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The Eye in Space: Optometry's Role in Managing Vision Challenges in Microgravity

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ABSTRACT

Background: Spaceflight-Associated Neuro-Ocular Syndrome (SANS) is a major health threat to astronauts experiencing long-duration spaceflight. SANS is characterized by optic disc edema, globe flattening, choroidal folds, hyperopic shifts, and increased retinal thickness. These changes are primarily caused by cephalad fluid shifts and altered intracranial pressure (ICP), all of which have implications for visual function, mission safety, and long-term ocular health.

Purpose: This paper reviews the literature related to the cause, diagnosis, treatment, and optometric consequences of SANS and discusses the essential role of optometry in the eye care of astronauts, as well as possible translational applications for eye problems on Earth.

Methods: A systematic narrative review was conducted using the databases PubMed, Scopus, Web of Science, and Google Scholar over the period of 2010–2025. Studies focused on ocular changes in astronauts, imaging modalities (OCT, MRI, ultrasonography), and countermeasures. Results were categorized into diagnostic modalities, pathophysiology, interventions, visual performance, and optometric implications.

Results: Approximately 60–69% of long-duration astronauts exhibited visual changes compared to 29% for shorter missions. Similar studies failed to replicate the same direction of the SANS condition, although modeling found evidence of orbital fat edema and the risk of structural vulnerability to increased intracranial pressure or IOP. Diagnostic methods are noninvasive, thus potentially improving utilization in space. Diagnostic methods such as OCT, ultrasonography, fundus photography, and AI-facilitated algorithms likely have more sensitivity than traditional methods. Countermeasures such as artificial gravity, lower body negative pressure, and fluid-shifting garments partially mitigated the incidence of SANS. Functional performance included decreased contrast sensitivity, loss of stereoacuity, and transient refractive shift.

Conclusion: SANS is a multifaceted syndrome that encompasses intracranial pressure, fluid mechanisms, vascular and glymphatic drainage, anatomical considerations, and environmental stressors. Optometry plays a critical role in diagnosing, monitoring, and rehabilitation and can impart translational information related to disorders such as idiopathic intracranial hypertension and glaucoma.

1. Introduction

Spaceflight-Associated Neuro-Ocular Syndrome (SANS) is increasingly becoming recognized as a major health concern for astronauts traveling on long-duration missions and describes changes in the physiologic, anatomic, and functional status of the eye and visual system (Meer *et al.*, 2025). Non-invasive methods such as optical coherence tomography (OCT), ultrasonography, and fundus imaging are becoming vital for the detection and monitoring of SANS in microgravity (Mehare *et al.*, 2024). Recent research has shown that approximately 60–69% of astronauts presented with ocular and refractive changes consistent with SANS after long-duration spaceflights (greater than one month), compared to about 29% on shorter missions (Soares *et al.*, 2024). Optic disc edema (ODE), choroidal folds, globe flattening, hyperopic refractive shift, and increased peripapillary retinal thickness are common observations seen in posterior segment imaging (Gracheva *et al.*, 2023). Pathophysiological theories for SANS include cephalad fluid shifts in microgravity, changes in intracranial pressure (ICP), hypercapnia, vascular changes, cerebrospinal fluid compartmentalization, and anatomical risk factors (Martin *et al.*, 2020). A new biomechanical theory suggests that swelling of orbital fat may have a greater effect compared to a slight increase in ICP (Taniguchi-Shinojima, 2022). Clinical case studies, including one involving a female astronaut with two risk factors (small optic cup and one carbon genetic variation), reported severe ocular changes, marked hyperopic shift, and increased retinal thickness (Brunstetter *et al.*, 2024).

