Research Paper

Big data-driven decision support systems for smart cities: challenges and solutions

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ABSTRACT

Smart cities are densely populated urban areas that leverage digital technologies to improve governance, sustainability and quality of life. Massive volumes of real-time data generated by sensor networks and connected devices create opportunities for more informed decision-making across transportation, energy, public health and other domains. This paper proposes a conceptual framework for a big data-driven decision support system (DSS) that integrates heterogeneous data sources, advanced analytics and domain-specific models to support urban planning and service delivery. We discuss the components of the framework, identify key challenges faced by practitioners, and suggest solutions and future research directions. Case examples of smart city initiatives illustrate the potential of big data-driven decision support to reduce congestion, optimize resource consumption and enhance citizen services.

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1. INTRODUCTION

Smart city is a city which cic uses digital information technology to solve social, economic problems and environmental problems in order to have better governance by improve cis life quality and good environment. Local and federal governments across the globe have actively advertised smart city practices to enhance citizens ‘quality of life and economic competitiveness [1]. At the basis of these operations is big data, a term used to highlight the huge amounts of structured, semi-structured and unstructured data whose volume (or plenty), variety (variation), velocity (fastness) and veracity (trustworthiness or reliability) exceeds beyond storage and processing boundaries [2].

Big data has five characteristics, known as "the five V's," which show why modern methods might be valuable. Volume refers to the size of data, from terabytes of information to petabytes. Velocity is the rate at which large volumes of data are produced, such as data from sensors, machines and social networks; Variety refers to various kinds of data (from structured to semi-structured and unstructured); veracity refers to the uncertainty introduced because of flawed, sensed or noisy data and interpolates the reliability or uncertainty period of data durability; value denotes its potential for actionable insights [2]. This is collected from sensors in the Internet of Things (IoT), social media, mobile phones and public records, and provides a fine-grained look at urban dynamics. As urbanization grows even faster than rural areas, more than 55% of the world's population live in cities and this figure is expected to reach 68 % by 2050–reports World Health Organization [3]. This population increase in urban areas poses some terrible transportation, environmental sanitation, and service problems.

Data can only be looked at decision making if they have been sifted through, analyzed, and turned into some sort of an action. The Data Decision Support System DSS is a computer-based system that is capable of sifting through and analyzing data sets of big proportions in order to offer judgements support and recommendations in certain situations [4]. In of their manifestations such systems combine modeling techniques with user interfaces knowledge-based systems for the decision maker to address semi-structured fuzzy-problems darkly glass [5]. At the smart cities level, big-data-based DSS can enable urban dwelling planners and managers to assess options, create predictions, and optimize resources at several levels of across board. Although the smart city vision by now receives a substantial degree of study consideration, a gap between the theory mapping and its practical implementation often exists.

Studies often concentrate on either the design of infrastructure for smart cities or on big data analytics; cross-disciplinary frameworks combining these areas with decision support and actual applications are only just beginning to appear [6]. This paper fills that gap by drawing together existing research on big data, decision support and smart cities and proposing an encompassing framework for future work.

2. RELATED WORK

2.1 Smart Cities and Big Data

In their paper Big Data–BSmart Cities: A Literature Review. comprehensively expound how sensor networks, IoT and cloud computing bring real time monitoring to every aspect of city operations, including transportation systems; energy consumption patterns or lack thereof in the city that provide lasting effects for generations(Green cities) and environmental conditions. The authors underline in their critique that government policies embody this trend. This emerges from government initiatives such as the U.S. Smart Planet plan, Singapore being a Smart Nation and the National Digital Economy strategy of Australia [1]. However, they observe that most projects specialize on certain areas rather than connecting data from one area to another.

Shahat and Elragal argue that big data analytics (BDA) is an essential tool for supporting the data-driven decisions taken by smart cities. They explain that BDA mixes together various types of information structured, semi-structured and unstructured data sources across different time periods using machine learning algorithms along with data mining techniques, deep learning approaches on behalf of its users thereby thus extracting patterns or forecasts from these larger quantities of information [6]. They also divide decision-making processes into strategic, tactical and operational levels: strategic decisions involve long-term, high-level planning; tactical decisions actualize a strategy by executing specific shorter time frame policies for example EU policy at different stages (1-3 years for example) to make stable and thus successful welfare decisions; at the same time, third operating level of control refers to day to day operations. Their study points out that sector-independent frameworks are essential in order to sustain the multifactor environment [7].

