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Enhanced astronaut hygiene and mission efficiency: a novel approach to in-suit waste management and water recovery in spacewalks

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The current waste management system within the Extravehicular Mobility Unit (EMU) consists of a disposable diaper—the Maximum Absorbency Garment (MAG)—that collects urine and feces during extravehicular activities (EVAs) that last up to 8 h. Such exposure to waste for prolonged periods of time contributes to hygiene-related medical events, including urinary tract infections and gastrointestinal distress. Historically, prior to using the MAG, astronauts have limited their food intake or eaten a low-residue diet before embarking on physically demanding spacewalks, reducing their work performance index (WPI) and posing a health risk. Furthermore, the current 0.95 L In-suit Drink Bag (IDB) does not provide sufficient water for more frequent, longer-range spacewalks, which carry greater potential for contingency scenarios requiring extended time away from a vehicle. High transport costs per pound to space and resource scarcity exacerbate these challenges, underscoring the need for water-efficient waste management. This paper introduces a novel in-suit urine collection and filtration system developed in the Mason Lab at Weill Cornell Medical College that could address these hygiene and hydration concerns. The device would collect astronaut urine via an external catheter and filter it using forward and reverse osmosis (FO-RO) into potable water, creating a sustainable and hygienic circular water economy, enhancing astronaut wellbeing. This research aims to achieve an 85% urine collection rate using a modified MAG. The modified MAG will be made of a flexible compression material lined with antimicrobial fabric, and urine is collected through a silicone urine collection cup, which differs for male and female astronauts to conform to anatomy. Urine collection via a vacuum pump is triggered by a humidity sensor that detects the presence of urine in the cup. The FO-RO filtration system targets a minimum of 75% water recovery, while consuming less than 10% of EMU energy. To meet health standards, the filtrate maintains low salt levels (<250 ppm NaCl) and effectively removes major urine solutes (urea, uric acid, ammonia, calcium).

However, further research and testing are warranted to refine and implement these innovations for future space missions, contributing to the advancement of deep space exploration technologies and astronaut health and performance.

KEYWORDS

space medical capabilities, space, medical technical devices, technology, innovation

1 Need for the innovation

Since the launch of the International Space Station (ISS) in 1998, astronauts have conducted a total of 269 spacewalks—in which an astronaut exits their space vehicle to perform an extravehicular activity (EVA)—using the Apollo Extravehicular Mobility Unit (EMU). During 2021–2023, 37 spacewalks were conducted for either scientific experiments or repair of the space station, with an average duration of 6 h and 26 min[1], with the longest on record lying at 8 h and 56 min. During long-duration EVAs, management of urination and defecation must be considered. Astronauts are expected to have 7 urination and 2 defecation events per day, but the frequency varies during spacewalks[2].

On 1 November 2023, the Suit Waste Management requirements for new spacesuits, documented in NASA Spaceflight Human-System Standard Volume 2, section 11.1.5[3], were updated. Reflecting the revised increase in the Extravehicular Activity (EVA) hydration guideline of approximately 240 mL per hour, the EVA suits are now designed to accommodate a total urine volume (Vu) calculated by the formula $Vu = 0.5 + (2.24t/24)$ L, where "t" represents the duration of the EVA in hours[4]. Therefore a spacewalk of 8 h must have a system capable of collecting 1.246 L of voided urine. Therefore, no matter the length of the scheduled spacewalk, the suits are required to have the capacity to collect and contain up to 1 L of urine and 75 g in mass or 75 mL in volume of fecal matter per day for each crew member—a minimum, in the case of extended contingency operations in spacesuits exceeding 24 h.

Beyond total waste collection, the suite waste management system must comply with hygiene and comfort requirements. The management of voided urine is critical for crew safety and equipment integrity. The containment system for urine must ensure complete isolation within the suit's disposal hardware, essential to prevent any accidental leakage or discharge into the suit, which poses risks of skin irritation or mucous membrane damage for the astronaut. Additionally, such leakage could lead to malfunction or deterioration of the suit's systems, compromising both the safety and operational effectiveness of the suit during missions. Astronauts reported leakage from the MAG to such an extent that they found it impossible to distinguish between their own urine and sweat from the liquid cooling and ventilation garment (LCVG); this is undoubtedly an environment not conducive to optimal performance or the maintenance of health (Scheuring et al., 2008).

