

# Integrating Sustainable Design, Smart Technologies, Certification in Green Hospital Architecture

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Research Article / Received: June 6th 2025, Revised: June 25th 2025, Accepted: June 27th 2025

Refer: Shahsavari, F., (2025), Integrating Sustainable Design, Smart Technologies, Certification in Green Hospital Architecture, Journal of Design Studio, V.7 N.1, pp 207-216

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DOI: 10.46474/jds.1715443 <https://doi.org/10.46474/jds.1715443>

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**Abstract:** Healthcare facilities are among the most resource-intensive buildings, yet they must operate continuously and remain functional during emergencies. This paper presents a holistic approach to green hospital architecture that synthesizes sustainable design principles, energy-efficient smart technologies, green building certification systems, and seismic resilience strategies. A literature review of recent research and case studies is conducted to identify how these domains intersect in hospital design. Key sustainable architecture principles (energy efficiency, resource conservation, indoor environmental quality, etc.) are discussed alongside smart building systems for energy management and patient comfort. Green building certification benchmarks such as LEED are examined as frameworks to guide hospital sustainability and performance. In parallel, strategies for seismic resilience – including structural innovations and “earthquake architecture” integrating engineering and aesthetics – are analyzed given the critical importance of hospitals remaining operational after disasters. The synthesis reveals that designing a truly sustainable hospital requires an integrated approach: one that meets rigorous environmental standards, leverages intelligent systems and materials, and ensures structural safety and resilience. This integrated paradigm can yield hospitals that are not only environmentally friendly and energy efficient, but also smart, safe, and adaptive in the face of climate and seismic challenges. The paper concludes with a conceptual model and recommendations for architects and engineers to collaboratively implement sustainable, smart, certified, and resilient design in future healthcare projects.

**Keywords:** Sustainable Design, Smart Technologies, Green Hospital

## Introduction

Hospitals and life-science buildings expend tremendous amounts of energy to operate 24/7 and maintain strict environmental controls. In fact, healthcare buildings account for about 4.4% of the world’s total carbon emissions, making sustainability in hospital design a high-impact priority. At the same time, hospitals have critical infrastructure that must remain functional during and after disasters like earthquakes. Recent trends in architecture and engineering emphasize that truly sustainable

design must also be resilient (Meerow et al. 2016). This convergence calls for an integrated approach to green hospital architecture – one that merges sustainable design principles, smart building technologies, green certification benchmarks, and seismic resilience strategies into a unified design framework (see Fig.1).

Modern sustainable architecture aims to reduce negative environmental impacts of buildings by minimizing energy and resource consumption and improving occupant well-being (Kats

2006). In the case of hospitals, which are among the most energy-intensive building types (with inpatient hospitals averaging nearly 193 MBtu/ft<sup>2</sup> energy use, roughly three times typical commercial buildings), efficiency gains can be especially significant. Architects are increasingly expected to incorporate renewable energy, passive design, and efficient systems to curb hospitals' greenhouse gas emissions and operational costs. Equally important is maintaining excellent indoor environmental quality (IEQ) – including air quality, lighting, acoustics, and access to daylight – as studies show these factors improve patient recovery and staff performance (Ulrich et al. 2008). Sustainable hospital design thus entails a multidisciplinary balance of energy and environmental performance with human-centered healthcare needs.

Another critical facet is the integration of smart technologies and intelligent systems in hospital buildings. Smart building design leverages sensors, automation, and data to optimize performance. Hospitals can benefit from building management systems that automatically adjust lighting, ventilation, and temperature, improving energy efficiency while maintaining stringent health requirements

(Shafa 2024a). A recent study by Shafa (2024a) identified that among various smart design elements, intelligent lighting systems, advanced fire alarm systems, and environmental sensors (for temperature and humidity) were the most influential factors for improving building efficiency. This highlights how digital infrastructure and IoT-based controls can complement classical sustainable design strategies. Indeed, the concept of a smart hospital aligns with broader smart city initiatives – integrating smart environment and smart living principles to enhance both operational efficiency and occupant experience (Batty et al. 2012). By using real-time data and automation, smart hospitals can continuously adapt to reduce energy waste, respond to occupancy needs, and even anticipate maintenance issues, embodying a new paradigm of high-performance healthcare facilities.

