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*Research Article*

# Impact of High-Rise Structures on Wind Flow and Thermal Comfort in Urban Environments

**Faezeh Bagheri-Moghaddam[1], Arslan Saleem[2], Akeem Animasaun[1], Mohammadreza Mohammadi[1]***

[1] School of Computing, Engineering & Digital Technologies (SCEDT), Teesside University, Middlesbrough, TS1 3BX, UK
[2] School of Engineering, Cardiff University, Queen's Buildings, The Parade, Cardiff CF24 3AA, Wales, UK

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* Correspondence: m.mohammadi@tees.ac.uk



## Abstract

Tall buildings are essential elements of urban canopy, significantly influencing wind flow over large areas. This paper presents the results of the "Influence of Urban Infrastructure on Natural HVAC Dynamics" project, focusing on the interaction between wind flow, tall buildings and the urban canopy in a real-time model of a neighborhood in South London, UK. A high-fidelity CFD simulation approach is employed to examine the wake of buildings and interactions within the canopy layer. Additionally, dynamic outdoor thermal comfort analysis is conducted to enhance understanding of the potential influence of high rises on the downstream buildings. The results show that a tall building located upstream significantly influences airflow at higher levels, whereas wind patterns near the roof level are primarily dictated by local buildings rather than the upstream high-rise. Additionally, high rises were found to be associated with lower thermal comfort factors.

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## Highlights

- A correlation between MRT and air temperature and the building heights is observed, this relationship suggests that building height can be used as a predictive input in ML-based urban comfort models.
- Roof-level wind patterns are dominated by local buildings rather than upstream tall structures.
- Upstream high-rise buildings significantly alter airflow patterns in the urban canopy.

# 1 Introduction

Outdoor thermal comfort is a critical dimension of sustainable urban design influencing pedestrian activity, public health and overall urban liveability. As urban areas densify, the interplay between built form and microclimatic conditions becomes increasingly complex particularly within urban canopies where diverse building typologies and spatial arrangements generate highly heterogeneous thermal environments. This paper presents a detailed investigation into the dynamic outdoor thermal comfort conditions of a representative urban canopy located in the Southbank area of London. The analysis draws on a comprehensive microclimatic simulation dataset developed using the Integrated Environmental Solutions Virtual Environment (IESVE), supported by validated computational fluid dynamics (CFD) models and geospatial analysis conducted in QGIS. IESVE provided detailed outputs on thermal and airflow conditions at multiple urban scales, while QGIS was employed to process spatial data, map building morphology, classify canopy positions and prepare georeferenced inputs essential for accurate simulation boundary definition and site characterisation.

The paper contributes to ongoing discourse in environmental urbanism by linking building morphology and spatial arrangement with outdoor comfort outcomes. It also demonstrates the application of high-fidelity simulation techniques in capturing dynamic environmental interactions within a dense urban setting. The outcomes are intended to inform adaptive design strategies aimed at enhancing outdoor thermal comfort across varying seasonal conditions in metropolitan contexts.

# 2 Defining Key Concepts

The Southbank, characterised by a mix of low-, medium- and high-rise buildings, exhibits varied urban morphologies that significantly influence airflow patterns, solar radiation exposure and surface heat retention. These factors, in turn, govern spatial and temporal variations in outdoor thermal comfort throughout the year. Given London's vulnerability to the Urban Heat Island (UHI) effect, exacerbated by surface materials, restricted airflow and anthropogenic heat emissions, evaluating comfort parameters at both pedestrian and mid-building elevations is vital for informing responsive urban design interventions.

This paper focuses on seasonal extremes, winter (December, January, February) and summer (June, July, August), to capture the full range of thermal stress experienced within the canopy. Key environmental indicators such as mean radiant temperature (MRT), air temperature, relative humidity, predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) were extracted for multiple building locations within the study area. These buildings differ in height, number of storeys and functional use, offering a nuanced understanding of thermal behaviour across typological and locational gradients.

## 2.1 Existing Theories and Frameworks

Recent research in CFD approaches has enhanced the accuracy and reliability of wake simulations (Abu-Zidan et al., 2021). Various approaches, for example, Reynolds-Averaged Navier-Stokes (RANS) and Large Eddy Simulation (LES), have been used to capture the complex turbulent flow in building wakes (Clannachan et al., 2009). These studies have shown promising results in representing flow patterns, turbulence factors and instantaneous flow components in the wake of high-rise buildings (Hertwig et al., 2019).