Currently, astronauts use the Maximum Absorbency Garment (MAG) to contain their bodily waste. The MAG is an adult diaper that incorporates sodium polyacrylate, a superabsorbent polymer, enabling the garment to absorb and retain approximately 300 times its weight in fluid (Gooch, 2010). The MAG has a capacity of 2 L of urine, blood, and/or feces, with the stated purpose of pulling moisture away from the skin to maintain astronaut comfort and hygiene.

Despite its ability to absorb waste within the requirements, the MAG's deleterious effect on astronaut health and comfort has been extensively documented. Astronauts often eat reduced meals or follow a low-residue diet for several days prior to the EVA in order to avoid using the MAG, which may reduce their performance during physically demanding spacewalks (Coyle, 2004). Previous crews have reported issues with odor that affects appetite, skin rashes necessitating immediate removal of the MAG after the EVA, discomfort due to the urine collection device, and failure of the fecal collection bag to adequately stick to the body. Medical risks include cross contamination with fecal matter, urinary tract infection, eye irritation, and gastrointestinal distress[5]. These risks are exacerbated by a lack of access to the same medical care that could be provided on. Lunar crew feedback also included improving the MAG's urine collection capabilities to function better in $1/6$ g, which extends to the lower gravity of low Earth orbit as well. The issues stemmed from poor fit, causing leaks and irritation (Scheuring et al., 2008).

Spacewalks are remarkably physically demanding, requiring high levels of muscular exertion and cardiovascular endurance, which causes astronauts to sweat profusely, increasing the probability of performance-impairing dehydration (Moore and Gast, 2010). Simply by existing in space, astronauts also place themselves in a state of dehydration—total body water drops by 2%–3% as microgravity shifts fluids towards the upper body causing increased urination. Dehydration even at this level in a non-exercising person is associated with decreased physical functioning (Murray, 2007). Astronauts are currently provided with 32 ounces of water, in addition to a small dose of glucose, for EVAs in the In-suit Drink Bag (IDB)[6]. They have stated that the current allotment of water is insufficient, and largely agree that a separate "non-caffeinated high-energy drink" should be added to the suit (Gernhardt et al., 2008). The IDB itself also presents significant

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[1] https://www.nasa.gov/international-space-station/space-station-spacewalks/

[2] https://www.nasa.gov/wp-content/uploads/2023/12/ochmo-tb-042-waste-management.pdf

[3] Available at https://standards.nasa.gov/standard/NASA/NASA-STD-3001-VOL-2

[4] https://standards.nasa.gov/standard/NASA/NASA-STD-3001-VOL-2

[5] https://www.nasa.gov/wp-content/uploads/2023/12/ochmo-tb-042-waste-management.pdf

[6] https://www.nasa.gov/history/alsj/alsj-DrinkFood.html

issues to astronauts embarking on EVAs. In the 2006 Apollo Summit, astronauts requested that the "time required to prepare [the IDB] prior to conducting an EVA be decreased," since "filling and degassing the drink bag used in the current [EMU] is time-consuming and contributes to a poor work efficiency index (WEI) of shuttle and ISS EVAs"[7]. Considering the upcoming Artemis missions, in which astronauts will return to the Moon, it is crucial to address the implications of and requirements for future lunar EVAs.

Average astronaut WEI is roughly 0.39–0.5, which NASA hopes to increase to roughly 3.0 by the next lunar Artemis mission, set to launch in late 2025 (Gernhardt et al., 2008). Increasing efficiency via improved astronaut hydration and hygiene could substantially further this goal. Crew members may be expected to perform up to 24 h of extravehicular activity per week, involving more physically demanding tasks in stronger gravity than they experience on the ISS, which may further increase water requirements. Contingency scenarios must also be taken into account. In a 10 km "walkback" simulation, modeling a case of rover failure, crew members drank 50%–100% of the 32 ounces of water provided and burned 944 kcal on average (Gernhardt et al., 2008). The situation demonstrated a need for an increase in both water and Calorie allotment, the latter of which should come in concert with waste management changes that reduce odor and contamination risk. Because total time from suit don to doff during an EVA can reach 10 h, Apollo crew members recommended additional water be allotted to account for this time (Scheuring et al., 2008).

