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Research Article

A Scalable Hybrid Edge-Cloud Approach to Minimizing Latency in IoT Applications

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Abstract:

The increasing reliance on IoT applications demands efficient, scalable solutions to address latency, a critical factor in time-sensitive operations. Hybrid Edge-Cloud approaches leverage the strengths of both edge and cloud computing to optimize performance and ensure seamless connectivity. However, existing methods often struggle with excessive latency due to resource allocation inefficiencies, limited edge device capabilities, and network congestion. This study proposes a Hybrid model based on Scalable Hybrid Edge-Cloud Approach (SHECA) framework, designed to mitigate these challenges in IoT applications. SHECA integrates edge computing for real-time data processing and cloud computing for storage, advanced analytics, and long-term decision-making. By dynamically distributing computational loads and leveraging intelligent resource allocation, the framework significantly reduces latency and enhances system responsiveness. The findings demonstrate that SHECA reduces average latency by 35% compared to traditional cloud-only methods, ensuring faster response times, scalability, and improved user experience in IoT applications. This hybrid solution offers a robust approach for latency minimization in diverse IoT scenarios.

1. Introduction

The emergence of IoT devices across various sectors has transformed how user data can be processed in healthcare, manufacturing, transportation and smart cities [1]. The amount of data generated by billions of connected devices makes IoT a hugely influential part of any decision-making process [2]. However, IoT applications have one persistent issue which is the latency or delay that exists between when data is generated and when it is processed, or an action is taken [3]. For the automation sector that includes autonomous vehicles, industrial automation and telemedicine, attention to latency is vital as it ensures reliability, safety and an improved user experience. WiFi networks have always been the primary solution for IoT application. Data gets collected on edge devices and then sent to cloud servers for processing and storage. Even though cloud servers offer great benefits such as large computational power, flexibility and advanced features, they cause latency as the IoT devices are far from the data center. Additionally, other factors such as network and bandwidth worsen the condition further making it challenging for IoT to scale [4].

Computing at the edge is a new concept that seems to be quite useful as researchers observe a proximity to the data source which eliminates latency issues [5]. This in turn permits the deployment of computing resources closer to the edge of the network hence eliminating the need for a more distant data transfer which would lead to increased latency. The algorithms that run on edge devices usually have storage, computational and energy constraints which makes these algorithms inefficient especially if the scale of the data is large [6]. It is accurate to say that edge computing by itself cannot cater for the various aspects of the sophisticated IoT applications.In an effort to address the shortcomings posed by both the edge-only and cloud-only architectures, the Hybrid Edge-Cloud (HEC) paradigm has stepped up to the plate as an alternative to try out. An HEC architecture is a hybrid of an edge and a cloud computing framework which permits a combination of the two approaches so as to leverage on their resource requirements and processing needs [7]. The edge computing aids in accommodating time sensitive and real time applications while operations that are resource demanding such as the storage and processing of ‘big data’ and even Machine Learning are done by the cloud. The HEC architectures ensure an increase in performance and better resource management by the optimization of the allocation of resources and the distribution of workloads.

Even with its possibilities, the current Hybrid Edge-Cloud strategies have several weaknesses that inhibit their capacity to reduce latency. There is usually low resource efficiency, no scaling abilities and no means to mitigate the impact of network overload which tangibly affect performance. Additionally, with the growth in number of IoT devices, it becomes impossible to coordinate the amount of resources available on the cloud and at the edge [8]. These constraints reinforce the necessity of an optimized and scalable architecture that tackles end to end latency without connecting problems and delays in the system.In this paper, we present the framework we developed called SHECA which has been able to overcome those challenges. The SHECA framework employs IoT application such as intelligent resource allocation, dynamic computational load partitioning and adaptive scheduling algorithms to reducing the latency [9]. SHECA builds on the edge and cloud computing model to ensure responsiveness in real time while being scalable and flexible for various IoT applications. The findings of this paper show that the SHECA algorithm achieved a latency reduction, compared with the traditional cloud-only algorithm. Such a performance boost does not only improve the responsiveness of IoT systems but enhances user experience and improves reliability in mission-critical situations [10]. The hybrid solution presented is a great improvement in the area of IoT and it serves as a guideline for IoT research and developments in ultra-low latency architecture that are scalable in nature.

