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Perspective

Advanced thermal management strategies for electric vehicles: enhancing efficiency, reliability, and performance

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ABSTRACT

Thermal management plays a crucial role in enhancing electric vehicles' performance, reliability, and lifespan (EVs) by effectively dissipating heat from key components, including electric traction motors, power electronic components (PECs), and batteries. This paper explores various thermal management strategies tailored for these systems, highlighting their advantages, limitations, and technological advancements. In electric traction motors, heat dissipation is primarily addressed through active and passive cooling techniques such as forced convection, heat pipes, and phase change materials (PCMs), with recent advancements like direct slot cooling (DSC) improving efficiency. Similarly, PECs and electronic chips face thermal challenges due to electrical resistance, requiring innovative solid-state, air, liquid, and two-phase cooling methods to prevent performance degradation and component failure. Battery thermal management systems (BTMS) are equally critical, as temperature variations directly impact efficiency, safety, and cycle life. Active, passive, and hybrid BTMS technologies—including liquid cooling, thermoelectric systems, PCMs, and heat pipes—are evaluated based on their effectiveness in maintaining optimal operating temperatures. This paper comprehensively analyzes emerging cooling solutions, addressing key trade-offs between efficiency, cost, and design complexity. By integrating advanced thermal management techniques, the EV industry can achieve improved energy efficiency, enhanced safety, and prolonged component durability, paving the way for more reliable and sustainable electric mobility.

1. Introduction

The global transition to electric vehicles (EVs) and hybrid electric vehicles (HEVs) is accelerating due to increasing environmental concerns and the demand for sustainable transportation solutions. However, one of the most critical challenges in EV and HEV development is thermal management, which directly impacts efficiency, reliability, and safety. Key components such as electric traction motors, power electronic components (PECs), and batteries generate significant heat during operation, which, if not managed effectively, can lead to performance degradation, energy loss, and potential safety hazards such as thermal runaway. Efficient thermal management is essential to dissipate excess heat, maintain optimal operating conditions, and extend the lifespan of these components [1,2]. Electric traction motors, which convert electrical energy into mechanical motion, experience heat generation primarily due to copper and iron losses, as well as mechanical friction. Overheating can lead to insulation degradation, efficiency loss, and irreversible demagnetization of permanent magnets. To counteract these issues, various cooling strategies have been developed, categorized into active and passive methods. Active cooling techniques, including forced air convection, liquid cooling via water jackets or microchannels, and advanced methods like direct oil spray cooling, enhance heat dissipation but require additional energy. In contrast, passive cooling solutions such as phase change materials (PCMs), heat pipes, and finned heat sinks offer efficient thermal management without external power consumption. Recent advancements, such as direct slot cooling (DSC), have further improved thermal regulation in modern permanent magnet synchronous motors (PMSMs), enabling higher efficiency and torque density [3,4]. Similarly, power electronic components, including inverters, converters, and semiconductor chips, face significant thermal stress due to electrical resistance, switching losses, and parasitic effects. Excessive temperatures in PECs can lead to reduced performance, shorter lifespan, and potential component failure. Various cooling techniques are employed to address this issue, including solid-state methods such as thermoelectric cooling, thermotunneling, and heat sinks with thermal interface materials. Air-based cooling, through either natural or forced convection, remains a common solution, while more advanced technologies such as piezoelectric fans, synthetic jet cooling, and electrohydrodynamic cooling offer innovative approaches to heat dissipation. Liquid-based cooling methods, including cold plates, microchannels, electrowetting, immersion cooling, and jet impingement, provide superior heat transfer efficiency. Additionally, two-phase cooling systems, such as heat pipes and spray cooling, leverage phase transition properties to enhance thermal performance, ensuring that power electronics operate within safe temperature limits [5].