Furthermore, the current shipping cost per kilogram to the low Earth orbit (LEO) was $2,720 as of 2018 on the SpaceX Falcon 9 rocket, with shipments to the Moon expected to be far more expensive. Though price per kilogram for LEO has been steadily decreasing, maintaining Earth-to-Moon supply chains at an increased cost will be unnecessarily expensive. Almost all human wastewater is recycled aboard the ISS by the urine processing assembly, significantly reducing water shipment costs, but it is completely discarded within spacesuits. Though the current limited number of spacewalks per year minimizes the impact of this water waste, the aforementioned lunar missions, with far greater spacewalk frequency, might also consider in-EMU water saving measures from a financial perspective. Any attempt to establish a presence on the Moon will require a significant resource expenditure, including of water, at a cost that makes any waste at all impactful. A urine collection and recycling system could reduce the initial supply of drinking water needed within the spacesuit, thus reducing water costs.

2 Description of the innovation

2.1 Theoretical foundation and similar technology

The system outlined here uses forward and reverse osmosis in series to remove contaminants from urine, filtering it to potable water. Forward osmosis (FO) is an energy-efficient method of water purification that relies on an osmotic gradient between a feed solution (FS; the liquid to be filtered; in this case, urine) and a draw solution (DS; often a concentrated salt solution) (Nagy, 2019). The salt gradient between the two drives water from the FS to cross a semipermeable membrane to the DS. Pure water can then be extracted via another process, such as reverse osmosis (RO), which is used in the proposed innovation, and frequently applied in industrial desalination to produce clean drinking water. In RO, an external pressure is applied to the solution, driving the water, now purified and called permeate, through a semipermeable membrane where it can be collected (Wenten and Khoiruddin, 2016a). While RO has a much higher water recovery rate when compared to FO, it is also much more energy-intensive. Thus, using FO as a "pre-filtration" stage before RO may provide a favorable mix of energy efficiency, as it dilutes the water that must be filtered by RO, and water recovery. RO is also more subject to membrane fouling—the deposition of particles onto the membrane surface, resulting in decreased filtration efficiency—because of the external pressure, so combining the two processes may prolong membrane lifespan (Nagy, 2019). Indeed, a study comparing integrated FO-RO to RO seawater desalination found that some key benefits of the hybrid system included reduced energy usage (see also Altaee et al., 2017; Woo et al., 2019), reduction in RO membrane fouling, and increased protection against solute leakage because two membranes were used instead of one (Blandin et al., 2016). FO-RO has become an increasingly popular alternative to RO alone because of these advantages in a variety of commercial applications.

The most relevant model system for this proposed innovation is the current water treatment system aboard the ISS. Over the past decade, NASA researchers have developed forward osmosis secondary treatment (FOST), a two-stage system using FO and RO in series, as a part of their new Alternative Water Processor (AWP) for the International Space Station (ISS). In FOST, impure water is filtered via an NaCl concentration gradient through an FO membrane, then extracted using RO. The system is compatible with microgravity (see also Hammoudeh et al., 2013), suggesting that a similar system would also be viable in spacesuits. FOST also averages 93% water recovery from ISS wastewater (including water from urine, hygiene, and laundry), peaking at 98% (Barta et al., 2015).

Despite the promise of an FO-RO based system, it faces some of the same challenges as RO alone, albeit to a lesser degree. For example, the FO membrane is still subject to fouling and contamination with organic contaminants, including alginates and humic acid, and inorganic contaminants including silica. Backwashing can prove an effective method for reducing membrane contamination, and was seen to work particularly well for alginates present on FO membranes (Kim et al., 2012). Backwashing for FO involves replacing the DS with deionized water, causing "backwards" osmotic movement from DS to FS. This has proven approximately 85% effective even in the face of caked particulate matter on the membrane surface (Kim et al., 2012). However, backwashing efficacy tends to decrease over time as solids accumulate in the membrane which are unable to be flushed back out of the membrane. Another strategy for reducing particle buildup is a preventative measure, using materials such as cellulose triacetate to construct the membrane, as this material tends to have suitable fouling reversibility (Kim et al., 2020). There are other proposed methods for mitigating fouling of FO membranes, including using

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[7] Available at https://humanresearchroadmap.nasa.gov/evidence/reports/EVA%20Injury%20Evidence%20Report%20FINAL_6-14-2023.pdf

FIGURE 1
Urine collection garment prototype, back (left) and front (right).

