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Soft Science

Kim *et al*. *Soft Sci.* **2026**, *6*, 58 **DOI:**10.20517/ss.2026.110

Challenges of advanced transient electronics for practical applications

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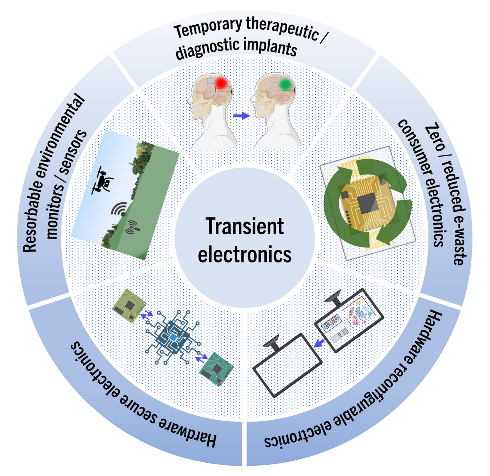
Citation: Kim, J.; Kim, K. S.; Koo, J.; Zhao, J.; Rogers, J. A. Challenges of advanced transient electronics for practical applications. *Soft Sci.* **2026**, *6*, 58. https://dx.doi.org/10.20517/ss.2026.110

Received: 14 May 2026
First Decision: 29 May 2026
Revised: 6 Jun 2026
Accepted: 11 Jun 2026
Published: 3 Jul 2026

Academic Editor:
Huanyu "Larry" Cheng
Copy Editor:
Pei-Yun Wang
Production Editor:
Pei-Yun Wang



INTRODUCTION

Since the introduction of transient electronics in *Science* in 2012[1], the field has established a transformative design paradigm in which electronic systems are engineered to physically disappear after a defined period of operation. This concept departs from the traditional goal of durability and long-term stability in electronics, instead emphasizing programmed functionality followed by controlled degradation.

This paradigm shift has unlocked a broad range of applications across diverse fields. The scope extends from biomedical implants[2] and environmental sensors[3] to military hardware and secure devices[4,5]. In biomedical engineering, transient devices have been realized across a range of implantable platforms, including sensors for monitoring physiological parameters and therapeutic devices for treating various

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diseases and injuries[6-14]. These systems address longstanding challenges associated with conventional implants, most notably the necessity of secondary surgical procedures for device removal, as well as risks of long-term toxicity and infection arising from persistent foreign materials in the body. In environmental applications, biodegradable sensors have been deployed to monitor ecological parameters such as soil conditions and water quality without leaving persistent residues[15-19]. Beyond these, transient electronics have been extended to security systems, in which devices self-destruct upon unauthorized access to prevent retrieval of sensitive information[20-22]. The concept of transient electronics has also been extended to reconfigurable devices, where controlled degradation serves not merely as an end-of-life mechanism but as an active functional property that enables dynamic switching between distinct operational states, opening new design possibilities beyond the traditional notion of programmed disappearance[23,24].

Despite these advances, several challenges remain before transient electronics can achieve their full potential. First, the material palette available for transient systems remains limited, constraining the diversity of achievable device properties and functionalities. Second, at the device level, current systems are heavily dominated by passive components, and the realization of high-performance active devices is therefore a crucial prerequisite for advanced functional complexity. Finally, the lack of scalable fabrication strategies compromises reproducibility and uniformity, precluding widespread practical deployment. Ultimately, resolving these interconnected challenges across materials science, device engineering, and advanced manufacturing is imperative to drive the continued evolution of the field.

This perspective focuses on the current state and future trajectory of transient electronics, with particular emphasis on the materials, devices, and fabrication strategies that will define the next generation of the field. We first summarize recent advances in transient passive and active components, spanning biodegradable sensors, dissolution-controlled substrates, and emerging functional materials that expand the accessible design space. We then identify the critical challenges that must be addressed to advance the field, including broadening the materials portfolio, transitioning from passive to high-performance active devices, and establishing scalable fabrication processes that ensure reproducibility and uniformity. Finally, we discuss the key requirements for practical deployment, encompassing long-term operational stability, integration with real-world application environments, and the broader design principles needed to translate laboratory demonstrations into viable transient systems.

RESEARCH TRENDS IN TRANSIENT ELECTRONICS

Emerging over the past decade, transient electronics is a novel engineering discipline characterized by devices engineered to fully or partially dissolve at programmed rates or upon specific trigger events, after completing their intended functions. These systems are designed to be resorbed through engineered chemical or physical processes after a defined period of operation, deviating fundamentally from the principle of permanence that underlies conventional electronics. Figure 1A illustrates the overarching concept and current research trends in transient electronics, highlighting the diverse application domains that have emerged over the past decade.