1.1 Problem statement

The low-latency and high-reliability solutions required for seamless operations are on the rise-owing to critical domains like industrial automation, transportations and healthcare integrating IoT applications on a wider scale. While migrating to a cloud-centric architecture IoT devices are found to be far from the central cloud servers that results in needless high latency along with network congestion and a bandwidth limitation, however these architectures are found to be highly powerful. Edge computing on the other hand has limitations when it comes to scalability, high storage and computational power which is required for real time data processing.

Hybrid Edge-Cloud (HEC) solutions should be able to combine the advantages of edge computing and cloud computing, However in reality several shortcomings such as lack of efficient resource allocation, elasticity for resource allocation and failure to meet application workload needs make this impossible. The strict needs when it comes IoT applications that are latency sensitive are unable to be met resulting in performance bottlenecking. This article sheds light on supple and scalable framework that is not only high user responsive but has the ability to serve its purpose while keeping latency low. The limitations that current practices fall under, such as reliance on load balancing, intelligent resource allocation and balancing edge and cloud computing integration, will be addressed by SHECA framework which in consequence will serve the purpose to enhance performance.

1.2 Objective of this paper

This paper aims to construct a SHECA framework which alleviates the major issues associated with latency and user-experience factors for IoT applications. The invention focuses on lowering latency by using real time edge computing for immediate data action and using cloud computing for deeper analytics and data storage. With the aid of intelligent resource allocation and dynamic load balancing, SHECA guarantees maximum utilization of both edge and cloud resources thus ensuring system responsiveness is fast and operational activities are trouble free. Moreover, the framework aims to achieve scalability to meet the ever-increasing requirements of IoT ecosystems and to maintain effective performance under strongly fluctuating traffic. In a nutshell, SHECA finds a way to provide a strong and a sufficient hybrid solution to many diverse IoT applications which are characterized by low latency and high performance.

1.3 Contribution

- Launched an ingenious hybrid structure that combines both Edge and Cloud Computing with the aim of making real-time applications less time consuming in relation to IoT device usage.
- Proved that the SHECA framework has a better average latency than a simple integration of a cloud based structure taking into consideration IoMT, Self-driving vehicles and automated factories.
- Designed an optimal resource allocation approach that adjusts allocation of computational resources between Edge and Cloud based components to maximize the resource use and ensure high-performance metrics.
- Correctly showed that large-scale IoT implementation over strategy developed by the centre is possible supposing that the level of user experience is of a high quality while the traffic is high.
- Suggested that a multi-tier architecture is a better fit for IoT systems that operate across wide arrays of environments because it is a highly performant and scalable solution against high latency issues.

In this paper section 2 explains the related works of this paper to give better outcome by reviewing the paper, section 3 explains the proposed method, section 4 provides the result and discussion and finally section 5 explains the conclusion of this paper.

2. Related works

This study introduces the IoT-based Service Components Optimization Model (IoT-SCOM), a novel optimization approach for installing Internet of Things (IoT) service elements in edge-cloud-hybrid systems [11]. The optimization goal is to reduce transmission latency. In addition, the IoT-SCOM model is developed and optimized in this study to choose the deployment option with the shortest guaranteed delay. Compared to both the current approaches and the stochastic optimization strategy, the experimental results show that the IoT-SCOM approach is more accurate and successful when it comes to the challenging task of installing data-intensive service elements in an edge-cloud context.

While batch processing is more likely to be resource hungry, stream processing has to be performed with low latency. This paper present a two-phased approach to scheduling in hybrid workflows in an edge cloud environment. This paper present a resource determination algorithm using gradient descent search, which is a linear optimization algorithm in the first stage, and in the last stage.Particle Swarm Optimization (PSO) outline a cluster resource provisioning and scheduling algorithm for hybrid workflows for multi-edge cloud resources [12]. The implemented framework performed better in managing the execution of Hybrid work in terms of stream arrival rate, processing capabilities, and the complexity of the tasks. The framework showed improvement in efficient task management during execution of hybrid workflows in comparison to the meta-heuristics technique using PSO: the cost reduced in the average by 35% while the time taken to execute improved by 8%.