Nevertheless, the application of CFD to high-rise building wake analysis has its limitations. The complex behaviour of turbulent flows in urban environments, the extent of scales involved and the necessity for high-resolution grids can make simulations computationally rigorous (Al-Saadi, 2022). Additionally, the accuracy of CFD projection can be sensitive to factors such as boundary conditions, mesh quality and turbulence model selection (Clannachan et al., 2009). Additionally, CFD analysis is subject to the boundary conditions, particularly when thermal conditions are studied. Consequently, thermal comfort analysis has been found to be better represented by tools like IESVE (Ji et al., 2019; Al Haddid & Al-Obaidi, 2022; Zoure & Genovese, 2023).

Recent literature in architectural engineering emphasises the role of vegetation, urban morphology and environmental factors in improving thermal comfort. Coccolo et al. (2018) and Hiemstra et al. (2017) highlighted the use of thermal comfort maps (TCMs) to assess the impact of urban greening, demonstrating how vegetation significantly reduces thermal discomfort by lowering the number of extreme heat hours. Back et al. (2023) proposed CFD-GIS hybrid approach to refine outdoor thermal comfort assessments by integrating wind velocity, MRT and land surface temperature (LST) into a more accurate framework. Additionally, Zhu et al. (2016) emphasised the importance of dynamic rather than static comfort assessments, considering transient thermal conditions and human adaptive responses, which are often overlooked in steady-state models.

### 2.2 Knowledge Gaps and Research Opportunities

Despite extensive research in the field and the importance of the topic, the effect of tall buildings on the urban microclimate, local winds and thermal comfort conditions is not yet fully understood. A key limitation of existing research is the frequent use of simplified geometries and idealised boundary conditions, particularly in wind engineering studies, which may not adequately represent the complexity of real urban environments. Another important research gap is the limited integration of wind and thermal analyses. Airflow within the urban canopy is often investigated independently of its thermal effects on pedestrians, despite the strong interaction between wind conditions and outdoor thermal comfort. Furthermore, the combined influence of multiple buildings and their spatial arrangement on pedestrian-level thermal comfort remains insufficiently explored.

In this study, a realistic canopy in Southbank, London is investigated by combining CFD and IESVE analyses to evaluate both the wind and thermal characteristics of the urban environment and assess outdoor thermal comfort. This integrated approach provides a more comprehensive understanding of how tall buildings shape the microclimate.

### 2.3 Proposed Conceptual Model

The Southbank of London, characterised by dense urban structures and a complex built environment, will serve as a real-time case study for analysing both dynamic and static outdoor thermal comfort, as well as dynamic and static indoor thermal comfort. QGIS, a geographic information system (GIS) tool, will be used for spatial analysis while IESVE will be employed for thermal simulations. Additionally, CFD analysis will be integrated into the methodology to enhance the accuracy of outdoor thermal comfort simulations.

## 3 Methodology

This study uses a combination of computational methodologies to assess airflow and dynamic thermal comfort in an urban canopy located in the Southbank of London. The CFD simulations were conducted using a three-dimensional geometry of a high-rise building along with the surrounding site, which was subjected to wind conditions within the computational fluid domain. The turbulence model used in the study was the SST k-ω model, which has been widely applied to represent turbulent flow in complex urban environments. The model was validated using wind tunnel data for a single tall building and later applied to the study configuration. A suite of building-specific and spatial microclimatic parameters was generated using IESVE, underpinned by climate-informed boundary conditions and validated numerical modelling. Additionally, QGIS was employed for spatial data processing, canopy mapping and the preparation of georeferenced inputs to contextualise the simulation domain and accurately delineate the morphology of the urban fabric. The methodological framework integrates both horizontal and vertical environmental profiles to provide a comprehensive analysis of comfort conditions during seasonal extremes.