Transient electronics present transformative opportunities for medical implants and advanced sensing applications. Bioresorbable implants have been demonstrated for transient physiological monitoring systems[27], optoelectronics[9], and electroceuticals[28] that perform therapeutic or diagnostic functions before undergoing complete, natural degradation, thereby eliminating the need for secondary surgical procedures. Initially, research primarily focused on single components such as encapsulation materials, electrodes[1,2], sensors, or single-modality devices. However, more recent studies indicate a clear progression toward closed-loop systems or multi-modal devices[29]. This transition toward higher levels of system complexity demands the heterogeneous integration and orchestration of distinct components.

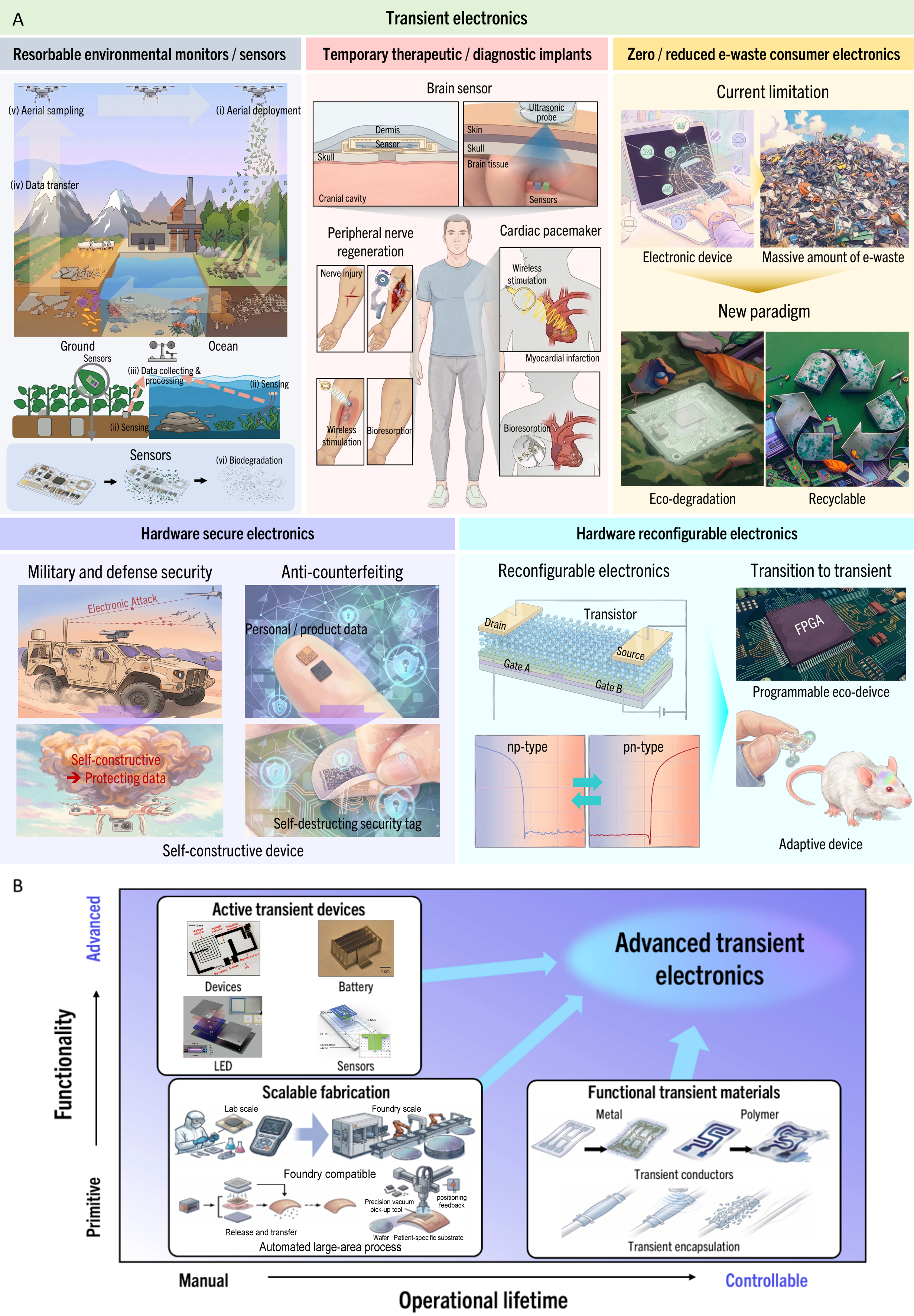

Figure 1. (A) Concept and current research trends in transient electronics; (B) Challenges in the practical realization of advanced transient electronics. The images in the "Active transient devices" panel of (B) are adapted with permission from the following sources: "Devices" from Ref.[1], Copyright © 2012 AAAS; "Battery" from Ref.[25], Copyright © 2019 Wiley; "LED" from Ref.[26], Copyright © 2014 Wiley; and "Sensors" from Ref.[10], Copyright © 2016 Springer Nature. LED: Light-emitting diode.

The same concept can be extended to environmental applications, where transient electronics offer a compelling approach to sustainable sensing and monitoring. Eco-transient sensors[19] and Internet of Things (IoT) nodes[23,30] that dissolve harmlessly after deployment address the mounting global problem of electronic waste. Abiotic variables such as soil pH, ambient temperature, and moisture impose unpredictable perturbations on degradation kinetics, requiring precise lifetime programming[31]. Given this challenge, a reliable power supply and continuous data transmission must be sustained throughout the operational lifetime. Meaningful environmental monitoring necessitates dense, large-area sensor deployment across heterogeneous terrains, which in turn demands scalable, cost-effective manufacturing processes that the field has yet to fully establish.

Beyond biodegradability, the concept of transient electronics can be extended to security systems and reconfigurable devices, broadening the scope of the field well beyond its original design intent. Data protection and information security can be achieved through the destruction or reconfiguration of internal circuitry via transience-based mechanisms. A key distinction in this field is that, rather than environmentally driven passive dissolution employed in conventional transient electronics, the priority lies in realizing self-destruction or functional switching that is triggered instantaneously by well-defined events. This necessitates materials and system designs that are responsive to specific stimuli. Representative triggering mechanisms include thermal triggers that exploit heat-induced compositional or morphological transformations to disrupt internal circuitry[32], optical triggers that utilize ultraviolet (UV)-responsive materials to induce dissolution upon light exposure[33], and electrical triggers that enable self-destruction through externally applied electrical stimuli[34,35]. Together, these applications establish transient electronics as a field capable of addressing challenges that are inaccessible to conventional, permanent device architectures.