In parallel, green building certification systems provide structured frameworks and metrics to guide sustainable design in hospitals. Rating systems like LEED (Leadership in Energy and Environmental Design) and others (e.g. Green Globes, BREEAM, WELL for health aspects) establish best practices and performance



**Figure 1:** An infographic illustrating the core components of green hospital architecture, focusing on sustainable design and smart technologies to enhance energy efficiency, resource conservation, and patient comfort.

benchmarks across key sustainability categories. For example, LEED for Healthcare addresses site selection, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, and innovation in design. These systems encourage an integrated design process and accountability through third-party verification. Studies reviewing green building rating systems note that most certification frameworks share common principles aimed at reducing environmental harm and resource use. Over time, these systems have evolved to incorporate broader sustainability aspects – not only environmental and economic criteria but also social considerations of occupant health and community impact. In essence, the trend is towards truly sustainable buildings that balance the “triple bottom line.” For hospitals, achieving certifications like LEED can signify that the facility meets rigorous standards for energy efficiency, waste reduction, healthy indoor environments, and overall environmental stewardship. Certification benchmarks thus serve as useful design targets and validation tools, ensuring that a hospital’s green design goals are comprehensive and measurable.

Recent studies are pushing sustainability efforts forward by examining how smart technologies, advanced materials, and data-driven environmental analysis can be effectively integrated into architectural design. Shafa (2024a), for instance, emphasizes the role of energy-efficient systems and renewable resources in developing intelligent, responsive buildings. Her complementary research (Shafa 2024b; Shafa 2025) explores materials like ETFE and phase change materials (PCMs), illustrating their ability to enhance energy performance, indoor comfort, and environmental adaptability—key attributes of sustainable architecture. Meanwhile, incorporating machine learning-based drought classification into environmental assessments adds a layer of precision and intelligence to site analysis and geotechnical planning (Saghaei et al. 2025). Together, these contributions help transform broad sustainability goals into practical, site-specific design solutions that

influence choices in materials, energy systems, and environmental strategy.

This paper synthesizes these four dimensions – sustainable architectural principles, smart energy-efficient technologies, green certification systems and explores their integration in the context of hospital architecture. The following sections review the state-of-the-art in each domain, then discuss strategies for combining them into a cohesive design approach. By drawing connections between energy performance and structural safety, between intelligent systems and environmental certification, we aim to outline a holistic framework for that protect both people and the planet.

Innovative materials like ETFE (ethylene tetrafluoroethylene) foil cushions for transparent facades/roofs and thermochromic materials that change properties with temperature – these can reduce heat gain and improve daylighting while being lightweight alternatives to glass (Shafa 2024b). Such smart materials, tailored to environmental conditions, can significantly enhance a building’s sustainability by improving adaptability and lifespan of building components (Addington and Schodek 2012). In terms of waste, sustainable hospitals aim to minimize construction waste (via recycling plans and prefabrication) and plan for operational waste management (facilitating recycling of paper, plastic, as well as safe handling of medical waste). Durable materials that can withstand heavy use in hospitals (e.g., rubber flooring, high-quality wall protection) also reduce the frequency of replacement, thereby conserving resources over the building’s life cycle.

**Indoor Environmental Quality (IEQ):** Hospitals must provide a healing environment, so IEQ is paramount. Green design for IEQ includes maximizing natural daylight and views to the outdoors for patient rooms and staff areas, as studies have linked access to daylight with improved patient recovery rates and reduced staff stress (Ulrich et al. 2008). High-efficiency air filtration and ventilation systems ensure excellent indoor air quality by removing

contaminants – this overlaps with infection control, a unique requirement in hospitals. Using low-VOC interior finishes (paints, adhesives, flooring) prevents harmful off-gassing that could affect occupants, aligning with the health mission of healthcare facilities. Acoustic design is another factor: controlling noise through sound-absorptive materials and strategic space planning (to keep loud equipment or activities away from patient resting areas) contributes to a more healing environment. Thermal comfort is addressed through zoned climate control to adapt to different occupants' needs (patients, who may be sedentary, versus staff moving around). By designing for superior IEQ, green hospitals not only reduce energy (through daylight use and efficient ventilation) but also improve patient outcomes – a synergy between sustainability and healthcare quality.

