JBCD

The Journal of Basic and Clinical Dentistry

Review

The Use of CO_2 9.3 µm Lasers for Dental Space Care in Microgravity: A Hypothesis-Driven Narrative Review

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Citation: Nassani, L.M., Nassani, A.A., Alolabi, I., Nassani, M., Fernandes, G.V.O. The Use of CO_2 9.3µm Lasers for Dental Space Care in Microgravity: A Hypothesis-Driven Narrative Review. J Basic Clin Dent, 2026;3(2), 1-11.

Received: 9th June 2026

Revised: 14th July 2027

Accepted: 20th July 2026

Published: 24th July 2026

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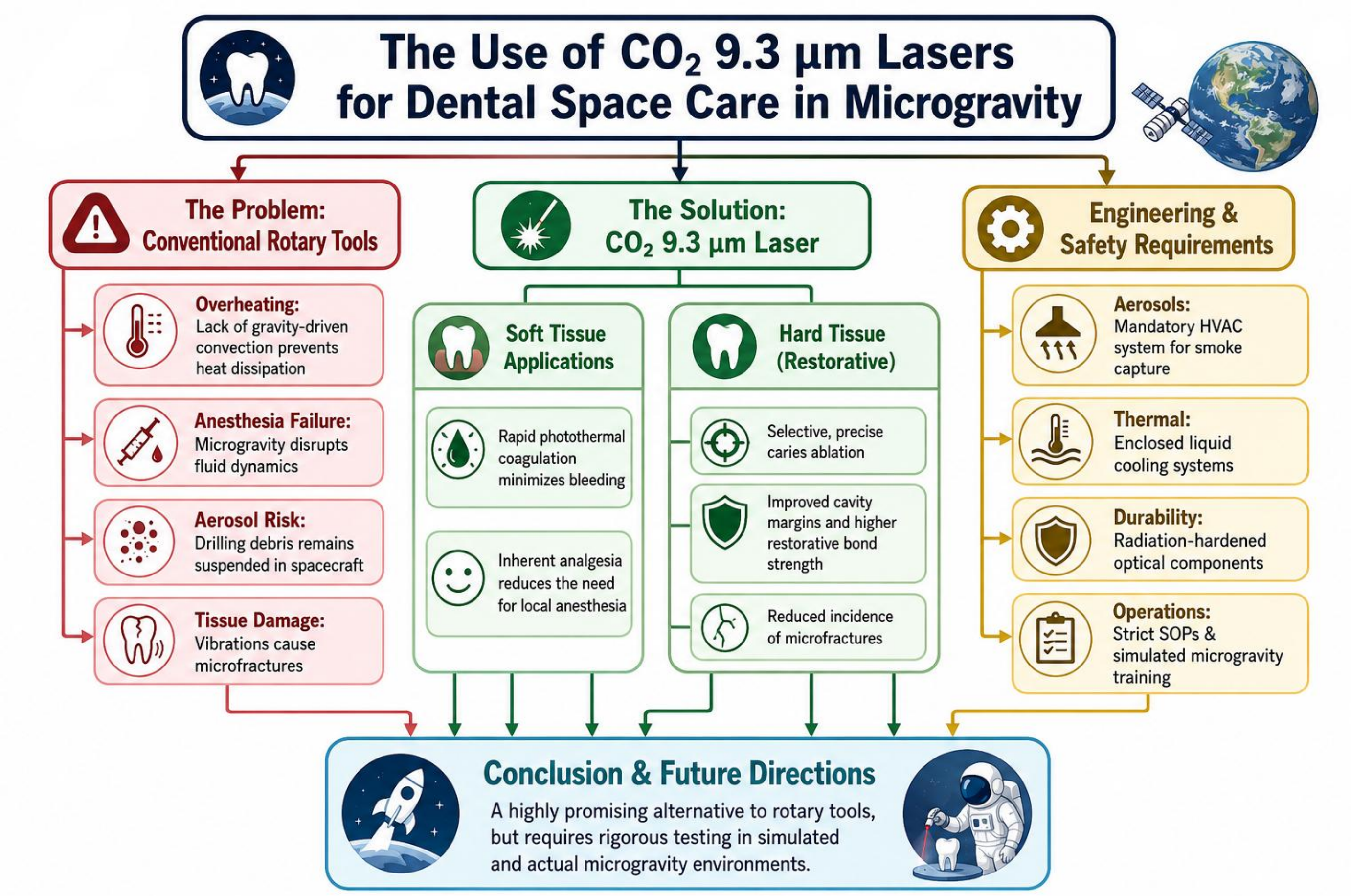
Abstract