DEVICE ARCHITECTURE AND PHYSICOCHEMICAL MECHANISMS

However, the realization of the applications mentioned above depends significantly on the material set that programs both function and transience. The functional architecture of a transient electronic system is organized around three interdependent axes: the active devices, the conductors, and the substrate/packaging. In the foundational platform, silicon nanomembranes (Si NMs) serve as the semiconductor, thin films of magnesium (Mg) as conductors, magnesium oxide (MgO) and silicon dioxide (SiO_2) as dielectrics, and silk fibroin as the substrate and packaging materials, all of which are transient in that they disappear through hydrolysis and/or simple dissolution in water[1,36]. For the active layer, monocrystalline Si NMs (thickness < 100 nm) undergo hydrolytic dissolution via the reaction $Si + 4H_2O \rightarrow Si(OH)_4 \rightarrow H_4SiO_4$, at a rate governed by pH, temperature, and ionic concentration[37]. For conductors, bioresorbable metals including Mg, Zn, Mo, and W dissolve through aqueous oxidation [e.g., $Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2$], with dissolution kinetics tunable via film thickness and encapsulant geometry[36]. Representative dissolution rates span several orders of magnitude across these metals: Mg thin films dissolve rapidly, with electrical dissolution rates on the order of ~0.5-3 $\mu m \cdot h^{-1}$ in simulated body fluids, whereas Mo and W dissolve far more slowly, at ~0.001-0.02 $\mu m \cdot h^{-1}$, enabling their use in applications demanding longer operational lifetimes[38]. For packaging and substrates, bioresorbable polymers including silk fibroin, poly(lactic-co-glycolic acid) (PLGA), polylactic acid (PLA), poly(vinyl alcohol) (PVA), and poly(ε-caprolactone) (PCL) undergo hydrolytic chain scission of ester or peptide bonds. The intrinsic degradation kinetics are dictated by the polymer's chemical composition and molecular weight. Dissolution timescales vary widely across commonly used substrates: PVA generally exhibits relatively rapid and formulation-dependent dissolution in aqueous environments[39], PLGA (e.g., ~20 μm thick) fully dissolves within 15 to 20 days[40], PLA degrades over several months to years[41], and PCL, being the most hydrophobic, requires 2-4 years for complete degradation[41]. Practically, material crystallinity and encapsulant thickness serve as the primary tunable parameters for precisely programming these dissolution schedules. The convergence of these three material axes, each with independently tunable dissolution kinetics, provides the foundational design space through which transient electronics achieves its defining attribute: stable operation followed by complete, on-schedule disappearance.