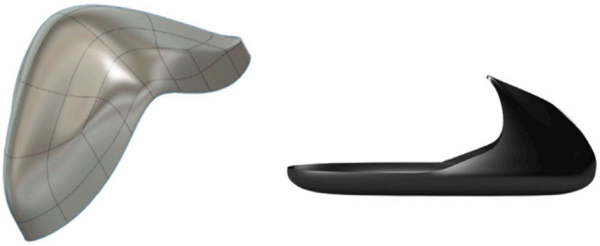

FIGURE 2
Urine collection cup CAD models (Left: male version, right: female version).

shear force and chemical cleaners (specifically for compounds such as silica), however backwashing is deemed the most efficient and effective method.

2.2 Proposed innovation system overview

2.2.1 Urine collection device (UCD)

The current MAG is a specially designed, highly absorbent adult diaper, able to contain up to 2 L of combined urine and feces (Barratt and Pool, 2008). To implement the proposed urine collection and filtration system, the MAG must be replaced with a device capable of collecting urine soon after it has been expelled from the body and containing feces in such a way that cross-contamination, a serious in-mission health risk, is prevented. The UCD will replace the MAG's absorbent, polyacrylate-coated fabric with several fabric layers designed to allow the passage of urine without posing a health risk to the astronaut via extended urine exposure. While the MAG can absorb several hundred times its weight in urine, the UCD should absorb as little as possible to maximize potable water recovery. One key feature of the UCD is a silicone "cup"—shaped and positioned differently for males and females—that surrounds the astronaut's genitalia, collecting urine. The inner face of the cup will be lined with a comfortable, moisture-wicking fabric such as polyester microfiber or a nylon-spandex blend. This will draw urine to the outer surface of the fabric, away from the body, where it can be removed via a vacuum pump connected to the outer surface of the cup. This inner layer also contains a small patch of highly absorbent hydrogel connected to a passive RFID tag. When the gel absorbs moisture, it will become conductive enough to transmit a signal to an RFID reader, activating the pump (Tajin et al., 2021). Given that small diaphragm pumps can transport between 0.1–2 L of water per minute, a typical void of 100–500 mL should be removed in a maximum of 5 min, limiting skin contact time. The urine will also pass through a layer of antimicrobial fabric before being removed by the pump, to reduce infectious disease risk and bacterial membrane fouling during filtration. The sizes, shapes, and positions of the cups will vary between male and female models, with the male cup being larger, more rounded, and placed higher on the body, similar to an athletic cup, and the female cup being smaller, having a lower profile, and being placed lower to match anatomical differences.

Initial prototyping for the UCD is currently underway; the latest version of the urine collection garment is shown in Figure 1 (below). It is made of a flexible fabric blend, allowing close contact of the urine collection cup with the skin (see Figure 2 below) while providing flexibility and comfort. The ideal material for the cup is molded silicone, allowing flexibility with body movement to prevent leakage but maintaining structural integrity. Thus far, initial fit testing for the garment alone has been conducted internally, and we have received institutional review board (IRB) approval to test the urine collection device in its entirety. Though the garment must be tested on a wider variety of body types and individuals, comfort has improved significantly already based on internal fit testing feedback.