Paper in the IJERT reveals the good prospects for big data analytics and IoT as smart city solutions. Plug in real-time sensors and pumps, be they for traffic flows, the use of energy or air quality improvement, you get the real-time information that managers need. It is in this way that cities can adjust traffic signals to deal rationally with congestion and waste, achieve an equilibrium in energy supply or extract rubbish at an optimal rate [8]. The article identifies technological obstacles (need for high-speed networks and cloud infrastructure), financial barriers (high capital and maintenance costs), privacy and data security concerns that are common to all stakeholders regarding the sharing of data or use thereof by one's superiors as well as governance issues raised by interoperability and regulation [9]. And this is why we need comprehensive solutions nowhere to be found today.

2.2 Decision Support Systems

A decision support system is an information system that aids decision-making by analyzing huge volumes of data, employing models and delivering recommendations. Investopedia defines a DSS as a computerized program that compiles comprehensive information for decision makers, distinguishing it from routine operational applications [4]. The Corporate Finance Institute further decomposes a DSS into three main components: a model management system that manages analytical models, a user interface that allows users to interact with data and models, and a knowledge base that stores data, rules and procedures [5]. DSSs may be data-driven, model-driven, knowledge-driven, document-driven or communication-driven depending on how they process information [10].

In smart cities, DSSs support decisions across multiple domains. For instance, digital twin platforms create virtual replicas of physical assets and use real-time sensor data to forecast maintenance needs and optimize operations. Describe a digital twin decision support system for urban facility management in which data from sensors are pre-processed and forwarded to a big-data processing framework. The system combines real-time and historical data to create predictive models for maintenance and scheduling [10]. They note that traditional batch processing frameworks (e.g., Hadoop) are being supplanted by stream-processing architectures that can handle the velocity of urban data [11].

2.3 Case Examples and Policy Initiatives

Many governments have run pilot programs to show use big data DSS. For instance, the Smart Nation programme that is being embarked upon by Singapore usesided technology including automatic immigration checkpoints with facial and iris biometrics enabled through big data solutions which cause 40 % less waiting time succinct: And systems for getting around without hindrance or use of stairs based on geospatial data that provide wheelchair-focused routing; as well as intelligent parking devices including both sensors and digital payments so there is no longer any need to go to an automated machine at the gate [12]. The project also attached great importance to the green environmental protection concept. And data are fused layer by layer in Open Digital Platforms to effect real-time improvements at every turn more cost-effectively than traditional capital repair or only doing it in "one fell swoop" like DOS NB.s for example. The interactive part is in contact with every other part, each of which is related to one other. Operations, also supporting the integration of urban data, broadened the scope of cities ' public services. Such cases illustrate in the end just how through cross-domain data integration really only did the services been provided by city improve, one academic pointed out.

International organizations have also noted that data-driven urban planning is indispensable World Health Organization warns that unceasing urbanization will overload infrastructure and health systems, and it requires in-depth data analysis as well as tools for decision-making. This is especially true at environmental emergencies or where there are big inequalities in health responsibility among population subgroups [3].

2.4 Advances in Big Data Analytics and Digital Twins

In recent literature, it goes on to explain in greater depth how digital twins and artificial intelligence support decision-making in smart cities. Digital City Twin for Cities: Najai and his colleagues presented the concept of using a computer-generated, dynamic, interactive virtual model to create their physical urban settings. It includes a physical object-the city itself, its digital duplicate and digital wire: both of these worlds pass data back and forth in two directions. [13] Digital twins allow urban planners to observe what is happening and take action in real time. The authors stress that data, analysis, and visualization are the building blocks for digital twins; scenario-based analyses become possible thanks to data connectivity [13]. Another systematic review on digital-twin-based decision making for policy implications points out that digital twins can help policymaker's model contextual situations, draw up specific action agendas, and simulate alternative scenarios to implement urban planning policy including potential success rates [14]. The writers also emphasize that increasingly people across domains are using digital twins today to allow them look at long-term planning options. By connecting data, analysis and visualization, digital twins help decision makers think about things in different ways [15]. Big-data analytics research continues. Document how large urban data sets can use pattern recognition for smart city services on large scale. They give an example from analytics of spatio-temporal crime data and show that if you look at such matter in a timely fashion, it is possible to catch the bad guys [14].They also present a case where a machine-learning model made the best predictions for controlling the spread of infectious diseases and another study in which it was used to find individual mobility patterns within large populations, naturally speaking. It looks increasingly likely that with city managers having such tools available today, models like these will be effective support [14]. Similarly, a study of artificial intelligence-driven decision support systems for sustainable energy management discusses how AI uses data analytics and machine learning to automate decision-making and optimize energy use [16]. Here, the writers show a sense of the integration between DSS and IoT implementations as well as predictive analytics in complex energy need situations [13].