The urban canopy of St George Circus in the London Borough of Southwark was modelled to investigate the flow dynamics in the urban canopy and to assess the effect of the tall building Two Fifty-One. The bounds of the flow domain were selected through an iterative process to ensure that no gradients were present at the far boundaries. The inflow boundary and the side boundaries were maintained at 2H, where H is the height of the building, Two Fifty-One, whereas the outflow boundary was maintained at a distance of 8H. The computational domain is shown in Figure 1. Velocity inlet and outflow conditions were applied on the inflow and outflow boundaries. Open boundary conditions were utilised on the top and two side boundaries of the domain, whereas a no-slip wall boundary condition was applied on all buildings in the urban canopy and the ground.

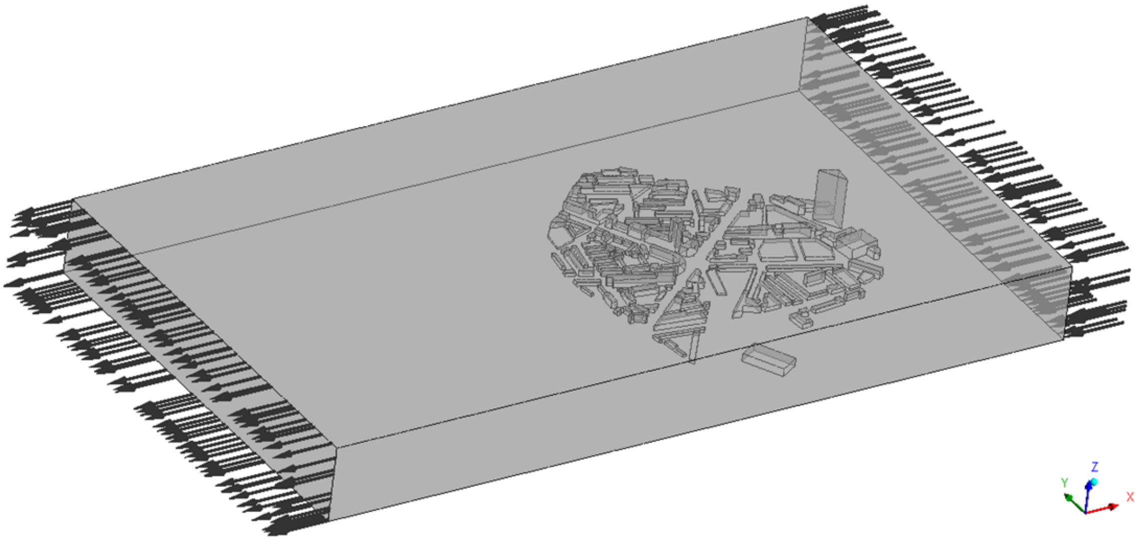



*Figure 1. Computational domain around the urban canopy (Source: authors).*

An unstructured mesh was generated over the computational domain, as shown in Figure 2. To accurately capture the flow boundary layer, prism layers were employed to provide mesh refinement near the no-slip walls and ground. A mesh independence study was performed to ensure that the results were independent of the mesh size.