Recent technology advances will allow for earlier detection: machine learning models such as the SANS-CNN platform were developed to predict SANS from astronaut OCT photos with high predictability (~84.2%), with good sensitivity and specificity (Kamran *et al.*, 2024). Plans for artificial intelligence frameworks would allow for image-based detection, interpretation of clinical imaging, and contribution to studies of the pathophysiology of SANS (Ong *et al.*, 2023). Groundbreaking imaging technologies such as enhanced depth imaging-OCT (EDI-OCT), OCT2, OCT angiography, and ultrasonography will be studied for the ability to detect microstructural ocular changes with improved resolution (Vandana, 2025). There has been an increased interest in the evaluation of the anterior segment, such as changes in the cornea and lens, monitoring of intraocular pressure, and risk of developing dry eye or cataracts as a result of radiation and microgravity (Ong *et al.*, 2025). NASA recognizes SANS as a significant health risk in space flight. Approximately 70% of ISS astronauts display sub-retinal fluid or structural changes (Ong *et al.*, 2023). Studies conducted on land-derived analogies, such as head-down tilts, have duplicated multiple changes in the posterior segment and support the validity of using land-based models to study SANS (Laurie *et al.*, 2021).

This data supports that eye alterations in space result from not only mechanical factors but also the interaction of various environmental stressors. For instance, Figure 1 illustrates that the factors of microgravity, radiation, and cosmic dust will induce systemic biological responses (e.g., oxidative stress, immune dysregulation, and fluid redistribution) that lead to ocular complications (e.g., corneal abrasions, infections, and vision changes) (Shah *et al.*, 2025). This holistic approach explains why both in-flight and terrestrial analog studies reliably reproduce the complex range of adaptations associated with SANS.

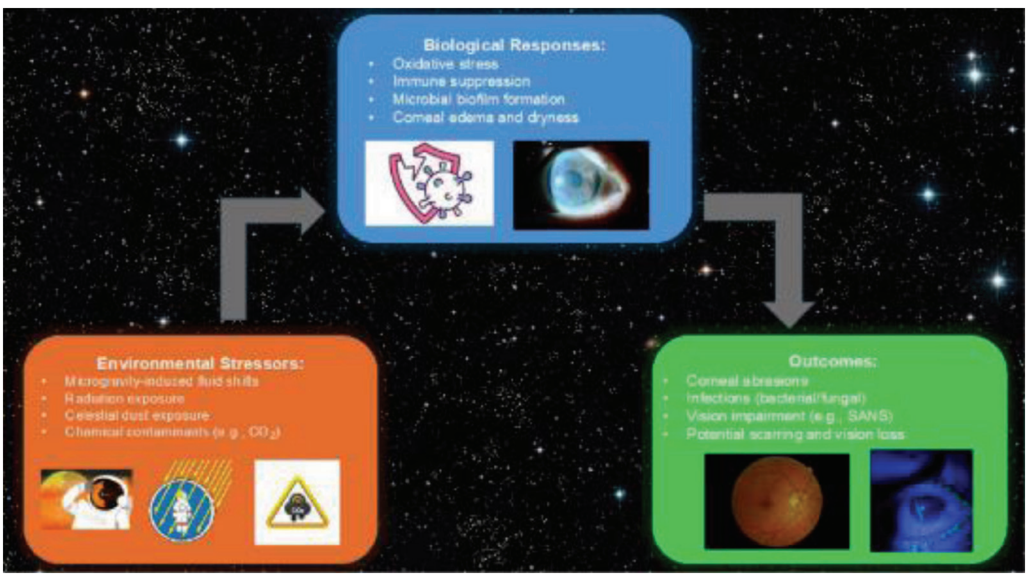

Figure 1: Environmental Stressors in Spaceflight and Ocular Outcomes

1.1. Diagnostic Modalities and Imaging Technology

Newer analog studies utilizing strict 6° head-down tilt bed rest (HDT-BR), with or without artificial gravity (AG), have demonstrated that HDT-BR causes increased peripapillary total retinal thickness (TRT), increased thickness of the retinal nerve fiber layer (RNFL), changes in choroidal thickness, and posterior globe flattening, while the effects of these changes are partially reversed or reduced with AG (Sater *et al.*, 2022). Along similar lines, MRIs performed before and after 60-day bed-rest investigations have shown that the posterior globe gradually flattens, but daily centrifugation countermeasures will reduce the extent of globe deformation (Reilly *et al.*, 2023). Furthermore, finite element modeling shows that swelling of orbital fat creates anteriorly directed mechanical stresses that could explain the amount of globe deformation associated with SANS, routinely higher than the deformations caused by moderate elevations in intracranial pressure (ICP) (Lee *et al.*, 2018).