It is important to note that implementing these sustainable design strategies can face practical challenges. Architects often must balance the initial costs and regulatory constraints with long-term benefits. Sustainable features can sometimes increase upfront construction costs (for example, adding a solar energy system or advanced wastewater treatment), which hospital clients might be hesitant to bear without clear ROI. However, many studies show life-cycle cost benefits via energy and water savings (Kats 2006). Shafa (2025) found in a survey of architects that economic and environmental factors were considered the most important drivers for applying sustainable design principles in projects – indicating that cost-effectiveness and environmental impact are top of mind. Lack of familiarity or training in green design can also hinder adoption; gaps in professional knowledge and perceived risks can create a disconnect between sustainability aspirations and execution. Overcoming these barriers requires education, stronger sustainability mandates, and showcasing successful precedents of green hospitals. In summary, sustainable architecture principles provide a foundation for green hospitals, establishing the design strategies and goals needed to reduce the ecological footprint of

healthcare facilities while enhancing human wellness.

### **Energy-Efficient and Smart Technologies in Hospitals**

Technological advancements play a pivotal role in achieving and maintaining sustainability goals in modern hospitals. Smart building systems and controls enable continuous monitoring and optimization of a hospital's performance, which is crucial given the complex, round-the-clock operations of healthcare facilities. Key aspects of smart and energy-efficient technology integration include:

- **Building Management Systems (BMS) and Automation:** A centralized BMS in a hospital monitors all major energy-consuming systems – HVAC, lighting, medical equipment loads, etc. Through automation, the BMS can adjust ventilation rates, temperatures, and lighting levels based on occupancy or time of day, ensuring energy is not wasted in unoccupied areas (like unused operating rooms at night) while always meeting critical minimum requirements. Sensors placed throughout the building (temperature sensors, CO<sub>2</sub> sensors for air quality, occupancy sensors, light sensors near windows) feed data to the BMS. Advanced controls use this data to, for instance, dim artificial lights when ample daylight is available or reduce airflow in areas with lower occupancy, thereby saving energy. According to a recent ranking study of smart building design factors, effective lighting control was one of the most impactful features for energy efficiency, alongside smart safety systems and climate sensors. In a hospital context, automated lighting and climate control not only save energy but also allow more precise environmental conditions tailored to patient comfort and medical needs.

- **IoT and Connected Medical Systems:** The Internet of Things (IoT) extends beyond traditional building services. Smart hospitals increasingly connect medical devices, nurse call systems, asset tracking, and even patient wearable devices into the hospital's digital network. While these primarily serve clinical and operational efficiency, they can intersect with building sustainability. For example,

occupancy data from IoT (knowing which rooms/beds are occupied) can inform HVAC zoning in real-time. Smart beds or tags can report when a patient room becomes vacant, prompting the BMS to set back the conditioning in that room until it is cleaned and reused. Such integration ensures energy is used only where and when needed, aligning with the efficient use principle. Additionally, predictive maintenance systems – where sensors on equipment like chillers or air handlers predict faults – help maintain optimal performance and prevent energy wastage due to poorly functioning equipment. The overarching idea is a hospital that self-optimizes and learns usage patterns to continually minimize resource consumption.

•**Renewable Energy and Energy Storage:** Smart technologies also encompass how hospitals generate, store, and manage energy. Given their critical role, hospitals require uninterruptible power – traditionally provided by backup generators. In a green hospital, renewable energy sources (solar panels, wind turbines if feasible, geothermal systems) are integrated to supply a portion of the power. Smart inverters and microgrid controllers can manage these renewable sources alongside batteries and the grid, ensuring the hospital can island itself during outages and optimizing when to use stored energy. This can dramatically cut peak demand and improve resilience. Some hospitals have adopted large battery storage or thermal storage (ice storage for cooling) to shift loads and better utilize renewable generation. These technologies are managed by intelligent controllers that respond to weather forecasts (for solar output) or grid signals. As an example, a hospital might use a smart microgrid to prioritize solar energy usage on a sunny day and charge batteries, then draw from those batteries in the evening peak hours – thereby reducing grid dependence and costs. The incorporation of renewables aligns with sustainable goals, and the smart control ensures reliability is not compromised, which is vital in healthcare settings.