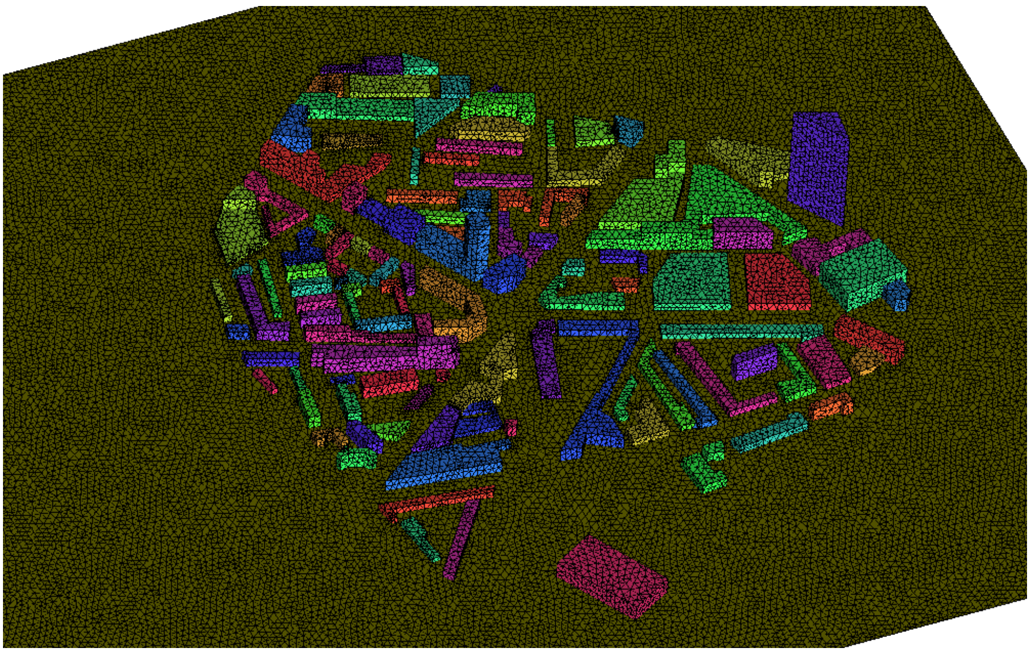
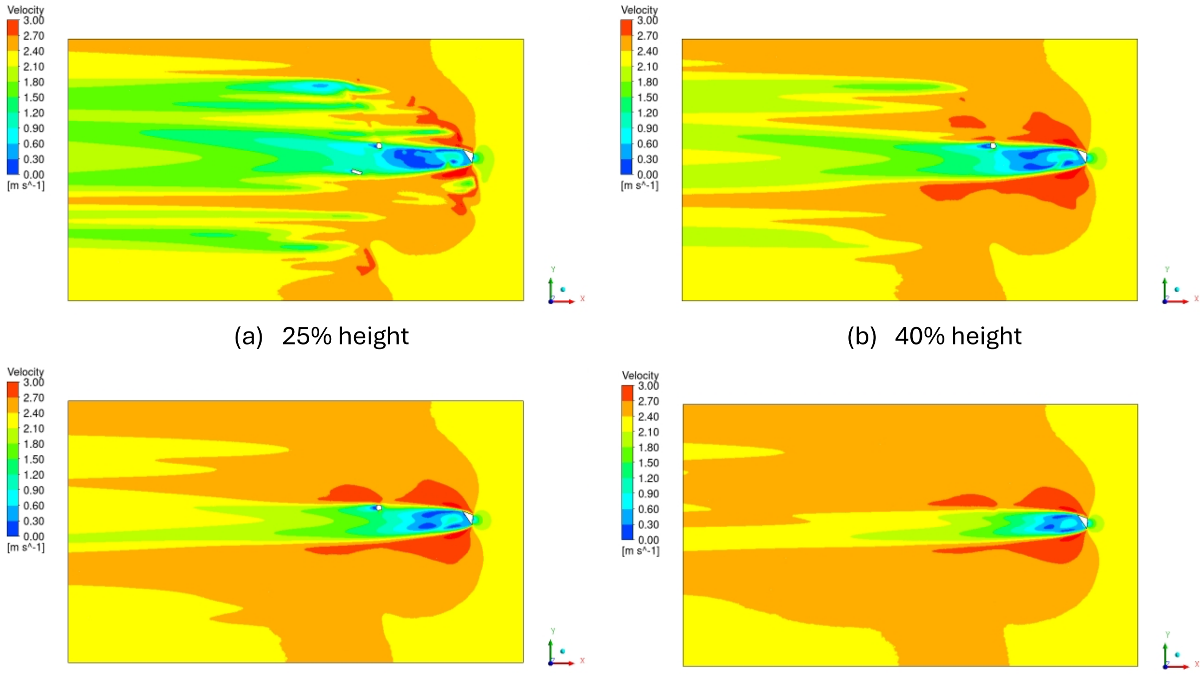


*Figure 2. Mesh over the computational domain (Source: authors).*

# 4 Results

## 4.1 CFD simulations

The total velocity contours on planes drawn at different building heights are shown in Figure 3. The contours show a clear wake region downstream of building Two Fifty-One at all heights. At 25% and 40% height, the wake is wider and more pronounced, indicating stronger blockage and slower flow recovery. At 55% and 70% height, the wake becomes narrower and more focused, with higher velocity in surrounding areas, showing less obstruction to flow and more rapid reattachment. The extent of the low-velocity region shortens with height, consistent with greater freestream influence and reduced wall effects.