Explore data driven decision-making in smart cities and point out that government smart city plans are designed to drive urbanization at two speeds whilst mitigating exhaust emissions. Therefore, the question is: 'What kind of people will live in this new urban environment - those who own cars, or someone who has no need for them? The resulting problems of traffic jams and pollution not just spur on a high maintenance lifestyle but they also wreck the balance of ecology.'

They hold that big data analytics have an important role in collecting and analyzing the data from IoT devices so as to enrich our urban life; however, they warn that data-driven measures are subject to problems with implementation as well as risks of security and safety. In addition, they offer some suggestions for dealing with these challenges: Methods may include one or more of the following: artificial intelligence, machine learning, data mining, and layered architectures, which combine instrumentation, middleware, and applications.

Historical and conceptual perspectives also guide current trends in decision-support systems. A conference review for 2019 points out that emerging Industry 4.0 technologies demand that cities reevaluate their infrastructure's kWh capabilities for the implementation of IoT and other digital innovations. Decision support systems could embed these new technologies in both government and private organizations and become platforms for judging a city's readiness to put SMART CITY initiatives into practice [15]. The review also notes that DSCs play an important role in guiding decision-making processes, part of a decision support system that completely supports the evaluation of the city's social and economic infrastructure. Institute of Electrical and Electronics Engineers IoT with cloud computing being integrated down to the urban space. Given the accessibility verification analysis function, data on population movement and form issued by city travel cards are automatically forwarded in real time to relevant administrative organs. In yet another application, cityscape attaching an urban growth simulation system enables officials to grasp at a glance how their policies would work out over time scale instead of merely being confined to academic research reports Learning about Smart Cities because how these very compressed domains intersect is a major characteristic of our work There is another emerging research direction: predictive data analysis for early warning forecasts of epidemics in Smart Cities. Ahmad and Badi think that by using big data and artificial intelligence techniques together, they can bring together all kinds of critical information sources--from electronic health records to incidents of social media participation traffic generated by IoT sensors outdoors of buildings online monitoring devices on city streets Using these multiple data sources, they predict the progression of epidemics and do real-time detection on the scale that others might think it raises many problems about privacy issues associated with so many different places. Storage is expensive, too slow, and has less data than modern computing centers. Although most observers know nothing more than their general values (if even that much) about them in follow-up cases separately [17].

3. METHODOLOGY

To address the need for a holistic framework, this paper proposes a conceptual architecture for a big data-driven decision support system tailored to smart cities. The methodology is composed of five layers Figure 1.

1. **Data Sources:** Diverse sources like IoT sensors, mobile devices, social media feeds, geospatial databases, weather stations, and public administration records are continuously producing data about traffic flows, energy consumption, environmental conditions, and social behavior.
2. **Big Data Storage and Processing:** Data streams are transferred to distributed storage systems (e.g., data lakes or cloud computing repositories) and real-time and batch analytics pipelines are used for processing. Stream-processing tools handle the data from sensors which are of high velocity, while batch frameworks carry out periodic aggregation and archival storage.
3. **Analytics and Models:** The algorithms of machine learning, data mining, and predictive modeling extract patterns, detect anomalies, and forecast future conditions. Some of the examples are traffic prediction models, energy demand forecasting, anomaly detection in water networks, and epidemiological simulations.
4. **Decision Support System:** The DSS merges the results of analytics with the knowledge of the domain to imply recommendations. Model management system picks the right models; a user interface provides decision makers the opportunity to analyze scenarios and state goals; and a knowledge base keeps rules, thresholds, and contextual information.
5. **Smart City Applications:** Recommendations can be seen in the following examples of transportation, energy management, waste management, public safety, and environmental monitoring. This architecture highlights interoperability between data sources and applications. At the same time, this framework ensures the scalability of deployments due to distributed storage and processing.