2.2.2 Urine filtration system (UFS)

Collected urine will be removed to the UFS, where it enters the integrated FO-RO membrane filtration system. This two-step filtration apparatus uses a concentration gradient to remove the water from urine into a salt solution and a pump to separate pure water from salt. Compared to traditional water filtration with RO, it can operate for longer before cleaning and with less energy cost, both of which are crucial in a spacesuit with limited battery capacity. The FO-RO module is based on the work of Parodi et al. (2016) that will filter the urine and return it to the IDB as potable water. They filtered 52 kg of wastewater over the course of 7 min, much faster than the proposed innovation would need to filter urine. The current state-of-the-art forward osmosis membranes, manufactured by Aquaporin and tested several times in space, have a filtration rate of 6.6 L/h[8], meaning that a large volume urination event of 500 mL could be processed in less than 5 min. Because the spacesuit would need to filter much less water (NASA estimates a maximum of 3L per day over an average of six events)[9], the proposed technology would likely be able to produce a greater yield of potable water than 86.8% (Parodi et al., 2016).

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[8] https://www.sterlitech.com/media/productattach/a/q/aquaporin-hffo2-datasheet.pdf

[9] https://www.nasa.gov/wp-content/uploads/2023/12/ochmo-tb-042-waste-management.pdf

One of the major issues that arose in the forward osmosis work of Parodi et al. (2016), Ali et al. (2021), and others is filtration rate slowdown due to draw solution dilution and membrane fouling, the accumulation of layers of solutes on the membrane, which increases membrane resistance. Draw solution dilution occurs naturally during FO, as water is filtered across the membrane, decreasing the concentration gradient between feed and draw and therefore reducing filtration speed. However, in an integrated FO-RO filtration system, the draw solution is concentrated simultaneously as it is diluted by feed solution water, effectively maintaining its original concentration. Because of the speed with which Parodi et al. (2016) filtered wastewater, the proposed system would likely not face the same issues with membrane fouling, as less external pressure would need to be applied to carry out RO. However, the conditions under which Ali et al. (2021) measured flux decline and membrane fouling more closely resemble the filtration of astronaut urine. They filtered 2 L of urine in each of six 24-h cycles, replacing feed and draw solutions (resetting the osmotic gradient) but not membranes between cycles. Given that an astronaut is expected to produce at most just over 1 L (using NASA MAG urine capacity formula) urine during an average-duration (6.5-h) spacewalk, it would be pertinent to consider a 3D-printed feed "turbospacer," as they did, which would be layered between membrane layers (see Graphical Abstract and Table 1 in Ali et al., 2020). This innovation decreases membrane fouling by increasing turbulence and shear force across the membrane, effectively disrupting the deposition of physical contaminants on the membrane.

Following filtration, permeate will be pumped into the IDB via a one-way valve, preventing permeate backflow, where it will be available to drink. Since the permeate will be void of salts, it will be necessary to replenish salts within the IDB to provide astronauts with electrolytes. NASA recommendations indicate that astronauts should consume less than 3,500 mg of sodium per day and while astronaut diets tend to be high in sodium, it is still important to provide electrolytes to astronaut drinking water to maintain homeostasis, particularly during the strenuous exercise they undergo during EVAs (Smith and Rice, 2002). In fact, supplementing NaCl, among other electrolytes in water supplied to astronauts during spacewalks would also reduce urine output, better preserving the filtration system and further reducing hygiene-related health risks (Valentine, 2007). For a 10-h spacewalk, up to 1,000 mg of sodium should be added to the IDB (depending on the concentration of salt in the other foods consumed by an astronaut on the day of their spacewalk). To improve water palatability, salts would be best added in the form of a flavored electrolyte powder, which would also deliver other key electrolytes and potentially also carbohydrates, to address Apollo astronauts' desires for a "non-caffeinated, high-energy drink" (Scheuring et al., 2008).

The whole FO-RO apparatus is intended to be placed in a pouch that could be mounted on the back of the EMU. The device is expected to add roughly 8 kg to overall EMU weight, fitting in an area of 38 cm by 23 cm with a depth of 23 cm.[10] While EMU weight is certainly a concern for upcoming lunar missions, we believe that the increased comfort and resource efficiency provided by the system will more than make up for the slightly increased bulk.