Battery thermal management is equally crucial in EVs and HEVs, as battery performance is highly sensitive to temperature fluctuations. The optimal operating temperature range for lithium-ion batteries is typically between 15°C and 35°C; deviations beyond this range can lead to increased internal resistance, capacity loss, and severe safety risks such as thermal runaway. Battery thermal management systems (BTMS) are classified into active, passive, and hybrid methods. Active BTMS technologies, such as forced air cooling, liquid cooling, and immersion cooling, provide effective temperature control, with some manufacturers, like Tesla and Audi, adopting direct dielectric coolant immersion for enhanced thermal regulation. Thermoelectric cooling (TEC) and thermoelectric generators (TEGs) are also gaining attention for their ability to convert excess heat into usable power. Passive BTMS techniques, including phase change materials (PCMs) and heat pipes, offer energy-efficient solutions by leveraging latent heat storage and efficient heat transport. Hybrid BTMS approaches combine active and passive methods, such as liquid-PCM or air-PCM hybrid systems, to optimize heat dissipation while minimizing energy consumption and design complexity [6].

Given the rapid advancements in EV technology, the development of effective thermal management systems is paramount to ensuring higher efficiency, prolonged component durability, and improved safety. This paper provides a comprehensive review of thermal management strategies across electric traction motors, PECs, and batteries, evaluating the strengths, limitations, and emerging trends in cooling technologies. The integration of innovative thermal solutions, such as immersion cooling, direct slot cooling, and hybrid cooling techniques, represents a critical step toward optimizing EV and HEV performance. By addressing thermal challenges, manufacturers can enhance energy efficiency, extend vehicle lifespan, and contribute to the broader adoption of sustainable electric mobility.

2. Thermal management in EVs

Thermal management methods are as essential as control strategies in PCU. Temperature has a great impact on the performance and durability of electronic components, and it also determines the magnetic flux of electric motors. Thermal management aims to dissipate heat from EVs' components to limit failure, optimize energy consumption, improve reliability, enhance power and flux density, and extenuate device quantity. In EVs, there are various systems, such as batteries, electric traction motors, and PCUs with subcategories, including electronic boards and PECs, each of which has different thermal management methods. In EVs that are equipped with engines (HEVs), using the term thermal management for the engine is not correct, and WHR is more appropriate instead, while applying WHR systems in other components of EVs is not justified, since they do not generate much heat [7].

3. Thermal management in electric traction motor

The main source of heat in high-torque traction motors in EVs is stator windings resistance, which brings copper loss as the most heated unit and major energy loss, respectively, although there is iron loss due to hysteresis in magnetic field and mechanical loss from the bearing's friction. High-temperature regions emerge in the winding copper core, air gaps between the stator and rotor, around the axial center of the rotor bar, and stator section. The high temperature must be managed seriously since a 10 C increase in temperature halves the lifetime of the insulation across the conductors and demagnetizes the permanent magnets irreversibly. Active and passive cooling are two main categories of EV electric traction motor cooling methods. Active methods refer to forced convection using fans or pumps to circulate the coolant with more capability to dissipate heat, although they consume extra energy, while passive cooling methods are based on natural convection such as fins and heat pipes, which limit the absorbing heat while they do not need energy and much maintenance cost. Solid-liquid phase change material (PCM) is one of the passive cooling methods applied around the stator coil and does not affect the reluctance much. PCM with high melting heat capacity can absorb the large heat generated from the coil by changing its phase from solid to liquid and back again to the previous state by transferring heat to the environment when the motor turns off.

The heat pipe, as a passive cooling, does not use any moving parts and is able to transfer large amounts of heat over long distances at a constant temperature. Generally, water is used as a cooling fluid in electric traction motors. Heat pipes could be installed in different locations, including motor housing, winding, stator shaft, rotor shaft, and stator core. There are so many methods to dissipate heat from EV electric traction motors, such as air-cooling, water jacket cooling, liquid/oil-based cooling, oil spray cooling, cooling tubes and microchannels, and potting silicon gelatin (PSG) cooling. In modern PMSMs, a direct spray of dielectric oil to cool the stator and windings with water jacket cooling has shown the highest torque achievement of electric motors compared to all other methods. Recent alternative optimal methods remove heat more accurately. Direct slot cooling (DSC) uses heat pipes applying a cooling channel to cool motor windings directly in the open slot of a motor stator as the cooling channel [8].