Objective: CO_2 laser operating at 9.3 µm offers a non-contact, precise alternative for both soft and hard tissues, as well as restorative applications. This review aims to evaluate the clinical potential of integrating CO_2 9.3 µm laser technology into space dentistry, offering improved treatment outcomes and enhanced safety compared to conventional rotary tools. **Materials and Methods:** A literature search was conducted on PubMed, Google Scholar, and IEEE Xplore databases. The search terms included "CO_2 9.3 µm dental laser", "space dentistry", "microgravity dental care", "rotary instrument limitations microgravity", "soft tissue laser dentistry", "restorative laser dentistry", "local anesthetic challenges microgravity", "gate control theory laser analgesia", "laser cooling microgravity", "laser safety spacecraft", "quality control laser microgravity", and "standard operating procedures laser space." Data extracted included study design, dental application (soft tissue vs. restorative), key findings, and relevance to space dentistry, quality control, and standard operating procedures. **Results:** Twenty-two studies were enrolled; four focused on the limitations of conventional rotary instruments and the effectiveness of local anesthesia in microgravity. The CO_2 9.3 µm laser offered precise, low-trauma soft tissue procedures with minimal bleeding, reduced aerosol production, and a lower need for anesthesia, key advantages in the microgravity environment. For hard tissue applications, it enables selective caries removal with superior cavity margins, reduced microfractures, and improved restoration outcomes. **Conclusion:** The CO_2 9.3 µm laser shows substantial promise as a precise alternative to conventional rotary instruments for space dentistry. However, as current evidence is largely hypothesis-generating, rigorous testing in simulated and actual microgravity is necessary to confirm these benefits.

Clinical application: The use of CO2 9.3 µm lasers in space dentistry provides a precise, non-contact clinical alternative that enables low-trauma soft tissue procedures with minimal bleeding and a reduced need for anesthesia. Furthermore, for hard tissue applications, this laser technology facilitates selective caries removal with superior cavity margins, fewer microfractures, and significantly decreased aerosol production compared to conventional rotary instruments.

Keywords: Aerosol management; Laser; Microgravity; Soft tissue; Space dentistry

Graphical Abstract



1. Introduction

Long-duration space missions require robust, highly reliable medical systems to ensure crew health. Although astronauts are rigorously screened and cleared for dental needs in accordance with NASA STD 3001[1] and ESA ECSS Medical Requirements,[2] dental emergencies may still arise due to unexpected trauma or the progression of subclinical conditions. Traditional rotary dental instruments were optimized for Earth's gravitational environment. Consequently, their use in a microgravity environment presents significant physiological and mechanical challenges due to increased friction-induced heat, inefficient aerosol settling, erratic fluid dynamics that compromise local anesthetic delivery, and amplified mechanical vibrations.[3-5]

LASER (Light Amplification by Stimulated Emission of Radiation) dentistry has emerged as a promising alternative for space care.[6-8] Specifically, the CO_2 laser operating at 9.3 μm demonstrates optimal tissue interactions; its wavelength is strongly absorbed by water, collagen, and hydroxyapatite, allowing for precise tissue ablation with minimal collateral damage. Its photo-thermal mechanism induces rapid coagulation, reducing intraoperative bleeding and aerosol spread. Moreover, its inherent analgesic effects, consistent with the gate control theory of pain, often reduce or eliminate the need for local anesthesia, which is especially critical in microgravity where fluid distribution for injections is unpredictable.[9-13] On Earth, gravity supports convection-driven heat dissipation; in microgravity, however, this natural cooling is compromised, leading to dangerous temperature elevations that may damage dental tissues.[3,4]

However, there are still some considerations for adopting a laser instrument in a spacecraft environment, such as the International Space Station standard operating procedures (SOPs). In addition, every laser procedure requires a high-vacuum aspiration system (HVAC) to capture smoke and air-water spray, thereby minimizing aerosol spread in confined spacecraft environments such as the International Space Station (ISS).[11,14,15]

This narrative review aimed to (1) detail the limitations of conventional rotary dental instruments in microgravity; (2) synthesize evidence on the clinical benefits of CO_2 9.3 µm laser technology for soft tissue and restorative dental applications; (3) review engineering and safety considerations for operating high-powered lasers in space; and (4) develop the hypothesis that integrating CO_2 9.3 µm laser technology into space dentistry protocols may safely enhance treatment outcomes.