Also, this architecture connects analytics and decision makers through an interactive interface. It is a simple and effective way to ensure evidence-based governance.

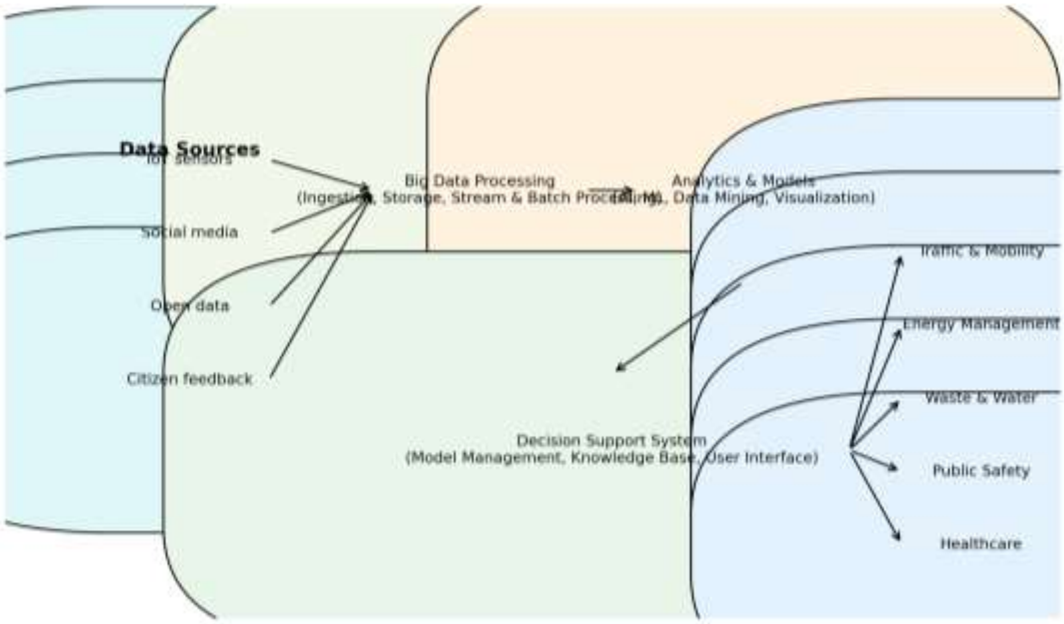

Figure 1. Conceptual Architecture of a Big Data-Driven Decision Support System (DSS) for Smart Cities

4. RESULTS AND DISCUSSION

4.1 Challenges

Implementing big data-driven DSSs in smart cities involves several interrelated challenges. The technological challenge concerns the need for high-speed networks, reliable sensor deployment and scalable processing infrastructures to handle the volume and velocity of urban data. There are a few factors that make deploying the whole system a financial challenge. The first one is the installation of the sensors, the second one is the maintenance of the infrastructure and the third one is the purchase of specialized analytics tools. When the question of privacy and security arises, it usually is about the collecting of PII and the possibility of the data breaches and cyber-attacks. It's not hard to say in the case of the lack of standardization, interoperability frameworks wherever sharing of data is concerned among the agencies and private partners that the main challenges of governance and regulation originate. These four categories are visualized in Figure 2.