4. Thermal management in PECs and electronic chips

Electrical resistance in semiconductors is the main heat source in electronic devices. The heat generation from switching losses, conduction losses, and parasitic effects degrade the performance, durability, and reliability of PECs. The essentials of innovative cooling technologies should be achieved by both high absorbing heat capacity and small module size. Thermal stress is the main reason for capacitor and semiconductor failures. Developing wide bandgap devices (WBG) with high heat generation in power electronic topologies requires more effective cooling techniques [9]. An appropriate cooling system must contain three proficiencies in absorbing, transferring, and removing heat out of the module. As indicated in Table 1, the cooling of power electronics is classified according to different heat transfer mechanisms or coolant agents. The cooling technologies are as follows [10]:

A) Solid-state cooling is employed in the technologies of solid materials with high thermal conductivity or thermoelectric effects.

1. Heat sinks, thermal interface materials, and conduction plates: Based on the amount of heat generation, different materials could be applied with various thermal conductivities, from conventional cheap devices like aluminum with limited ability in terms of heat dissipation and density to high-performance devices like pyrolytic graphite. They are used to eliminate the gap between a semiconductor and a heat sink instead of air. Their main restriction is uncontrollable heat spread that requires thin plates.

2. Magnetic cooling: In this method, integrating magnetocaloric devices and a temporary magnetic field leads to a drop in the temperature of the electronic components. This method is performed according to a four-stage cycle of increasing the temperature of the device, magnetizing it, releasing heat, decreasing the temperature, and finally, demagnetizing. The importance of this method is determined when volume and weight are constrained and high efficiency is considered.

3. Thermoelectric cooling: This method works exactly the opposite of the TEGs. DC low voltage current flows through the device to enable heat transfer based on the Peltier effect. This method, despite its low efficiency, low heat transfer capability and high cost, is used in applications where there is volume and weight limitation, and temperature changes are extremely transient and require precise control.

4. Thermotunnelling and thermionic cooling: The operation of this method is inverse of a battery and uses two electrodes, one to absorb heat as an emitter and the other to repel as a collector, then transmission the front of electrons, and finally to drive an electric current and generate electricity. No mechanical moving parts like other solid-state methods, high power density, high reliability, good stability, and high efficiency are the main advantages of this method. Its main restrictions are only supporting localized cooling and low cooling power from ambient temperature.

B) Air cooling technologies: This method does not have complications of liquid heat transfer, and it is done in two ways: natural and forced convection.

Table 1. Thermal management strategies in power electronics

Heat Transfer Mechanisms \ Coolant Agent	Solid	Gas (Air)	Liquid	Two-Phases
Conduction	Conduction plates and heat sinks, Thermal interface materials, Advanced conduction plates	Not applicable	Not applicable	Not applicable
Natural Convection	Not applicable	Air cooling	Immersion cooling	Immersion cooling
Forced Convection	Not applicable	Standard fans, Piezoelectric devices, Synthetic jet impingement, Electrohydrodynamics, Thermoacoustic cooling	Cold plates, Microchannel cooling, Electrowetting, Immersion cooling, Jet impingement cooling	Cold plates, Microchannel cooling, Electrowetting, Immersion cooling, Jet impingement cooling, Heat pipes, Spray cooling, Phase change materials
Magnetocaloric Effect	Magnetic cooling	Not applicable	Not applicable	Not applicable
Peltier Effect	Thermoelectric cooling	Not applicable	Not applicable	Not applicable
Tunnel and Thermionic Effects	Thermotunnelling and thermionic cooling	Not applicable	Not applicable	Not applicable

1. Natural air convection: This heat transfer mechanism is the simplest way to cool electronic boards, and it is done due to the bouncy force and the density difference between the hot device and the cool surrounding air. Limiting the amount of heat transferred is the main challenge of this method.

2. Forced air convection: The combination of fan and thermal heat sinks causes more heat transfer than natural convection. This method is the most common way to cool PECs. The main limitations of this method are fan energy consumption, high volume-to-weight ratio, and lower capability than other novel methods based on energy efficiency.

3. Piezoelectric devices: Piezoelectric fans use vibrating cantilevers instead of rotating fans to generate cooling flowing air. This method has higher preferences than conventional fans in positional accuracy, reliability, and flow direction, although limiting heat dissipation is its main obstacle.

4. Synthetic jet impingement: A pump with a controlled diaphragm is equipped to jet turbulent airflow to dissipate heat from the electric device. This method is restricted by a low heat dissipation capability, while high reliability, low energy consumption, and noise are its main benefits.