(a) 25% height (b) 40% height

(c) 55% height (d) 70% height

*Figure 3. Total velocity contours along the height of building Two Fifty-One (Source: authors).*

For the quantitative analysis the flow characteristics inside the urban canopy are plotted at different heights and distances downstream of the building Two Fifty-One. The positions of these locations are shown in Figure 4.

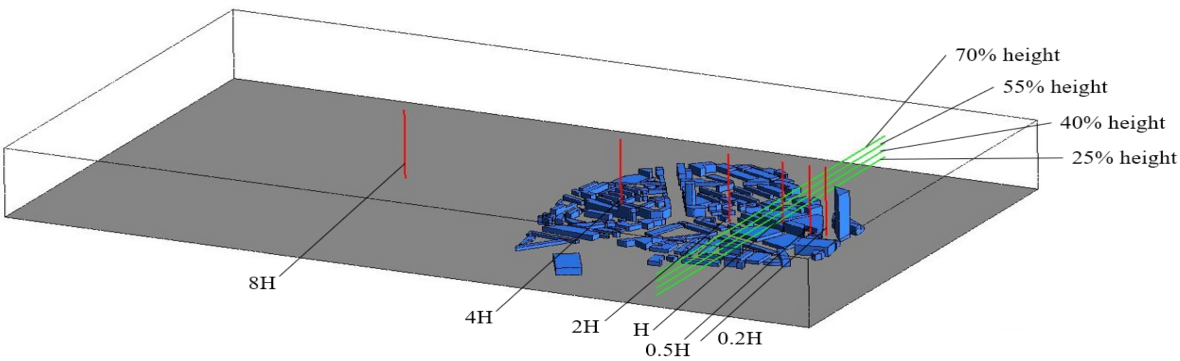



*Figure 4. Position of lines for quantitative data comparison (Source: authors).*

The velocity profiles downstream of building Two Fifty-One at different heights are plotted in Figure 5. The profiles reveal that the wake is broad and well-developed at lower heights (25% and 40%) with significant lateral spread. This is due to interactions with the urban canopy and stronger turbulence. At higher levels (55% and 70%), the wake becomes narrower and more confined, indicating reduced lateral mixing and a transition towards freestream conditions.

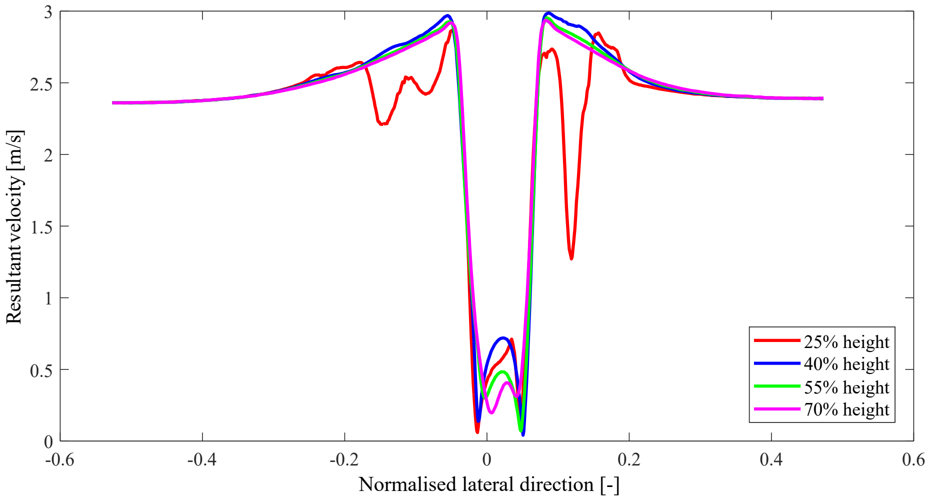



*Figure 5. Total velocity along the lateral direction at different vertical heights of building Two Fifty-One.*

## 4.2 IESVE simulations

This section presents a detailed analysis of the dynamic outdoor thermal environment across 12 selected buildings listed in Table 1 and shown in Figure 6, within the Southbank urban canopy. These buildings differ in height, typology (low-, medium-, and high-rise) and spatial positioning (centre, edge or corner of the canopy), which contribute to distinct microclimatic variations across the area. The simulation outputs focus on two seasonal extremes, winter (December, January, February) and summer (June, July, August), to capture the full range of thermal stress. The following sub-sections evaluate the maximum and minimum values of MRT, PMV and PPD. In addition, simulation-based contour plots at various heights are interpreted to visualise airflow and temperature layering throughout the urban canopy.