KEY CHALLENGES IN THE PRACTICAL REALIZATION OF ADVANCED TRANSIENT ELECTRONICS

While the materials described above demonstrate the feasibility of transient operation, they represent only a fraction of what practical deployment demands. Figure 1B summarizes the key challenges that must be addressed for the practical realization of advanced transient electronics, spanning materials, device, and fabrication perspectives. The first challenge lies in establishing a comprehensive materials portfolio that spans the full spectrum of intended operational lifetimes: from short-term (hours to days), through mid-term (weeks to months), to long-term (months to years) applications. While pioneering works demonstrate the feasibility of biodegradable substrates such as silk fibroin, PLGA, and transient dielectrics including SiO_2 and MgO, the library of materials with well-characterized, controllable dissolution kinetics remains limited[2]. Expanding this portfolio demands the synthesis and systematic evaluation of novel transient conductors, semiconductors, and encapsulants whose degradation profiles can be precisely tuned to match clinical, environmental, or security-driven use cases. Equally important is ensuring that these materials maintain mechanical robustness and biocompatibility throughout their functional lifetime before undergoing complete, harmless dissolution. Achieving this balance remains a formidable challenge, and close collaboration among materials chemists, device physicists, and biomedical engineers is essential. Looking ahead, several promising emerging candidates warrant attention. Organic semiconductors such as DNTT and TIPS-pentacene derivatives offer low-temperature processability and tunable dissolution kinetics[42]. Biodegradable variants of poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS)-based conductive polymers represent a compelling route toward transient conductors with retained electronic performance[43]. Finally, elastomeric copolymers such as poly(glycolide-co-ε-caprolactone) (PGCL) address the longstanding mechanical mismatch between rigid transient substrates and soft biological tissues, opening new possibilities for stretchable transient platforms[44].

The second challenge concerns the advancement of active device components and the engineering infrastructure required to support reliable transient systems[45]. Although foundational transient passive elements have been demonstrated, the performance of active components including transient diodes, light-emitting devices, thin-film transistors, photovoltaic cells, bioresorbable batteries, wireless power and data transmission modules, and triboelectric nanogenerators must be substantially improved to meet real-world operational demands[2,46]. Each of these components introduces distinct materials and processing constraints. For instance, achieving sufficient carrier mobility in transient semiconductors and realizing stable wireless communication within the lossy electromagnetic environment of biological tissue remain critical hurdles. Beyond individual device performance, the establishment of robust packaging and encapsulation processes is critical to governing the spatiotemporal profile of transient system operation, protecting sensitive components during the functional phase while enabling deterministic, triggered, or environmentally responsive dissolution thereafter.

In addition to these technical challenges, the third challenge concerns the lack of system-level infrastructure. Dedicated manufacturing equipment compatible with transient material sets, standardized processing protocols, and regulatory certification frameworks tailored to these emerging technologies have not yet been established, creating significant bottlenecks in the transition from laboratory validation to clinical and commercial applications. From a regulatory standpoint, bioresorbable materials and their dissolution byproducts must satisfy stringent biocompatibility and toxicology requirements - such as those defined under ISO 10993 - before clinical deployment, yet systematic certification frameworks tailored to transient material sets remain largely undefined. Furthermore, conventional foundry infrastructure is optimized for oxide–semiconductor-compatible materials, and the limited process compatibility of transient conductors and substrates such as Mg or PLGA with existing manufacturing lines presents a significant barrier to their seamless integration into commercial fabrication workflows. Several research groups have addressed this bottleneck by exploring foundry-compatible materials and fabrication processes. Chang *et al.* demonstrated wafer-level manufacturing of transient electronic components, including metal–oxide–semiconductor field-effect transistors (MOSFETs) and complementary metal-oxide semiconductor (CMOS) circuits, establishing a scalable fabrication pathway[45]. Heterogeneous integration via standardized advanced packaging further advances device complexity and technical maturity[47]. Nevertheless, a more systematic and field-wide discourse on the transition from laboratory-scale to foundry-compatible fabrication remains necessary.

