiovascular diseases remain the leading cause of death globally, and stroke prevention depends on consistent assessment of carotid artery stenosis in routine imaging. In clinical reporting, stenosis is typically expressed as a percentage reduction relative to a reference lumen diameter, for example the NASCET-style definition:

$$S(\%) = \left(1 - \frac{D_{\min}}{D_{\text{ref}}}\right) \times 100,$$

where D_{ref} is measured in a normal distal internal carotid artery segment. Although vessel lumen segmentation is a necessary prerequisite, the clinically relevant endpoint is the measurement pipeline that converts masks into auditable stenosis values, locations, and quality warnings. This work presents a practical post-processing workflow that takes carotid CTA lumen segmentations and produces reproducible stenosis profiles with explicit choices for centerline extraction, orthogonal cross-sections, reference selection, and failure handling. [1–3]

Main Part. The input to the workflow is a contrast-enhanced CTA volume in Hounsfield units and a binary lumen mask for each carotid side, typically spanning the common carotid artery (CCA), bifurcation, and internal carotid artery (ICA). Because CTA is often anisotropic, the mask is resampled to an isotropic grid (linear interpolation for intensities, nearest-neighbor for masks) before geometric measurements. Small one- to two-slice gaps may be repaired conservatively to avoid breaking centerline extraction; however, any gap-repair step is coupled with later near-occlusion checks to prevent artificially creating lumen where none exists. [4]

A centerline representation p(s) is extracted from the lumen mask to define measurement planes. Two practical strategies are supported: (i) skeletonization followed by graph pruning and ICA path selection, or (ii) minimal-cost path extraction in a distance-transform-weighted cost volume, which tends to remain near the medial axis. The centerline is then smoothed and re-parameterized by arc length to stabilize tangents. At each position along p(s), an orthogonal multiplanar reformat (MPR) plane is constructed using a rotation-minimizing frame (parallel transport frame) to avoid sudden in-plane flips. On each orthogonal slice, the workflow selects the connected component containing the projected center point (critical near bifurcation), traces the contour, and computes a lumen metric such as cross-sectional area *A(s)*, equivalent diameter:

$$D_{\text{eq}}(s) = 2 \cdot \sqrt{\frac{A(s)}{\pi}},$$

and/or minimum caliper diameter $D_{\min}(s)$. [5–7]

To obtain a robust minimum, the raw profile is filtered (small median window; optional Savitzky–Golay smoothing) and candidate minima are required to persist over a minimum physical length, reducing sensitivity to single-slice glitches caused by segmentation noise or side-branch intersection. Reference selection is treated as an explicit policy: for NASCET-style reporting, Dref is computed in a distal ICA window beyond the bulb and estimated as a robust statistic (e.g., median diameter across the window) to reduce noise sensitivity. The pipeline reports not only the maximal stenosis value but also its anatomical location (e.g., bulb/proximal ICA), lesion length (extent of narrowing), and discrete quality-control flags indicating conditions that make the estimate unreliable (bifurcation ambiguity, distal reference instability, continuity gaps, calcification/bone adjacency suggesting blooming, and large area jumps suggesting leakage). [2,6,8]

Validation is planned at the measurement level rather than only at the mask level. Agreement with a reference standard based on manual curved-MPR measurements is assessed using absolute stenosis error and agreement statistics (e.g., Bland–Altman bias and limits of agreement). Because stenosis is a ratio, reporting errors in both $D_{\min}(s)$ and $D_{\mathrm{ref}}(s)$ helps localize bias sources (minimum vs reference). In addition, robustness analyses—such as boundary perturbation tests (±1 voxel) and inter-operator variability in the semi-automatic segmentation stage—are used to characterize when the pipeline should trigger manual verification. [6,9]

Conclusion. The proposed workflow bridges the gap between lumen segmentation and clinically interpretable stenosis reporting in carotid CTA. By making geometric choices explicit—centerline extraction and smoothing, rotation-minimizing orthogonal cross-sections, robust minimum detection, and configurable reference policies—the pipeline improves reproducibility and auditability compared to ad-hoc measurements. Equally important, it includes a failure-mode taxonomy and quality-control flags that promote safe use: when the measurement is fragile, the system reports why and where manual review is required. This framework is designed to be integrated with semi-automatic lumen segmentation and can be extended to other vascular territories where stenosis profiling is needed.

References

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