*Figure 6. Studied buildings in Southbank urban canopy, building numbers are available in Table 1.*

*Table 1. Buildings analysed within the Southbank urban canopy.*

| | Building | Height (m) | Building Type (Low, Medium, High) |
|---|---|---|---|
| 1 | Clarence Centre | 9 | L |
| 2 | Residential Houses | 4.02 | L |
| 3 | Conquest tower | 92.3 | H |
| 4 | London Southbank University | 27 | M |
| 5 | Friars primary school | 4.36 | L |
| 6 | Manna Ash House - Sanctuary students | 23.66 | M |
| 7 | Delphini apartments | 24 | M |
| 8 | McLaren house | 24.64 | M |
| 9 | H10 London Waterloo | 36.86 | H |
| 10 | Residential flats | 16.18 | M |
| 11 | Imperial war museum | 20.7 | M |

The results presented in Table 1 show a correlation between MRT and air temperature on one side and the building heights on the other. Additionally, across all buildings, winter PMV values were clustered at the lower end of the comfort spectrum, with the minimum reaching -3.0 across multiple sites, indicating strong cold stress. Summer PMV values varied more widely, with several buildings such as Conquest Tower and Two Fifty-One registering values close to or above +3.0, the threshold for extreme heat discomfort. The corresponding PPD results underline widespread dissatisfaction. In winter, dissatisfaction rates frequently exceeded 90% due to cold exposure. In summer, PPD surpassed 99% in multiple buildings, particularly in high-rise and centre-located structures (e.g., Delphini Apartments: 99.6%; H10 London Waterloo: 99.6%; Two Fifty-One: 99.8%). These results suggest that thermal discomfort is systemic across the canopy under seasonal extremes, reinforcing the need for passive mitigation strategies.

# 5 Discussion

A Major challenge from ventilation perspective identified in this study is the presence of reduced wind velocity zones downstream of high-rise buildings such as Conquest Tower and Two Fifty-One. Conquest Tower is located in the north-western part of the study area along Blackfriars Road. Two Fifty-One is situated approximately 400-500 m to its south-east, near the northern edge of Elephant and Castle. The downstream areas of these buildings corresponded with the highest PPD values and lowest air movement, resulting in reduced thermal comfort.

To mitigate these effects, following actions can be done:

i) Establish ventilation corridors: linear open spaces aligned with prevailing wind directions that pierce dense building clusters. These can take the form of urban boulevards, which combine public space with wind passage; green spines, which use vegetated strips to enhance aesthetics and airflow; view corridors or “urban lungs”, which are preserved voids between tall buildings that enable wind acceleration and reduce tall building wake effects.

ii) Promote open ground floors in new high-rise designs, to allow air to pass beneath buildings at pedestrian level.

iii) Minimise street-wall continuity along prevailing wind paths and allow for breach points within perimeter blocks or podium designs.

These ventilation strategies must be considered at both the master planning level and plot scale ensuring that airflow is not disrupted during phasing or densification of urban sites.

## 6 Conclusions

This research demonstrates the significant influence of tall buildings on the urban microclimate, an aspect that is often overlooked. The study integrated CFD and IESVE analyses to investigate how tall buildings influence wind flow and outdoor thermal comfort within an urban canopy. The results showed a negative correlation between building height and several thermal comfort factors, indicating the taller the buildings are, the thermal comfort factors are reduced. Additionally, the CFD results highlighted the importance of the height of local buildings in shaping airflow patterns within the urban canopy.

In a complex urban environment such as Southbank, London, these findings highlight the need for integrated design approaches that consider both aerodynamic and thermal effects at an early stage of the urban planning process.

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### Ethical Approval Declaration

The study was conducted in accordance with established standards for research integrity and ethics. The authors declare that this research did not involve human participants or animals, and therefore, ethical approval was not required.

### Informed Consent Statement

Not Applicable

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### Data Availability Statement

Data are available on request.

### Conflicts of Interest

The authors declare no conflict of interest.

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