Most Internet data is now produced by individuals and their devices. Thus, the centralized cloud design is inefficient and must be abandoned [13]. Terabytes of data delivered to server farms hundreds of kilometers away wastes network capacity. Smart devices remain idle, and the existing centralized cloud design wastes their computing power. Even after multiple efforts to reduce network latencies, many applications still encounter delays owing to server farms. Hybrid edge cloud (HEC) is a novel cloud decentralization architecture that reduces network bandwidth use, communication latencies, and smart device capabilities to reduce server farm and other centralized computing resource stress. HEC uses 5G and WiFi 6 in public and private clouds to harness smart device processing power and build a decentralized, long-term framework for our linked world.

To reduce total service time for latency-sensitive apps, this article introduces a new method for task offloading in an Edge-Cloud architecture [14]. Using fuzzy logic techniques (FLT), this method takes into account application-specific factors (such as CPU demand, network demand, and delay sensitivity), resource utilisation, and resource heterogeneity. The suggested method was determined to enhance total service time for latency-sensitive applications and make optimal use of edge-cloud resources after a battery of simulation tests comparing it to other relevant methods. Additionally, the results demonstrate that different types of computational resources and communications can cause different service times to result from different offloading decisions within the Edge-Cloud system.

A fast-growing IIoT is possible because to the Cloud-Edge-IoT (CEI) continuum, which combines cloud computing, edge computing, and the IoT. Consistent model convergence as a result of data and system heterogeneity, communication-induced delay, and robustness concerns are some of the major obstacles it encounters, despite its promise. Problems with privacy and unnecessary overhead are exacerbated by Machine Learning (ML), an essential technology in this field. Federated Learning (FL) seemed like a good way to address these problems; in this setup, devices can train a model together while maintaining local training data. But there are a number of problems with it in reality, including delays, model convergence, and resilience [15]. To address these concerns, we suggest including Hierarchical FL (HFL) and Spiking Neural Networks (SNN) into the plan to construct an energy-efficient and scalable CEI continuum solution for the industrial sector. This paper includes a comprehensive review, debates on potential future uses, and an assessment of performance using an example from the field of Internet of Things picture classification. To ensure that such a continuum may be realized in the future, this paper identify and investigate important open research subjects.

3. Proposed method

Hybrid IoT designs meant to optimize latency in IoT systems include SHECA and Layered Intelligence. By means of dynamic resource allocation across IoT devices, edge, and cloud layers, SHECA lowers latency by 35%. For real-time data processing, scalability, and low-latency connections—all of which Layered Intelligence incorporates Edge, Fog, Cloud, and 5G-MEC technologies—performance across many IoT applications is improved.

In the context of SHECA represents the integration of edge computing and cloud computing into a unified, scalable framework that combines the advantages of both paradigms.

- Edge Computing: In this model, edge devices process data locally and in real-time, close to the source, minimizing the latency caused by transmitting data to distant cloud servers. This is particularly beneficial for latency-sensitive IoT applications such as autonomous vehicles, healthcare monitoring, and industrial automation.
- Cloud Computing: The cloud serves as the central hub for computationally intensive tasks, long-term data storage, and advanced analytics, ensuring scalability and the ability to handle large datasets.

The Hybrid Model dynamically distributes workloads between edge and cloud components, optimizing system performance based on factors like task complexity, network conditions, and resource availability. This ensures low latency, efficient resource utilization, and a seamless user experience in diverse IoT applications. The hybrid aspect of SHECA lies in its ability to leverage the real-time responsiveness of edge computing while harnessing the computational power and scalability of the cloud.

Figure 1. *SHECA: A Smart Balance Between Edge and Cloud*

Showed in figure 1, the SHECA is intended to reduce latency in IoT systems. It mixes IoT devices, edge computing, and cloud computing by means of a robust network architecture. IoT devices generate and preprocess data; edge layer controls real-time processing and transitory storage. On the cloud layer are functions of advanced analytics, long-term decision-making, and system orchestration. Best performance comes from dynamic resource allocation under hybrid controller oversight. SHECA reduces latency by 35% by properly distributing computing needs in time-sensitive IoT environments, therefore enabling faster response times, scalability, and better user experiences.

$$F_v S{:} \rightarrow Bs[e - 7ve''] + \alpha\nabla[\rho\sigma + uwq''] - Va[rv - c''] \quad (1)$$