5. Electrohydrodynamic: By increasing the voltage difference between two electrodes with different thicknesses until the electric arc does not occur, the electric field around the anode electrode is enhanced. As a result, the gases around the anode are ionized, leading to the phenomenon of corona discharge. The collision of ions with neutral molecules causes the transfer of momentum and cooling of the power device. Silent operation, high cooling power density, and low energy consumption are the best options, although degradation of the electrodes, high operating voltage, and complex equipment are its main disadvantages.

6. Thermoacoustic: This property refers to producing sound waves and, consequently, pressure fluctuations from heat for a cooling mechanism. No moving parts, silent operation, and simplicity are the charms of this method, and the low capability to dissipate heat is its major restriction.

C) Liquid cooling technologies: The conductivity coefficient in liquids is significantly more than in air, and as a result, their cooling capacity is higher. Although air cooling causes additional weight and volume to be imposed on the system due to the fan and heat sink, the main challenges of liquids are leakage, corrosion, electrical conductivity, and flammability.

1. Cold plates: Cold plates are the main alternative to air cooling with heatsinks. In this method, a pump replaces the fan to circulate the liquid in a heat exchanger. Although it has more ability to dissipate heat, it increases weight and reduces reliability.

2. Microchannel: Microchannel is a much more efficient method than cold plates because they are more capable of dissipating heat from the power device with less volume and weight. Different types of fluids and even nanofluids are used in them, but their main challenge is high-pressure drop.

3. Electrowetting: Applying an electric field to the fluid causes its surface tension to change, and a droplet is sprayed on the power device. This spray can be applied directly on the part board (wetted surface) or at a distance from it (dry surface). The fluid must be dielectric, such as de-ionized water, liquid electrolytes, or ethanol. This method has a very high ability to absorb heat with low pump energy consumption.

4. Immersion: In this method, the whole power device is submerged in the dielectric coolant fluid through natural convection or forced with a pump. The coolant fluid can even reach the boiling point, which is called nucleate boiling. This method has a great ability to dissipate heat due to its high-power density and high efficiency. This method is mostly used in microelectronics.

5. Jet impingement: In this method, liquid jet spraying in the form of regular matrices on the electric board with a high flow rate as a free surface or immersed with a dielectric fluid that causes significant heat transfer. The arrangement and number of nozzles, spray flow velocity, and properties of the coolant fluid are among the most important factors that determine the amount of heat dissipated in this method.

D) Two-phase cooling technologies: Two-phase cooling methods can absorb considerable heat from the high latent heat capacity of phase change, also due to their low volume-to-weight ratio, they have a higher power density and efficiency than other methods, but their most important challenge is the selection of coolant fluid and complexity of their control and design.

1. Heat pipes: A heat pipe uses evaporative cooling to transfer thermal energy from one point to another. The operation is based on evaporation and condensation, relies on the temperature difference between the two ends of the pipe, and cannot reduce the temperature on both sides. The heated side of the heat pipe evaporates the coolant and increases the vapor pressure inside the heat pipe. The latent heat of vaporization absorbed by the fluid causes the temperature to drop on the tube's hot side. High thermal convection, isothermal operation, durability, and low costs are the most important strengths of the heat pipe, despite the control of the temperature range that depends on the material and fluid of the coolant since the liquid in hot temperature evaporates completely, and in low temperature there is no evaporation, to create a two-phase flow.

2. Spray: Spray cooling is defined as the passage of a high-pressure liquid through a nozzle and its atomization. Liquid droplets have a great ability to absorb heat and consume low power but choosing the right fluid that has the right chemical properties, dielectric constant, and adequate non-conduction thermal due to direct contact with the power device is its main challenge. The performance of this method depends on the number and arrangement of nozzles, flow rate, and many other parameters.

3. Phase change materials: Phase change materials (PCMs) store energy in the form of latent heat of fusion. PCM absorbs heat as part of a continuous cycle, which has high heat dissipation density and does not need a heat sink. High melting point, high volumetric storage density, uniform melting ability, stable chemical properties, high fusion temperature, and reliability are its strengths, but low thermal conductivity in the solid state is its main weakness.