2. Materials and Methods

A narrative review framework was adopted to identify and synthesize the literature regarding dental care in microgravity and CO_2 9.3 µm laser applications. A literature search was conducted from January 2023 to December 2023 across PubMed, Google Scholar, and IEEE Xplore databases. The primary search strategy utilized combinations of the following terms: "CO_2 9.3 µm dental laser", "space dentistry", "microgravity dental care", "rotary instrument limitations microgravity", "soft tissue laser dentistry", "restorative laser dentistry", "local anesthetic challenges microgravity", "gate control theory laser analgesia", "laser cooling microgravity", "laser safety spacecraft", "quality control laser microgravity", and "SOP laser space."

Inclusion criteria were limited to peer-reviewed systematic reviews, narrative reviews, and engineering studies published in English from 1990 onward that evaluated the CO_2 9.3 µm laser or the physiological limitations of space dentistry. Publications discussing material compatibility, power consumption, failure modes/redundancy, human factors, and training for spaceborne medical devices were included. Studies not focused on dental applications, articles unavailable in full text, and those addressing exclusively terrestrial applications without implications for microgravity were excluded.

3. Results

3.1 Study Selection

The initial search retrieved 86 records. After duplicate removal (n = 51), titles and abstracts were screened. Full-text articles of 35 records were assessed for eligibility; 13 articles were excluded due to irrelevance or non-dental focus, leaving 22 studies that were included for qualitative synthesis. A flow diagram (Figure 1) documents the selection process. Data extracted included study design, dental application (soft tissue vs. restorative), key findings, and relevance to space dentistry, quality control, and SOP.

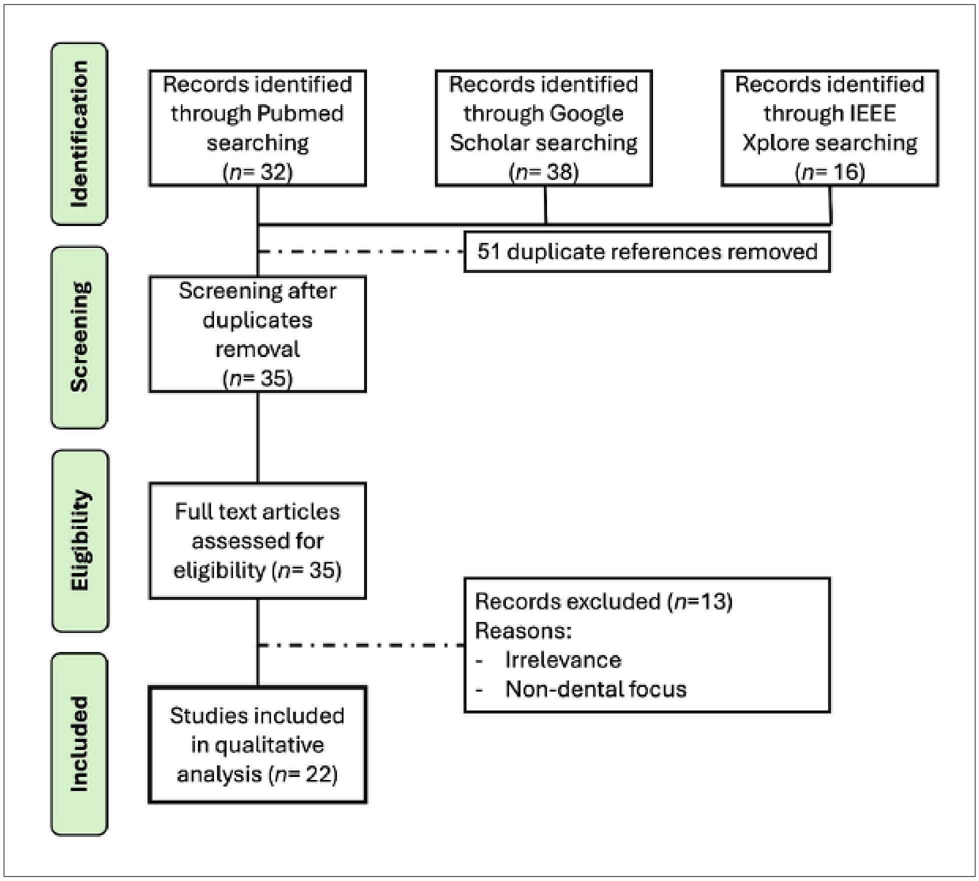


Figure 1. Flow diagram for study selection.