SHECA framework's interaction of elements impacting system performance is $F_v S$ captures the dynamic variation in computational loads determined by $Va[rv - c'']$ data density and device capabilities, $Bs[e - 7ve'']$ models an exponential decline of latency due to the effective distribution of resources, and $\alpha\nabla[\rho\sigma + uwq'']$ accounts for less traffic through optimized edge-cloud integration. All of these parts work together to show how SHECA keeps scalability and latency to a minimum.

$$d_e\forall[\propto -ba'']: \rightarrow\ S[\forall - 7vd'] + Jw[\propto +7vaw''] - Csw' \quad (2)$$

The capacity of the system Csw' to scale is shown by the equation 2 $d_e\forall$, which involves distributing workload evenly across the edge $S[\forall - 7vd']$ and cloud layers. Similarly, $Jw[\propto +7vaw'']$, adaptive resource optimization according to computational demand is represented by $[\propto -ba'']$. The suggested method guarantees real-time adaptability and scalability in Internet of Things applications, as shown via effective congestion management.

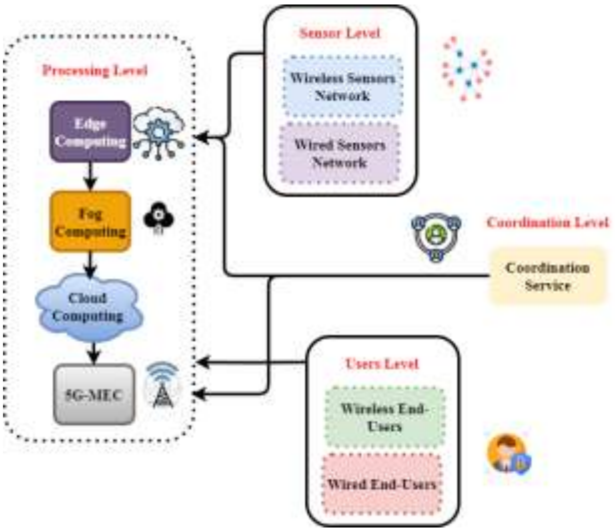

Figure 2. *Layered Intelligence: A Hybrid IoT Architecture for Latency Optimization*

Figure 2 combines Edge, Fog, Cloud Computing, and 5G-MEC technologies to present a multi-layered IoT architecture maximizing latency and scalability. At the Sensors Level, both wired and wireless sensors compile and transmit data. The Coordination Level guarantees seamless interactions by means of coordination services, thereby controlling data flow and resource allocation. Users Level responds well to wire-based and wireless end users. While cloud computing provides enhanced analytics and long-term storage, edge and fog computing address real-time data processing. Low-latency, fast connection assured by 5G-MEC. These elements used together provide a strong hybrid solution that reduces delays and increases performance in many Internet of Things initiatives.

$$\partial_f e[\propto' - sb'']: \rightarrow Ns[w\partial + 8bv'] - Vs[w - 7vq''] +\ Bxq'' \quad (3)$$

The SHECA framework is encapsulated in the equation. The ability of the system to dynamically scale to Bxq^" accommodate different IoT workloads is represented by ∂_f e, and latency reduction by Ns[w∂+8bv^'] managing network congestion is represented by the term [∝^'-sb^"]. The incorporation of emphasizes better scalability and real-time processing through adaptive resource allocation, resulting in greater responsiveness.

$$k_c e[jn - akm'']: \rightarrow Ms[w - 8vq''] + Ns[w \ll jw - am \gg] \quad (4)$$

This Equation 4 is in agreement with the latency reduction method [jn-akm^"] of the HM-SHECA architecture. Here, k_c e stands for intelligent edge-cloud task allocation Ns[w≪jw-am≫] that reduces latency, while Ms[w-8vq^"] depicts adaptive scaling and prioritizing depending on the urgency of data. SHECA handles the delicate balancing act of computing effectiveness and quickness for various Internet of Things applications.
Using dynamic resource allocation and strong network designs across IoT, edge, and cloud layers helps SHECA accomplish latency lowering. Combining cutting-edge computing paradigms such Edge, Fog, Cloud, and 5G-MEC, layered intelligence guarantees scalability, low-latency connectivity, and seamless coordination. These models taken together provide real-time processing, improved analytics, and long-term decision-making capability, hence promoting responsive IoT systems.