4. Thermal management in batteries: The electricity produced in the battery is created during the electrochemical process, which is accompanied by heat generation. Therefore, the temperature of the battery increases and affects its performance. The ideal temperature for battery operation is between 15 and 35 degrees Celsius; providing this condition, along with creating a uniform temperature distribution in cells, is the responsibility of the battery thermal management system (BTMS). Temperatures below 15 degrees increase resistance and charge failure, and temperatures above 35 degrees intensify side reactions and cause thermal runway [11]. A conventional classification of BTMS is presented in Figure 1.

1. Active BTMS: Forced heat transfer of air or liquid coolant, as an active method, is the most common BTMS technology in EVs. Toyota and Lexus use a fan to circulate air over the battery cells, but Tesla and Audi use direct contact immersion with dielectric coolant. Indirect cooling technology causes the loss of an important part of the cooling power due to the conduction resistance in the pipe.

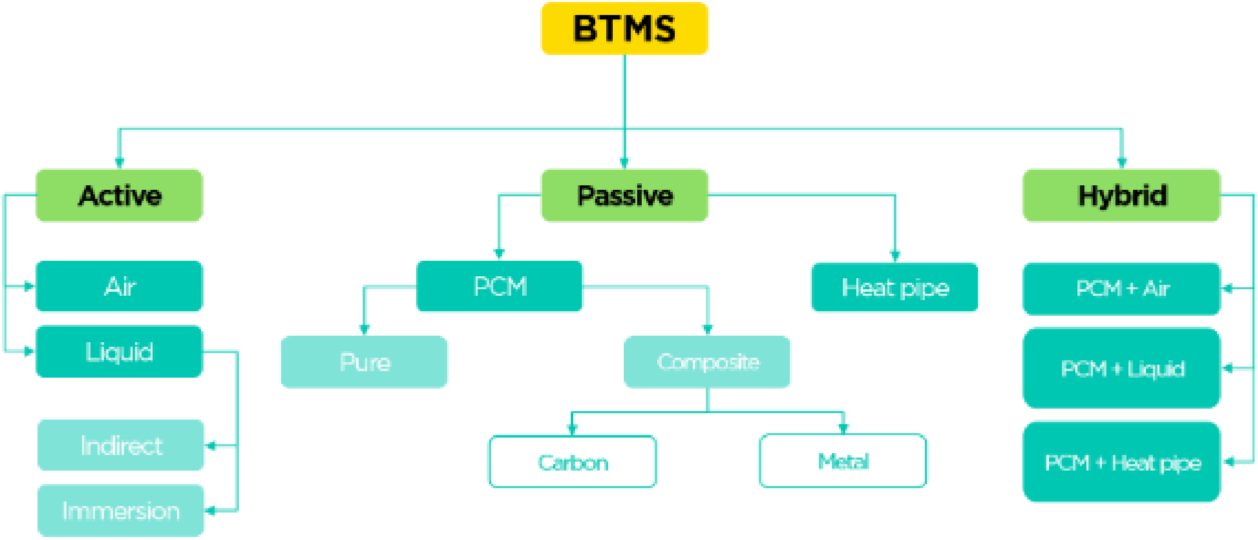

Figure 1. Classification of BTMS technologies

Table 2. The advantages and disadvantages of BTMS technologies

BTMS Technologies	Advantages	Disadvantages
Air	1-simple design, low cost and maintenance, 2-low volume occupation 3- compatible with different batteries	1-Low efficiency and heat transfer rate 2-high energy consumption 3- Non-uniform temperature distribution
Liquid	1-High efficiency and heat transfer rate 2- uniform temperature distribution	1- Leakage risk 2- high occupied volume 3- complexity 4- Short system lifespan
Thermoelectric System	1-Switching capability between cooling and heating mode 2-no coolant nor mechanical component 3- light-weighted	1-high cost 2-low conversion efficiency
PCM	1-Simple design 2-Light weight 3-low volume occupation 4- low maintenance 5-no power consumption	1-low thermal conductivity 2- continuous operation difficulty 3- Leakage risk 4- Risk of supercooling 5- Limited thermal storage capacity.
Heat pipe	1-High thermal conductivity 2- no power consumption 3-reliable 4- low maintenance 5-compact and light	1-low efficiency and capacity due to the limited contact area 2-High initial costs 3- Leakage risk
Hybrid BTMS	1-light weight 2-high cooling performance	1-complex structure 2-expensive