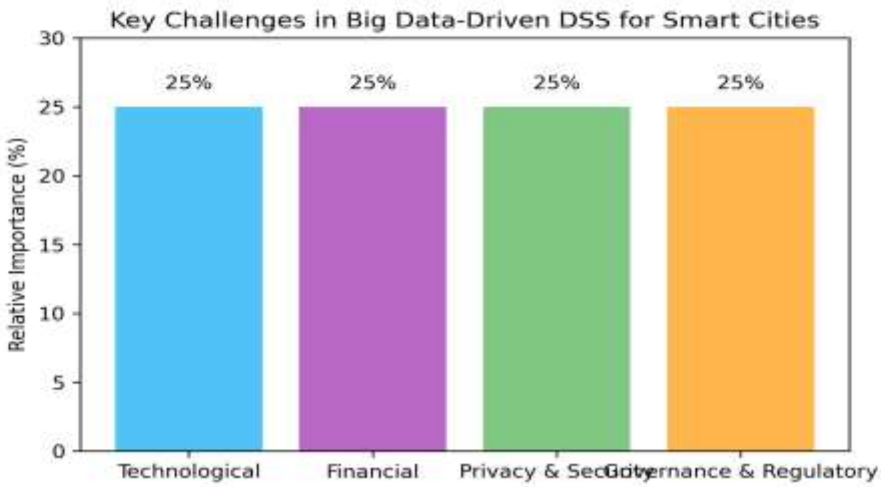

Figure 2. Frequency/Importance of Challenges (Illustrative, Normalized Values)

The following Table 1. Each challenge category corresponds to multiple mitigation strategies.

Table 1. Summarizes the Major Challenges and Outlines Potential Solutions

Challenge	Description	Potential Solutions
Technological	Insufficient network bandwidth, heterogeneous sensor data formats and limited real-time processing capabilities.	Invest in high-speed broadband and 5G networks; adopt standardized data formats and interoperability protocols; use scalable cloud and edge computing for real-time analytics.
Financial	High costs of deploying and maintaining sensors, computing infrastructure and analytics platforms.	Employ public–private partnerships; implement phased roll-outs with cost–benefit analyses; leverage open-source platforms and shared infrastructure; explore innovative financing (e.g., green bonds).
Privacy and Security	Risks of unauthorized access, surveillance concerns and misuse of personal data.	Implement privacy-by-design principles; use encryption, anonymization and differential privacy techniques; adopt cybersecurity frameworks and regular audits; engage citizens through transparency and consent mechanisms.
Governance and Regulatory	Lack of unified standards, data-sharing agreements and cross-agency coordination.	Establish governance bodies and regulatory frameworks; develop open standards and APIs for data sharing; encourage inter-agency collaboration;

		enact legislation that balances innovation with privacy and public interest.

4.2 Application

When big data technology supports DSS, its benefits for our physical and social world can be seen immediately. At one transportation deployment point, traffic light systems, adopting adaptive principles for their operation (thus capable of adjusting cycle lengths in response to live vehicle counts manually recorded on a video screen and vacancy storage in computer memory) are not only regulating safety on the highways but also helping to ease congestion by shortening delivery times. Using smart meters in conjunction with predictive algorithms to forecast demand and adjust supply results in a reduction of peak load, which makes outages less likely while stability is increased. Facility management platforms use digital twins to keep an eye on how well buildings are performing, predict when equipment will pack in and schedule maintenance before things go wrong. Singapore's Smart Nation program offers several specific examples. The automated immigration checkpoints have two kinds of identification recognition, facial and eye. Due to these two upgrades, while people on the bus pass through separately without smearing fingerprints all over visa-it takes nearly 9 seconds fewer per person than before. Barrier-free traffic guidance services--merely authored geospatial graphs that display routes suitable for wheelchairs - are combined with geospatial data sources to create routes that can be used by wheelchairs in contrast with traditional public transit industries, whose production models are based on apps for wheelchair users to find the nearest accessible route and book a seat before going anywhere. In most cases, these routes are not accessible because they are prohibitively expensive or require too much effort on the part of travelers. Instead of SPS sensors and electronic payment methods smoothing over parking problems--a holistic environmental model copies out microclimatic patterns to inform urban decisions. Smart water meters, for example, can provide real-time data on the use of the average family. As a result, early leaks are discovered in time and resources are rationally managed. This and other examples of combining cross-domain data show how any type of household-level technology has been put to use according to local conditions so efficiently. It also means that people don't have to wait so long: people who cannot travel by public transport because of physical handicaps. We can utilize more from the same resources; in a word it is environmentally sound. Figure 3 its ideal appearance already for an intelligent city that extends into the future.