1.2. Pathophysiology and Risk Factors

The orbital fat edema model highlights the importance of anatomical vulnerability, such as orbital shape, globe size, and optic disc size, in determining one's risk for SANS (Meer *et al.*, 2023). Headward fluid shifts continue to be a primary theory, supported by similar studies that describe brain fluid redistribution, changes in venous drainage, and changes in capillary pressures as related mechanisms (Sater *et al.*, 2022).

1.3. Establishing Countermeasures

Artificial gravity countermeasures (short-arm centrifugation), continuous and intermittent, have shown partial effectiveness to decrease retinal thickening and globe flattening during HDT-BR; again, optic disc edema and chorioretinal folds were measured in some subjects (Petersen *et al.*, 2019). NASA has also conducted preliminary research on additional countermeasures using alternate means, such as fluid-shift restraining garments and lower body negative pressure (LBNP) suits, which may be capable of addressing cephalad fluid shifts (Macias *et al.*, 2020).

1.4. Visual Effectiveness and Functional Implications

The main emphasis of SANS is on functional vision. Research suggests that astronauts may experience reduced contrast sensitivity, disturbances in stereoacuity, and alterations in peripheral vision in microgravity (Roberts *et al.*, 2015). These changes may put high-precision tasks, such as controlling navigation, robotic tasks, and docking, directly at risk for mission effectiveness and safety.

1.5. Continuing Concerns Related to Eye Health

Analyses after flight suggest that some astronauts display transient refractive shifts, optic disc abnormalities, and minor retinal changes (Lee *et al.*, 2019). These may increase the risk of eye disease and ocular morbidity, including accelerated cataract formation and glaucoma-like optic nerve dysfunction (Marshall-Goebel *et al.*, 2021). Therefore, SANS is recognized as a new potential occupational eye disease entity in space medicine.

1.6. Implications for Optometry and Vision Science

Studying SANS has broader implications outside of aerospace medicine, bringing valuable implications for optometry and vision science. An ocular change caused by microgravity can be a similar model for understanding eye diseases on Earth, like idiopathic intracranial hypertension (IIH), papilledema, glaucoma, and progressive myopia (Marshall-Goebel *et al.*, 2021). Optometrists are a key component of this area when involved in ocular imaging modalities, screening astronauts for risk factors, and developing vision-based countermeasures such as adaptive optics, prism corrections, and filtration for both in-flight and post-flight rehabilitation (Marshall-Goebel *et al.*, 2021).

2. Methodology

2.1. Study Design

The study presented in this document is a narrative review using a structured method, which centers on contemporary knowledge of Spaceflight-Associated Neuro-Ocular Syndrome (SANS), diagnostic imaging, pathophysiological mechanisms, and countermeasures from an optometry perspective.

2.2. Search Strategy

A comprehensive literature search using PubMed, Scopus, Web of Science, and Google Scholar was performed to identify peer-reviewed articles published between 2015 and 2025. Included in the search were keywords and MeSH terms: "Spaceflight-Associated Neuro-Ocular Syndrome," "SANS," "microgravity and eye," "space medicine optometry," "ocular imaging in astronauts," "intracranial pressure and vision," "artificial gravity countermeasures," and "optometry in space." Boolean operators (AND, OR) were also used in the search process. The process of selection for studies included in this review is presented in Figure 2, which illustrates the four stages (identification, screening, eligibility, and inclusion) of the PRISMA process**.**

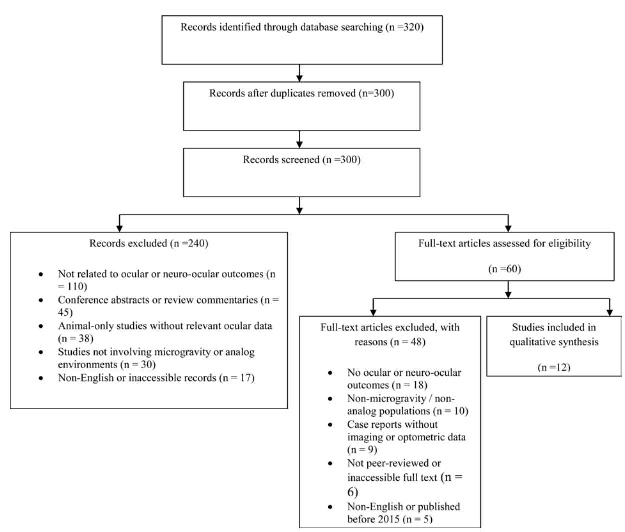

Figure 2: PRISMA flow diagram showing the process of identification, screening, eligibility, and inclusion of studies.