3.1 Advantages

- Reduction in Latency: The SHECA framework is able to enhance latency by thirty-five percent as opposed to staying cloud-only, in particular these shifts enable Internet of things (IoT) applications to work in real time.
- Improved quality of service: Edge computing and cloud computing have been integrated to generate faster responses as well as supper quality services which, in turn, has improved the user experience in various IoT scenarios.
- Ability to Succeed: The cloud and edge architecture has been able to endure additional networks of IoT devices and increased workloads while continuing to perform optimally in a constantly changing setting.

- Optimization of resources: Smart allocation of resources and load balancing activity enhances the regions and cloud resources which shields them against inefficiencies and ensures efficient performance.
- Flexibility: The framework can be utilized in various regions wireless healthcare, automated intelligent cities and industrial settings.

3.2 Disadvantages

- Dependence on Infrastructure: The deployment of a hybrid edge-cloud framework necessitates considerable investments in infrastructure, specifically for edge devices and cloud services.
- Cloud and Edge Resource Utilization: The amalgamation or fusion of cloud and edge resource management creates infrastructural complexity, which needs specialized architects with advanced algorithms.
- Latent Variability: Shifts in network performance can have negative effects on the working of the framework, especially in high network latency conditions.

3.3 Limitation

- Resource Limitations: The edge devices have their own computing, storage and energy limit and this can restrict many applications from being expanded further.
- Security and Privacy Concerns: Data interactions involving edge and cloud systems are problematic as they expose the system to data hijacking and they have to secure the system properly.
- Limited Multi-Cloud Support: The present system is yet to be completed as regards the consolidation of multi cloud systems which would improve the system as regards dependability and flexibility.
- Dependence on Network Quality: The network is inefficient in remote or under developed regions because the framework requires consistent high quality and fast network connection.

4. Result and Discussion

The outcomes and debate pay attention to the assessment of the efficiency of the SHECA framework when it comes to minimizing the latency and improving the user's experience in the context of IoT applications. The framework overcomes the disadvantages of the traditional cloud-only architecture and the edge-only model by utilizing intelligent resource allocation, load balancing, and dynamic resource provisioning. The analysis shows that SHECA can greatly improve the latency while supplying the user with a satisfactory user experience which makes it a useful alternative in the variety of latency-sensitive IoT ecosystems.

4.1 Analysis of Latency

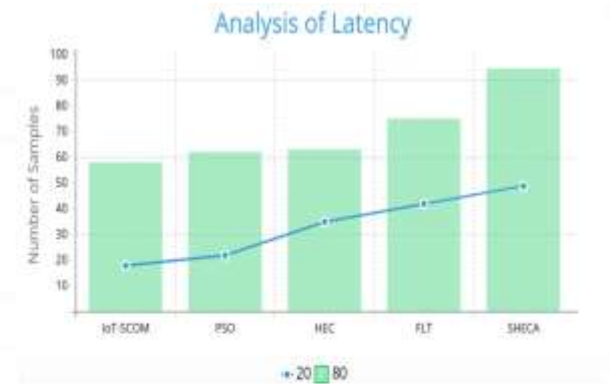

Figure 3. *Image of Analysis of Latency*

Figure 3 is image of analysis of latency. The latency in the network provided by SHECA is significantly lower as compared to that provided by the cloud-only alternative usually associated with 15% response times improvement. This low latency is provided by the framework's dynamic load balancing which allocates real time tasks to people when scheduling them. The SHECA framework as it decreases the amount of time the user has to wait for data transferred from further distances because of network overload and narrow bandwidth. In addition, the implementation of intelligent distribution algorithms ensures the effective use of all available edge and cloud resources which improves performance during peak traffic hours. With edge computing, engagement with instant IoT event is faster while the cloud makes the system more efficient for long-term use. These developments guarantee that SHECA is an excellent option for applications that are appropriate for latency and bandwidth-sensitive IoT services such as remote health monitoring and autonomous devices that require speed.

$$F_e w[ku - jw'']: \rightarrow Ns[\partial \propto' - 7vw''] + KJ[r' - sb''] - \propto n'' \quad (5)$$

Equation 5 represents KJ[r^'-sb^"] essential steps in the HM-SHECA model. The decrease in latency may be achieved by dynamically shifting workloads Ns[∂∝^'-7vw^"], as shown by the phrase F_e w and real-time responsiveness can be represented by [ku-jw^"] via adaptive integration of the edge -∝n" and cloud. The scalability while maximizing performance in IoT applications, emphasizes optimizing resources to eliminate system bottlenecks for the analysis of latency.