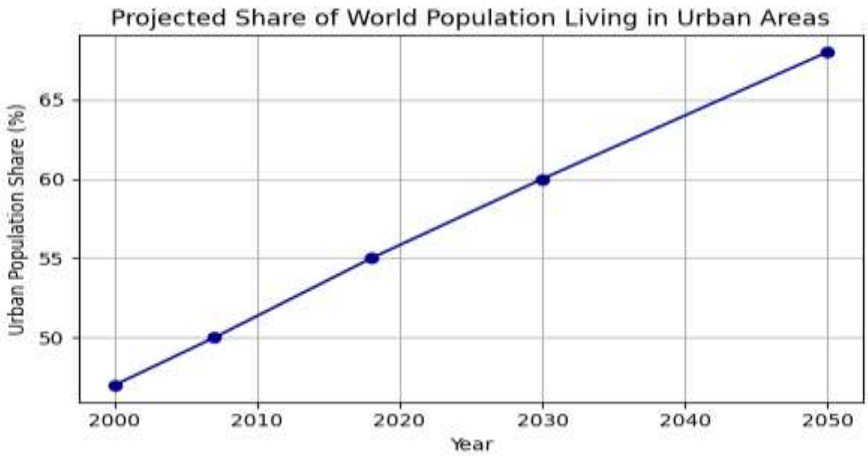

Figure 3. Projected Share of the World's Population Living in Urban Areas Based on United Nations Data

The Line Chart Uses Approximate Values: 47 % in 2000, 50 % in 2007, 55 % in 2018, 60 % in 2030 And 68 % In 2050.

4.3 Discussion

Such a framework gives any reader on the ways in which big data analysis operates whether it is used in consultancy or any other situation of civil engineering consulting. By using Decision Support Systems, (DSS), we can integrate different data sources and perform predictive analytics for better management of transportation networks, power grids, public health and environmental quality. These gains, however, require overcoming a number of long-standing obstacles.

Instead of heading directly for commercial products, to develop fully all our technological investments we must thoroughly build our institutional capabilities and use open standards that make it certain that various systems will be able to talk with each other. A project as large as this one, at least one, can be started in someone's garage in Silicon Valley or any other location. Conversely, it can be initiated by large, and often quite revolutionary social program investments. So, in this context, citizen protection has to be provided through legal and technical means, they need to be necessary, effective and have transparency at the same time, as well as communication towards the citizens, explaining how their systems and their data work. Governance and sound regulation could be the art of keeping the means and the ends of the rather slippery relationship between data sharing, on the one hand, and the threats of malicious or unethical public data usage, on the other hand, in balance. For instance, Singapore's "Smart Nation" is a prominent example of how concerted efforts between nation-state, industry and civil society can result in impactful, enduring outcomes.

5. CONCLUSION

In the next decades, data-driven decision support systems based on large-scale big data infrastructures become one of the fundamental pillars that empower smart cities across the globe, especially for the megacities that undergo through high rate of urbanization and face complex eco-social issues. AI-ML techniques can be applied to these systems that can be aggregated from diverse data sources in order to create valuable insights for diversity, sustainability, and citizen wellbeing.

We describe a novel integrated layer design (IHS-based) covering the data acquisition, data processing, and analytical research and decision-support applications as a new phase of this study. The literature review covered significant definitions, theoretical frameworks, and applied cases from a scientific viewpoint, and the research discussion discussed technological, financial, privacy, and governance issues. Others may see these challenges simply as impediments to be addressed with an overarching strategy based upon investment in infrastructure, open standards, privacy by design, and co-governance frameworks. With urbanization rising and populations continuously expanding, you can bet big data–driven decision support will be critical in creating resilient and inclusive cities.

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Author Contributions Statement

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Maryam Jawad Kadhim	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	

C: **C**onceptualization
M: **M**ethodology
So: **So**ftware
Va: **Va**lidation
I: **I**nvestigation
R: Resources
D: Data Curation
O: Writing- **O**riginal Draft
Vi: **Vi**sualization
Su: **Su**pervision
P: **P**roject administration
Fu: Funding acquisition

Fo: **Fo**rmal analysis E: Writing- Review& **E**diting

Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Informed Consent

All participants were informed about the purpose of the study, and their voluntary consent was obtained prior to data collection.

Ethical Approval

The study was conducted in compliance with the ethical principles outlined in the Declaration of Helsinki and approved by the relevant institutional authorities.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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