3.2 Limitations of Conventional Dentistry

Four included articles evaluated the mechanical and physiological limitations of conventional dental tools under simulated or theoretical microgravity conditions. Studies demonstrated that high-speed rotary drills generate significant friction-induced heat and produce suspended aerosols and debris;[3,4] in microgravity, these particles remain suspended, increasing the risk of cross-contamination and infection in the confined environment of a spacecraft.[2,4] Additionally, Wen et al. provided evidence that microgravity-induced fluid shifts adversely affect the reliable dispersion of injected therapeutics, analogous to local anesthetics.[5] It was also reported that mechanical vibrations from rotary instruments can induce microfractures in dental tissues.[4]

3.3 CO_2 9.3 µm Laser: Soft Tissue and Restorative Findings

Evidence from terrestrial clinical studies indicates that the CO_2 laser induces rapid photothermal coagulation in soft tissues.[9,11] Clinical evaluations reported markedly reduced intraoperative bleeding compared with conventional scalpel techniques.[11] Furthermore, studies noted that laser soft tissue procedures are associated with low mechanical trauma, reducing the reliance on local anesthetics.[9,13] Moreover, significant evidence-based changes within the oral cavity related to the space environment are changes in the salivary components and oral microbiology, which are in strict relation with soft and hard oral tissues.[29]

For hard tissue applications, in vitro studies demonstrated that the CO_2 9.3 µm laser enables selective ablation of decayed tissue. Chan and Fried[31] showed that the 9.3 µm wavelength successfully achieves selective caries removal with high precision. Furthermore, Anton y Otero et al.[30] and Rechmann et al.[32] observed that CO_2 9.3 µm laser-prepared cavities exhibit improved marginal adaptation and higher bond strengths for restorative materials compared to rotary bur preparations. Thermal studies indicated that while the laser generates high temperatures for vaporization, terrestrial water-mist cooling successfully limits temperature increases to less than 5 °C above baseline.[14]

3.4 Engineering and Safety Considerations

High-powered laser systems in space must meet stringent safety and engineering requirements. Radiation and optical safety are critical, as high-powered lasers emit intense infrared radiation that can pose ocular and dermal hazards. Protective measures, including specialized eyewear, beam enclosures, and interlock systems, are essential to mitigate these risks. Rigorous optical safety protocols significantly reduce exposure risks; these protocols must be adapted to comply with NASA STD 3001[1] and ESA ECSS Medical Requirements.[2]

Thermal management and cooling strategies are equally important. In microgravity, the absence of convection-driven cooling necessitates innovative thermal management solutions. Real-time thermal monitoring, integrated with automated shutdown protocols and enclosed cooling systems, ensures that both the device and adjacent tissues remain within safe temperature ranges. Cooling systems can effectively regulate temperatures in microgravity environments, and optimization of laser parameters is essential to mitigate thermal risks.[4,14,20]

Electromagnetic compatibility and system integration are also crucial. Laser systems must be designed to meet IEEE standards for electromagnetic compatibility, ensuring that their emissions do not interfere with spacecraft avionics. Rigorous EMC testing and appropriate shielding are necessary to safely integrate laser devices in the space environment.[20,21]

Quality control and SOPs are indispensable for reliable operation. Pre-flight calibration using traceable standards and validation under simulated microgravity conditions, in accordance with NASA STD 3001[1] and ESA ECSS Medical Requirements,[2] is required. Continuous in-flight monitoring through sensor-based systems enables early detection of performance deviations, while routine maintenance following ISO 13485 standards (adapted for space) ensures system integrity. Detailed SOPs covering pre-operation checklists, emergency shutdown procedures, and post-procedure decontamination are necessary, and comprehensive crew training in simulated microgravity environments is critical.[22,23]