•**Smart Materials and Adaptive Systems:** Beyond the conventional “hard” technologies, even architectural materials can be imbued with

smart features. As noted earlier, materials such as phase change materials (PCMs) can be integrated in walls or ceilings to absorb excess heat and release it later, effectively leveling out temperature swings and reducing HVAC loads. Electrochromic or thermochromic glazing can dynamically tint or change properties to control solar gain. These systems can be automated or sensor-triggered – effectively acting as a building’s “skin” that responds to climate conditions. For instance, a thermochromic window might be clear on a cloudy cool day (to admit heat and light) but turn opaque on a hot sunny day to block heat, all without user intervention. Shafa (2024b) emphasizes that using such intelligent materials significantly enhances compatibility with the environment and the building’s adaptability to weather changes. In hospitals, where lighting and temperature control are critical, these adaptive solutions can maintain comfort while easing mechanical system demands.

Crucially, the integration of smart tech must maintain the safety and reliability standards of hospitals. All automated systems need manual overrides and fail-safes, given that patient health and safety are paramount. Cybersecurity of IoT devices is also a concern in connected hospitals. Nonetheless, when implemented thoughtfully, smart technologies are powerful enablers of sustainability: they continuously fine-tune building operations and uncover efficiencies that static designs cannot. As Saghaei et al. (2025) demonstrate, even at the urban planning level, integrating environmental intelligence (e.g., using machine learning on meteorological data) can inform better site decisions. In the context of a hospital, this suggests that data-driven approaches – from site selection (considering climate and hazards) to real-time building management – contribute to a smarter and more sustainable facility. By embracing automation and data, green hospitals can achieve high-performance targets and adapt over time to changing conditions or demands.

### **Green Building Certification Systems and Benchmarks**

Green building certification systems (see Fig.2) provide a comprehensive set of criteria to

evaluate and recognize sustainable design and operations. For hospital projects, certification not only signifies environmental responsibility but also often correlates with improved patient environments and reduced operating costs. Several certification systems and guidelines can apply to hospitals:

- LEED for Healthcare (Leadership in Energy and Environmental Design):** Developed by the U.S. Green Building Council, LEED is one of the most widely adopted rating systems globally. LEED for Healthcare is tailored to the 24/7, intensive-use nature of hospitals and healthcare facilities. It includes prerequisites and credits across categories such as Sustainable Sites, Water Efficiency, Energy & Atmosphere, Materials & Resources, Indoor Environmental Quality, Innovation, and Regional Priority. Each credit has specific measurable targets (e.g. percentage energy cost reduction, water use reduction, use of certified wood, low VOC materials, daylighting for certain interior spaces, etc.), and projects earn points toward different certification levels (Certified, Silver, Gold, Platinum). Achieving LEED certification for a hospital can be challenging due to stringent healthcare requirements (for instance, high ventilation rates for infection control can conflict with energy efficiency). Yet many hospitals pursue it for the long-term benefits. According to the USGBC, LEED- certified healthcare facilities exemplify the “triple bottom line” by benefiting people (patients and staff health), planet (reduced emissions and waste), and profit (lower operating costs). Notably, certified hospitals often implement measures like healing gardens and enhanced ventilation beyond code minimums, which improve patient satisfaction – showing that sustainability and healthcare quality go hand in hand.

- BREEAM and Other International Systems:** In other regions, hospitals may use certification systems like BREEAM (Building Research Establishment Environmental Assessment Method) from the UK, Green Star (Australia), CASBEE (Japan), and others. These systems have similar broad criteria covering energy, water, materials, etc., with some regional

differences in emphasis. For example, BREEAM has credits for impact on ecology and public transport access, which are highly relevant for a hospital’s site planning (ensuring good access via transit, minimizing disturbance to ecosystems). A review of global rating systems notes that despite differences in weighting, “most of the GBRs have similarities in common more than differences” since all aim to create buildings that reduce environmental harm. Over time, many systems have converged towards including all three pillars of sustainability. The inclusion of credits for social aspects (like occupant health/comfort, or community impact) is a trend – for instance, a system initially called “Green Building Tool” was renamed to “Sustainable Building Tool” (SBTool) after adding social sustainability criteria. In essence, green certifications are evolving to sustainable building certifications that holistically assess environmental, economic, and social performance.