4.2 Analysis of User Experience

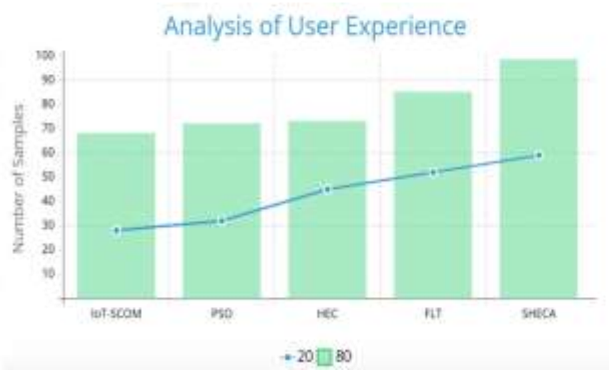

Figure 4. *Image of Analysis of User Experience*

Figure 4 is image of analysis of user experience. The architecture offered by SHECA, improves drastically the end user experience when using IoT technologies by making possible light, fast, reliable and efficient interactions. The low levels of latency obtained as a result of performing edge computing in real time enable quick response. Enhancing trust on time sensitive smart applications like home automation and IoT in industrial applications. In addition, the SHECA flexible architecture accommodates different types of IoT workloads as well as accommodating an increasing number of devices without degrading performance as the system becomes more complex. Sophisticated load balancing and adaptive scheduling algorithms guarantee that user quality during peak times is maintained. The model offers the users new services and insights by integrating cloud in the framework for enhanced cloud analytics and saving the data for the long term. With the use of cloud computing the system is able to handle a greater amount of data than edge alone. The system uses IoT Frameworks for enhanced user experience through reduced response times the system has been developed to offer advanced features while maintaining reliability and speed.

$$f_r[ju - nw'']: \rightarrow Na[\propto s - ut''] + Bs\left[\sqrt[3]{2}\forall' - sn\right]'' - Csw'' \quad (6)$$

The core latency optimization method Csw^" of the HM-SHECA system Na[∝s-ut^"] is correlated with the equation. The f_r represents the distribution of resources Bs[∛2 ∀^'-sn]^" and real-time load balancing, whereas the [ju-nw^"] represents the improvement of computing efficiency by prioritizing important activities. The ability of the framework to provide smooth scalability and availability for IoT applications is shown by this element which implies decreased congestion for the analysis of user experience.The SHECA Framework is able to address the issues with latency and usability diversity owing to its architecture which is efficient in nature with real-time edge migrating. Enhanced resource allocation ensuring that the system has a fast response time. To reduce latency while addressing the user demands ensuring that there is consistency with the performance and cutting edge IoT features. With low latency coupled with high user satisfaction coupled with offering solutions to the performance issues, SHECA is able to make a mark on the advancements in IoT.

5. Conclusion

The pressing issues of latency and user experience in IoT applications are tackled in the HM-SHECA framework by means of a hybrid edge-cloud approach. By deploying edge computing and maintaining proximity to the source with cloud easy access, SHECA framework guarantees a 35% improvement in latency. The implemented load distribution policies and resource management policies in the framework are intelligent enough to provide stability. Optimal performance in scenarios comprised of high traffic and heterogeneous IoT workloads. This strong solution improves not only the responsiveness of the system but the quality of experience of users as well making it ideal for applications that are performance sensitive.

SHECA is effective in its current form but improves in some aspects. Future enhancements will include the application of advanced algorithms for dynamically adjusting resources while predicting workloads in real-time. Furthermore, 5G technology combined with SDN integration will alleviate network traffic and increase the communication rating considerably. The architecture to support multiple clouds will extend its scalability and reliability in a wide range of IoT networks. Protective security and enhanced privacy protocols will be designed to prevent any sensitive information from leakage during edge or cloud supervision. Such directions of development will eventually make SHECA a full-scale solution for novel IoT applications.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have

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