Engineering challenges include material compatibility, power consumption, failure modes, redundancy, human factors, and training. Long-term exposure to space radiation and vacuum conditions can degrade laser components; Nicoletta and Eubanks demonstrated that optical materials degrade under space radiation, necessitating the use of radiation-hardened components.[18] Energy efficiency is critical, as spacecraft power systems are limited; Asrar et al. discussed strategies for optimizing energy consumption in spaceborne medical devices.[24] Robust failure mode analysis and redundancy strategies are vital to ensure continuous operation; Antonsen et al.

outlined mitigation strategies for spaceborne medical systems.[17] The design must also account for ergonomics to minimize operator fatigue and error in confined spacecraft, as emphasized by Mancl and Andrews.[19] Finally, specialized training programs for onboard dental operations are essential; Messerschmid et al. highlighted the need for dedicated training for crew members responsible for medical procedures in space.[25]

A summary table was constructed: one for soft tissue applications and one for restorative applications (Table 1).

Table 1. Key findings of applications

Study (Author, Year)	**Study Design & Level of Evidence**	**Sample Size**	**Application**	**Key Findings**	**Major Limitations**
Ghasemi et al., 2021 [11]	Narrative Review (Level V)	N/A	Soft Tissue Surgery / Space Dentistry	Precise soft tissue cutting with immediate coagulation; minimal bleeding and reduced aerosol spread.	Theoretical application; lacks clinical trials in actual microgravity.
Thamboo et al., 2020 [16]	Systematic Review (Level I)	N/A	Aerosol Management	Substantially reduced aerosol production when surgical lasers are paired with high-vacuum aspiration.	Focuses on terrestrial COVID-19 protocols; not specific to spacecraft HVAC systems.
Coluzzi & Parker, 2017 [15]	Textbook / Expert Opinion (Level V)	N/A	Various Soft Tissue Procedures	Lower tissue trauma, reduced intraoperative bleeding, and enhanced postoperative healing compared to scalpels.	Broad terrestrial overview; does not account for altered fluid dynamics in space.
Chan & Fried, 2018 [30]	*In Vitro* Experimental (Level V)	Extracted teeth	Decay Removal / Cavity Prep	Selective ablation of dental caries using CO_2 9.3-µm laser with high precision and minimal thermal spread.	Terrestrial lab conditions; lacks *in vivo* fluid and thermal dynamics.
Rechmann et al., 2017 [31]	*In Vitro* Experimental (Level V)	Extracted teeth	Restorative Procedures	Higher bond strength and improved adhesion of restorative materials	Does not simulate microgravity-induced microfractures or vibration limits.

				compared to rotary drills.	
Anton y Otero et al., 2021 [29]	*In Vitro* Experimental (Level V)	Extracted teeth	Enamel Surface Modification	Improved marginal adaptation in enamel and dentin for mixed cavity preparations compared to bur preps.	Does not account for convective heat dissipation limits in a vacuum/space environment.
Sasaki et al., 2002 [27]	*In Vitro* SEM Analysis (Level V)	Bone/Tissue samples	Hard Tissue Ablation	Reduced incidence of microfractures and better preservation of healthy tissue during ablation.	Older study; primarily focused on comparing Er:YAG and general CO_2 lasers on bone.
Fujiyama et al., 2008 [9]	Clinical Trial (Level II)	60 patients	Restorative / Patient Comfort	Non-contact ablation significantly decreases pain and vibrations, reducing the need for local anesthesia.	Focuses heavily on orthodontics; terrestrial gravitational fluid distribution for the control group.

N/A – not applicable; CO_2 - Carbon dioxide; Er:YAG - Erbium-doped Yttrium Aluminium Garnet; COVID-19 - Coronavirus disease 2019; HVAC - Heating, Ventilation, and Air Conditioning.