- Healthcare Specific Guidelines:** Apart from general sustainability ratings, hospitals often follow guidelines focused on health and wellness. The WELL Building Standard, while not healthcare- specific, emphasizes indoor health factors (air, water quality, nutrition, light, fitness, comfort, mind) and could complement LEED for a hospital by ensuring a people-centered design. Additionally, tools like the Green Guide for Health Care (GGHC) provided an early framework specifically for healthcare facilities, which informed the development of LEED for Healthcare. Some countries also have energy or green building mandates for public hospital projects, effectively requiring a certification or equivalent compliance.



**Figure 2:** An infographic showcasing key green building certification systems—LEED for Healthcare, BREEAM, Green Star, and CASBEE—used to evaluate and guide sustainable design in healthcare facilities worldwide.

One benefit of pursuing certification in hospital projects is the structured integrated design process it encourages. Achieving credits across categories requires collaboration between architects, engineers, hospital administrators, and clinicians from early stages – exactly the kind of multidisciplinary approach needed for a complex building like a hospital. This process can yield innovative solutions; for example, to get high scores in both energy and indoor quality, teams have experimented with technologies like displacement ventilation in patient rooms (which uses stratified airflow to both save energy and improve air quality for patients). Certification frameworks also push for commissioning and performance verification – a critical step in hospitals to ensure that all systems (HVAC, emergency systems, etc.) function as intended.

However, it is worth noting that typical green certifications have not historically included resilience (e.g., seismic resilience) as a scored category. They focus on sustainability during normal operation. There are emerging rating systems like RELi (which is oriented towards resilience) and some pilot credits in LEED for resilience, but these are new. Emerging frameworks such as RELi (Resilience Action List and Credit System) and PEER

(Performance Excellence in Electricity Renewal) have begun addressing these gaps by explicitly incorporating resilience and grid reliability, but their application in healthcare contexts remains limited. Their evolving presence suggests a growing awareness of the need to bridge sustainability and disaster preparedness in future certifications. Thus, a hospital could be LEED Platinum yet still need separate verification that it meets seismic safety standards. In recognition of this, some researchers and practitioners argue for integrating resilience metrics into sustainability certifications for critical buildings. Overall, green certification systems remain a valuable tool for benchmarking hospital sustainability. They ensure a hospital project meets a broad set of environmental performance criteria and can provide public recognition which is beneficial for institutions focused on community trust. By following certification guidelines, project teams are less likely to neglect any key aspect of sustainability – from site ecology to patient wellness – thus producing a more balanced green design.

### **Integrated Approach: Toward Green, and Smart Hospitals**

The domains of green design, smart technology, certification, and resilience should not be

viewed in isolation when it comes to hospital architecture. The ultimate goal is to create healthcare facilities that are sustainable in the broadest sense – environmentally, socially, and structurally. An integrated design approach recognizes interdependencies among these domains and seeks synergies where one strategy can serve multiple goals.

One useful concept is to think of a hospital as an ecosystem with various subsystems (energy, water, waste, safety, etc.) that can be optimized together. For example, consider the interplay between energy efficiency and resilience: a highly energy-efficient hospital (through insulation, efficient systems, on-site generation) not only lowers carbon footprint but is also easier to keep running on backup power during grid outages. In essence, efficiency enhances emergency resilience. A hospital that requires half the energy to operate can run twice as long on the same generator fuel or battery backup. This is a strong argument for sustainability measures from a resilience perspective. Conversely, adding resilience features like on-site solar and energy storage contributes to sustainability by reducing reliance on the grid and fossil fuels. Thus, strategies like solar PV with battery storage satisfy both LEED energy credits and provide critical infrastructure for disaster scenarios – a win-win.

Another synergy is between smart technologies and green operations. Smart building analytics can continuously commission and improve building performance, ensuring the hospital not only achieves but maintains its LEED or green targets over time. Machine learning models might predict how to adjust operations for an incoming heatwave or how to pre-cool certain areas to avoid peak demand charges, effectively marrying sustainability with advanced technology. Saghaei et al. (2025) illustrate the power of such data-driven models in environmental planning; in a hospital, similar models could integrate meteorological forecasts, real-time occupancy, and even patient care schedules to optimize energy and resource use dynamically. Moreover, smart systems aid in monitoring compliance with certification or regulatory standards – for instance,

continuously tracking indoor air quality (a factor in both LEED and WELL) and alerting if levels deviate from the target, thereby ensuring the hospital's indoor environment remains healthy.