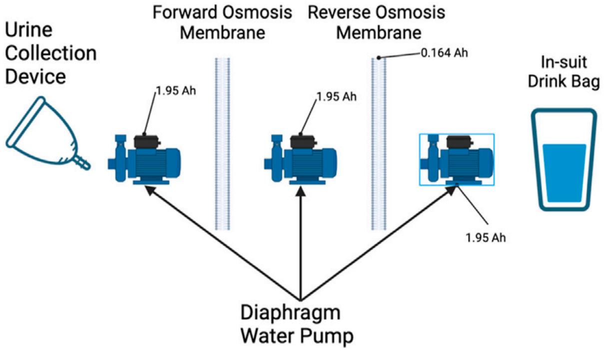

FIGURE 3
Estimated energy consumption for the proposed system.

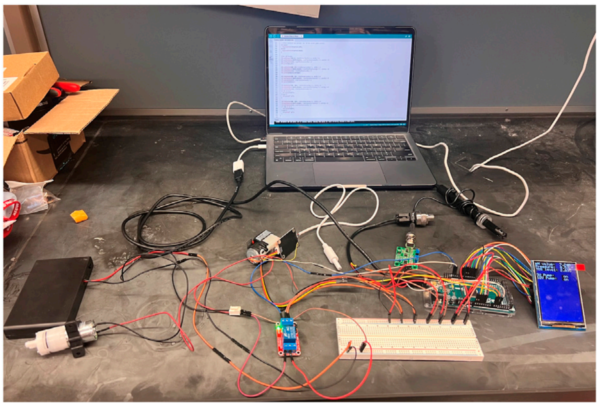

FIGURE 4
Current whole-system circuit draft.

2.2.3 System energy demand

System energy demand is driven primarily by the Urine Filtration System. Though up to 35% more energy-efficient than RO alone, a combined FO-RO filtration process still consumes considerable power, particularly relevant in the context of an energy-limited spacesuit (Chekli et al., 2016). FO-RO consumes roughly 2.5 kWh/m^3 in industrial settings, or 0.149 Ah/L, in terms more relevant for this application. Given the 1.1-L maximum expected urine output during a 6.5-h spacewalk, the UFS would consume up to 0.164 Ah during the duration. Recent reports describe the EMU battery as a five-unit module operating at 20.5 V with a total capacity of 40 Ah (Jeevarajan and Darcy, 2004). Figure 3 below details estimated power consumption of the proposed system.

Currently, electrical circuitry to operate the system is complete, and awaiting completion of other system components for testing. Circuits operate to control pumps,

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[10] Product information available at https://aquaporin.com/products/aquaporin-inside-hffo14/

sensors, an LCD display screen, and to synchronize disparate components of the system. The most recent circuit completed, which incorporates pumps for the urine collection device and FO-RO system, as well as an LCD screen and several sensors, is shown below in Figure 4.

3 Conclusion

With the upcoming Artemis missions, in which NASA plans to return to the Moon, a re-evaluation of the current EVA spacesuit is taking place. Both Axiom Space and Collins Aerospace are currently developing new spacesuits, with Axiom's AxEMU being specifically designed for lunar EVA activity, which is expected to take up 24 h per week of astronaut time during a lunar mission. One area of spacesuit development that has received little attention is hygiene and hydration systems. In light of this, the proposed technology seeks to address some key issues with the current Maximum Absorbency Garment and astronaut hydration status during EVAs. In response to difficulties astronauts have faced with personal hygiene and performance and work efficiency during EVAs, we designed a novel urine collection and filtration system for the next-generation of spacesuits. With an understanding of the space and battery capacity limitations of spacesuits, we argue that the trade-off for improved performance and sufficient water in case of a contingency scenario is well worth it.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SE: Writing–review and editing, Writing–original draft, Project administration, Investigation, Funding acquisition, Conceptualization. LB: Writing–review and editing, Writing–original draft. JR: Writing–review and editing, Writing–original draft. KM: Writing–review and editing, Investigation, Conceptualization. AB: Writing–review and editing, Investigation, Conceptualization. CW: Writing–review and editing, Writing–original draft. EM: Writing–review and editing, Writing–original draft. KP: Writing–review and editing, Writing–original draft. RL: Writing–review and editing, Writing–original draft. SR: Writing–review and editing, Writing–original draft. EL: Writing–review and editing, Writing–original draft. CM: Writing–review and editing, Project administration.

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Conflict of interest

Researchers working on the innovation are founding members of Fremen Space, Inc., a Cornell-based startup working on commercializing the described technology.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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