FROM LABORATORY DEMONSTRATION TO REAL WORLD APPLICATION

Despite these challenges, the trajectory of transient electronics promises transformative impacts across medicine, environmental monitoring, hardware security, and reconfigurable electronics. As the field matures, continued advances in materials design, device engineering, and manufacturing infrastructure will unlock applications fundamentally unattainable with conventional, persistent electronics. In biomedicine, fully bioresorbable implants spanning neural probes, cardiac monitors, and drug delivery platforms could eliminate the need for secondary retrieval surgeries, reducing patient risk and healthcare burden while enabling seamless, temporary physiological intervention when and where such intervention is most needed. Furthermore, translating these demonstrations into repeatable clinical-grade performance will require the establishment of accelerated testing protocols that ensure consistent degradation kinetics and long-term biocompatibility across patient populations and deployment environments. Environmentally, distributed transient sensor networks capable of dissolving harmlessly after deployment could enable unprecedented spatiotemporal resolution in ecological monitoring, precision agriculture, and disaster response, without accumulating electronic waste that plagues conventional sensing infrastructure. Realizing this potential, however, will necessitate the development of verification methods that confirm dissolution controllability and sustained sensing accuracy under heterogeneous real-world conditions, including varying soil compositions and natural water chemistries[17]. Looking further ahead, the integration of transient electronics with emerging paradigms including soft robotics, brain-machine interfaces, and the IoT will demand not only continued innovation at the materials and device level, but also a broader rethinking of how electronic systems are designed, deployed, and retired. Critically, transitioning from laboratory prototypes to clinical implants or field-deployable sensor networks requires the co-design of transient power sources, wireless communication modules, and encapsulation strategies into a single, reliable platform. Recent demonstrations of fully integrated bioresorbable systems combining energy harvesters, data transmission units, and programmable encapsulation layers represent important early steps toward this goal, illustrating that the scientific foundations of transient electronics are being actively translated into verifiable, engineered systems[48,49]. The pioneering research shows that electronics need not be permanent fixtures, but rather ephemeral tools precisely matched to the duration and demands of their intended function, offering a compelling and ultimately more sustainable model for the next generation of electronic systems. Realizing this vision will require coordinated efforts across disciplines and industries, but the scientific foundations laid over the past decade provide strong reason for optimism that transient electronics will transition from laboratory curiosity to a cornerstone technology of the coming decades.

DECLARATIONS

Authors' contributions

Supervised the review: Rogers, J. A.; Zhao, J.; Koo, J.
Conceived the topic, defined the scope, and established the overall framework: Rogers, J. A.; Zhao, J.; Koo, J.
Performed the literature search, collected key references, and organized the materials: Kim, J.; Kim, K. S.
Wrote the initial draft: Kim, J.; Kim, K. S.; Koo, J.
Prepared the figures and tables with input from Kim, J.: Kim, K. S.; Rogers, J. A.

Provided critical revisions and refined the manuscript for important intellectual content: Rogers, J. A.; Zhao, J. All authors discussed the content and commented on the manuscript.

Availability of data and materials

Not applicable.

AI and AI-assisted tools statement

During the preparation of this Perspective article, the authors used ChatGPT (GPT-5.5/used in 2026), developed by OpenAI, to assist with English language editing, grammatical correction, and improving the clarity and readability of the text. Figure 1A, as well as the images in the "Scalable fabrication" and "Functional transient materials" panels of Figure 1B, were created using Nano Banana Pro (powered by Gemini 3 Pro Image, used in 2026, Google). These tools were not used to generate scholarly arguments, develop the conceptual framework, or draw the conclusions of the article. All AI-assisted outputs were carefully reviewed, edited, and verified by the authors, who take full responsibility for the accuracy, originality, and integrity of the final manuscript.

Financial support and sponsorship

This work was supported by the Korea Health Industry Development Institute (KHIDI) (RS-2026-25507828 and RS-2023-KH136924). This work was supported by the Science and Technology Commission of Shanghai Municipality (23160714000) and the Shanghai Municipal Health Commission's Special Research Project (2025ZHYL042).

Conflicts of interest

Rogers, J. A. is the Honorary Editor-in-Chief of the *Soft Science* journal. He had no involvement in the review or editorial process of this manuscript, including but not limited to reviewer selection, evaluation, or the final decision, while the other author has declared that he has no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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