4. Discussion

4.1 Addressing microgravity challenges with laser technology

The findings of this review suggest that the CO_2 9.3 μm laser uniquely addresses the core limitations of conventional rotary instruments in space. On Earth, gravity helps dissipate friction-induced heat from rotary drills via natural convection.[4] The absence of gravity-driven convection in space results in inefficient heat dissipation, which can lead to dangerous temperature elevations and irreversible damage to the dental pulp.[3,4,10] Because the CO_2 laser relies on photothermal ablation rather than mechanical friction, it alters the thermal dynamics of the procedure. However, because natural convective cooling is lost, engineers must adapt terrestrial water-mist cooling protocols into enclosed fluid delivery systems or counter-cooling techniques to maintain safe baseline temperatures in microgravity.[14,20]

Furthermore, effective local anesthesia relies on predictable fluid dynamics. Microgravity disrupts these dynamics, causing erratic dispersion of anesthetic agents and compromising pain control during conventional drilling.[5] The inherent analgesic properties of the CO_2 laser, which activate non-noxious neural pathways, frequently reduce or eliminate the need for local anesthesia, presenting a highly advantageous workaround for unpredictable fluid shifts in astronauts.[13]

Aerosol management is another critical safety factor. Rotary drills produce aerosols that remain indefinitely suspended in weightlessness, severely increasing cross-contamination risks.[10] The laser's photothermal action produces minimal mechanical debris, and when paired with a mandatory high-vacuum aspiration system (HVAC), it actively captures smoke and limits aerosol spread within the confined ISS environment.[14,16]

4.2 Restorative Benefits and System Integration

The precision of the 9.3 μm wavelength allows for the selective removal of caries while minimizing microfractures in healthy enamel and dentin.[6,8] This precision, combined with improved restorative bond strength,[7,8] is critical for long-term restorative success during isolated space missions. However, translating these terrestrial benefits into space requires rigorous system integration. Standard optical materials degrade under space radiation, meaning any spaceborne laser must utilize radiation-hardened optics.[18] Devices must also be engineered for electromagnetic compatibility, optimal power consumption, and ergonomic usability in confined spaces.[17,19,24] Implementing detailed SOPs, emergency shutdown protocols, and robust crew training programs in simulated microgravity are indispensable for operational safety.[25]

4.3 Limitations of the Review

A primary limitation of this narrative review is the reliance on terrestrial and simulated evidence, as no clinical dental laser trials have been conducted in actual microgravity. Consequently, the proposed benefits of the CO_2 9.3 μm laser remain a promising hypothesis rather than a definitive clinical reality. Furthermore, the inclusion criteria were broad to capture the limited aerospace dentistry literature available, which resulted in varying levels of evidence ranging from in vitro laser studies to narrative aerospace reviews. Future tables should formally incorporate study design, sample size, and level of evidence to better stratify these findings.

5. Conclusion

Current evidence supports the hypothesis that CO_2 9.3 μm laser technology presents a highly promising alternative to conventional rotary dental instruments for microgravity applications. Its precise tissue ablation, inherent hemostasis, reduced reliance on local anesthesia, and minimal aerosol production directly address the critical challenges of space dentistry. While effective cooling and system integration remain significant engineering challenges, they can likely be mitigated through enclosed delivery systems, radiation-hardened components, and strict SOPs. Moving forward, rigorous laboratory experiments using parabolic flights, space analog facilities, and in vivo clinical trials in microgravity are essential to validate this hypothesis and confirm the technology's superiority and safety in space.

Abbreviation	Full Form
N/A	not applicable
CO_2	Carbon dioxide
HVAC	Heating, Ventilation, and Air Conditioning
Er:YAG	Erbium-doped Yttrium Aluminium Garnet
COVID-19	Coronavirus disease 2019
SOPs	Standard Operating Procedures
ISS	International Space Station
ESA	European Space Agency
ECSS	European Cooperation for Space Standardization
NASA STD	NASA Technical Standard
LASER	Light Amplification by Stimulated Emission of Radiation
ISO	International Organization for Standardization
EMC	Electromagnetic Compatibility

Declarations:

Supplementary Materials: Not applicable.

Author Contributions: Conceptualization: LMN, AAN, IA, MN, GVOF; Methodology: LMN, GVOF; Software: LMN; Validation: LMN, GVOF; Formal analysis: LMN, AAN, IA, MN, GVOF; Investigation: LMN, AAN, IA, MN, GVOF; Resources: LMN, GVOF; Data curation: LMN, MN, GVOF; Writing-original draft preparation: LMN, AAN, IA, MN, GVOF; Writing-review and editing: LMN, AAN, IA, MN, GVOF; Visualization: LMN, AAN, IA, MN, GVOF; Supervision: LMN, GVOF; Project administration: LMN, GVOF; funding acquisition, ø. All authors have read and agreed to the published version of the manuscript.

Funding: This review received no external funding

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

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