Immersion technology is at the cutting edge of science, and there is a long way to go in its development. Usually, a mixture of water and ethylene glycol, besides acetone and oil, is used as a dielectric fluid in this method. On the other hand, the design of the system using coolants that experience phase change conditions in the operating temperature range of the battery can enhance the heat transfer rate up to 10 times. Thermoelectric cooling (TEC) and thermoelectric generator (TEG) are the other approaches in active BTMS, which require electrical power to cool the battery. TEC application had been considered before when it could be integrated with TEG. TEG converts the lost heat from the battery to power TEC to improve heat absorption capability. They need no coolant fluid or moving components, which gives them high heat absorption density and low weight.

2. Passive BTMS: These methods are not very popular, but they have advantages that can cover the challenges of active technologies. Its most famous subcategories are phase change materials (PCMs) and heat pipes (HPs). PCM has two attractive features: one is to create a uniform temperature through the battery, and the other is to operate at the melting temperature, which causes suitable heat absorption. Paraffins, fatty acids, or hydrated salts are the most important materials that can work in the operating temperature range of batteries between 30-50 degrees Celsius. Low thermal conductivity is the most important challenge for the advancement of PCMs, which restricts heat transfer since researchers have been trying to solve it with different approaches, including porous structures combined with nanoparticles, fibers, and graphite. Heat pipes are an alternative option in the passive approach, whose main application is in PECs and electronic chips and not in BTMS. HPs are vacuum tubes consisting of three sections of an evaporator, an adiabatic fragment, and a condenser. HPs have a great ability to absorb heat, do not need external energy, are adaptable and flexible, and do not have maintenance costs, but their design is complex and expensive.

3. Hybrid BTMS: Hybrid methods are a combination of active and passive technologies that enhance strengths and eliminate weaknesses of them alone. In this approach, PCM is central to creating a uniform temperature distribution throughout the battery, while the integrated method could be air or liquid to improve the heat transfer rate or HPs to increase natural heat transfer. Although the results of this approach meet expectations, their main problem is the expensive design and their complexity. In short, the advantages and disadvantages of these technologies are mentioned in Table 2.

5. Conclusion

Effective thermal management is essential for ensuring the efficiency, reliability, and safety of electric and hybrid electric vehicles (EVs and HEVs). As these vehicles continue to evolve, advanced cooling strategies are required to address the heat dissipation challenges in key components, including electric traction motors, power electronic components (PECs), and batteries. Each of these systems generates significant heat during operation, which, if not properly controlled, can lead to performance degradation, reduced lifespan, and critical failures. Electric traction motors face thermal challenges due to copper and iron losses, which impact efficiency and durability. A range of cooling methods, from conventional air cooling to advanced liquid cooling techniques such as direct oil spray cooling and microchannel cooling, have been developed to enhance thermal regulation. Additionally, passive methods like phase change materials (PCMs) and heat pipes offer energy-efficient solutions without the need for additional power consumption. Similarly, power electronic components experience substantial heat generation due to electrical resistance and switching losses. Innovative cooling solutions, including solid-state methods like thermoelectric cooling, air-based convection techniques, and liquid immersion cooling, have significantly improved heat dissipation, increasing the efficiency and lifespan of PECs. Battery thermal management remains one of the most critical aspects of EV and HEV performance, as temperature fluctuations directly affect battery capacity, charging efficiency, and safety. Active cooling techniques such as liquid immersion and forced air circulation provide effective temperature regulation, while passive methods like PCMs and heat pipes contribute to improved heat distribution. Hybrid approaches, combining both active and passive cooling, have emerged as optimal solutions to maximize efficiency while minimizing energy consumption and design complexity. The continuous development of innovative thermal management technologies is crucial for advancing EV and HEV performance. Emerging trends, such as direct slot cooling, advanced two-phase cooling systems, and immersion-based cooling, are pushing the boundaries of heat dissipation efficiency. By integrating these advanced solutions, automakers can achieve higher energy efficiency, extend the operational lifespan of components, and enhance overall vehicle safety. As the demand for sustainable transportation grows, refining thermal management strategies will play a pivotal role in the future of electric mobility, ensuring that EVs and HEVs continue to provide a reliable and efficient alternative to internal combustion engine vehicles.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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