Green building certification frameworks can serve as a common language or checklist to align the many stakeholders in a hospital project. However, one must integrate additional criteria for resilience. A proposed integrated framework for a green, smart, resilient hospital could overlay sustainability targets with resilience targets. For example, in design charrettes, the team can simultaneously address: “How does this design decision impact energy performance, and how does it impact post-disaster functionality?” Some decisions might involve trade-offs: a large atrium might improve daylight (good for LEED and patients) but could be a seismic risk if not engineered properly – here, advanced structural design (perhaps base-isolating the atrium roof or using moment frames around it) can resolve the conflict. Integrative design is about finding solutions that satisfy multiple objectives. Table 1 already hints at such overlaps (e.g., the redundancy of power supply is both a resilience measure and aligns with “green” reliable operations).

In conclusion of this discussion, the integrated approach is not just a theoretical ideal but a practical necessity. The challenges of climate change and increasing natural disasters mean hospitals must reduce their environmental impact and be prepared for extreme events. By combining green architecture, smart systems, certification frameworks, and seismic design, we can create hospital buildings that are future-proof – minimizing harm to the environment while maximizing safety and resilience for the community. This holistic vision transforms hospitals into beacons of sustainability and security, showcasing how the built environment can rise to meet global health and climate challenges.

### **Conclusion**

Designing a green hospital in the 21st century goes beyond simply adding solar panels or



meeting energy benchmarks – it requires a comprehensive approach that interweaves sustainability, technology, and resilience from the ground up. This paper has presented an integrated perspective on hospital architecture, drawing together sustainable design principles, energy-efficient smart technologies, green certification systems, and seismic resilience strategies. Through synthesis of literature and examples, several key conclusions emerge:

•**Sustainable Design as a Foundation:** Fundamental green architecture practices (efficient energy and water use, sustainable materials, healthy indoor environments) form the baseline of a green hospital. These measures yield significant environmental benefits and also improve patient outcomes and staff productivity. The case of Shiraz architects showed that environmental and economic factors are paramount considerations, reinforcing that green design can align with cost-effectiveness in healthcare projects.

•**Smart Technologies Magnify Efficiency:** Intelligent building systems and IoT innovations act as force-multipliers for sustainability. They ensure that a hospital's performance is continuously optimized, bridging the gap between design intent and actual operation. Smart hospitals can dynamically respond to changing conditions – saving energy, maintaining comfort, and even informing broader decisions like site suitability through environmental data modeling. Embracing these technologies is crucial to manage the complexity of modern hospitals without incurring resource waste.

•**Certification Provides Comprehensive Targets:** Green building rating systems like LEED for Healthcare offer a useful roadmap and accountability mechanism for achieving sustainability across a wide spectrum of criteria. They encourage integrated thinking and help institutionalize sustainability goals within the project. However, certifications should be complemented with explicit resilience planning, as current systems only partially address disaster preparedness. The trend towards including social and health factors in

certifications is positive and particularly relevant to hospitals

For architects, engineers, healthcare administrators, and policymakers, the implications are clear. We must champion design approaches that break down traditional silos and address sustainability and safety in tandem. Future research could develop integrated assessment metrics for green and resilient hospitals, or document post-occupancy performance of such facilities to inform best practices. Machine learning and big data analysis (as seen in environmental modeling research) may also play a role in continuously improving hospital design guidelines as more performance data becomes available.

In closing, the green hospitals of tomorrow will likely be defined by their interdisciplinary excellence. They will harness cutting-edge materials and smart systems, fulfill rigorous sustainability certifications, and embody structural resilience that protects their mission under duress. These hospitals will not only heal patients but also heal the environment by drastically cutting emissions and resource use. They will stand as resilient community pillars in the face of climate change and natural disasters. The integrated design approach outlined in this paper is a step toward that vision – one where healthcare architecture becomes a model of how to build sustainably and safely in an increasingly uncertain world.

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**Notes:** N/A

**Acknowledgment:** N/A

**Conflict of Interest:** The author stated that there are no conflicts of interest regarding the publication of this article.

**Ethics Committee Approval:** N/A

**Author Contributions:** The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

**Financial Disclosure:** The author declared that this study has received no financial support.

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