

INTEGRATED ASSESSMENT AND MATHEMATICAL MODELING OF Cerebrovascular Reactivity in Patients with Carotid and Coronary Atherosclerosis

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Introduction

Combined atherosclerotic lesions involving both the carotid and coronary arterial basins constitute a highly critical clinical state, exponentially elevating the risk of synchronous ischemic strokes and myocardial infarctions. Cerebrovascular reactivity (CVR) represents the fundamental compensatory capacity of the cerebral microvasculature to dilate or constrict in response to metabolic and hemodynamic shifts. While structural assessments like lumen stenosis are standard, they often fail to capture latent perfusion failures, necessitating multi-parametric functional modeling

Materials and methods

This study aims to establish a reliable, comprehensive clinical assessment protocol combined with a predictive mathematical regression framework to quantify and simulate CVR alterations in individuals suffering from concurrent carotid and coronary atherosclerosis. A prospective clinical cohort of 142 patients diagnosed with multi-vessel coronary artery disease (evaluated via the Gensini score) and concomitant internal carotid artery stenosis (ranging from 50% to 75%) was examined. CVR was functionally mapped using non-invasive transcranial Doppler (TCD) ultrasonography of the middle cerebral arteries. Vasomotor challenges included a hypercapnic breath-holding test to calculate the Breath-Holding Index (BHI) and a hypocapnic voluntary hyperventilation test. Systemic hemodynamic metrics, carotid bifurcation intima-media thickness (IMT), plaque morphology (echogenicity and ulceration index), and wall shear stress (WSS) parameters were integrated. A multi-parametric non-linear regression model was formulated to simulate blood flow distribution and map zones vulnerable to paradoxical perfusion steal syndrome during hemodynamic stress

Results and discussions

The clinical analysis revealed a statistically significant, profound depletion of cerebral circulatory reserve in individuals with synchronous multi-focal lesions compared to historical cohorts with isolated carotid disease. The mathematical model demonstrated high predictive robustness ($R^2 = 0.86$, $p < 0.001$). Carotid wall shear stress gradients, local plaque ulceration indices, and systemic coronary Gensini scores emerged as the most heavily weighted independent determinants of functional CVR failure. The computational framework successfully predicted regional cerebral hypoperfusion zones under simulated vasomotor stress with a sensitivity of 89.4% and specificity of 84.1%

Conclusion

Transitioning from purely anatomical profiling to an integrated functional-mathematical approach provides a substantial clinical advantage. The combined model serves as a precise, non-invasive digital twin framework capable of revealing hidden cerebrovascular reserve depletion, optimizing patient selection for synchronous or staged revascularization, and personalizing targeted pharmacological therapies.

References

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