2.3. Inclusion Criteria and Exclusion Criteria

The criteria applied for selecting and excluding studies are outlined in Table 1 below.

Table 1: Inclusion and Exclusion Criteria Considered in the Study

Criteria Type	Description
Inclusion Criteria	Studies reporting ocular or neuro-ocular changes in astronauts or in Earth-based analog models such as head-down tilt bed rest. Studies investigating imaging modalities related to optometry, including optical coherence tomography (OCT), ultrasonography, fundus photography, and visual function assessments. Studies examining countermeasures or the clinical implications of Spaceflight-Associated Neuro-Ocular Syndrome (SANS). Publications containing original research, peer-reviewed clinical trials, findings, systematic reviews, or consensus statements that met the eligibility criteria.
Exclusion Criteria	Articles not published in English. Case reports not related to imaging or optometry. Studies published in 2015 or earlier, except for seminal or historically important works. Non-credible or non-research sources such as blogs, editorials, and opinion pieces not based on empirical data.

2.4. Data Extraction and Synthesis

The data obtained contained information on the study design, including, but not limited to, clinical, experimental, review, and analog models. Data regarding target populations, including astronauts, head-down bed rest subjects, and animal models, was also included. The imaging techniques used in the studies, including optical coherence tomography (OCT), magnetic resonance imaging (MRI), fundus photography, and ultrasound, were all documented. Noteworthy outcomes included the pathophysiological findings of optic disc edema, globe flattening, choroidal folds, refractive changes, and anterior segment findings. Pathophysiological risk factors included increased intracranial pressure, fluid tracts upward, orbital fat edema, and genetic predisposition. Documented countermeasures included artificial gravity, lower body negative pressure (LBNP), fluid-shifting clothing, and artificial intelligence (AI)-based diagnostic devices. The data were qualitatively summarized and organized into five broad themes: (1) Diagnostic modalities, (2) Pathophysiology, (3) Countermeasures, (4) Visual performance, and (5) The role of optometric medicine. The summary included optometry-related implications within screening, monitoring, and rehabilitation. After completing the screening process, data were extracted from all eligible studies and organized by imaging modality, study design, and outcome measure. A descriptive synthesis was used to isolate key themes related to ocular structural changes and fluid dynamics, as well as any countermeasures. Due to the heterogeneity of study designs and outcome reporting, a quantitative meta-analysis was not able to be performed. Each included study was critically assessed for methodological quality and relevance to optometric assessment of SANS.

Even if original research was preferred, we included appropriate review publications that synthesized data from studies with astronauts or analogs, which would otherwise not have been included.

3. Results

The literature reviewed indicates that the syndrome known as spaceflight-associated neuro-ocular syndrome (SANS) represents a serious risk to astronauts on long-duration space missions. Findings suggest that 60–69% of astronauts develop ocular and refractive changes on long-duration missions compared to around 29% of astronauts on shorter-duration flights. The most frequent ocular and refractive changes include optic disc edema, globe flattening, choroidal folds, hyperopic shifts in refractive error, and increased retinal thickness near the optic disc. Research using 6° head-down tilt bed rest on Earth correctly recreated these eye-related changes: thickened retina, flattened posterior globe, and changes to choroidal volume and distribution. MRI studies confirmed the utility of daily centrifugation to partially reverse these changes. Finite element modeling and ideas of orbital fat swelling suggest that mechanical loads and anatomical susceptibility resulted in deformation of the globe that exceeds small increases in intracranial pressure. Screening modalities that are non-invasive, including optical coherence tomography (OCT), ultrasonography, fundus photography, and MRI, are important to establishing a SANS diagnosis and monitoring. Innovations, including OCT angiography and increased depth imaging, as well as machine learning systems like SANS-CNN, show substantial promise and have demonstrated forecasted accuracies greater than 80%.

According to research on countermeasures, artificial gravity, lower body negative pressure (LBNP), and fluid-shifting clothing helped partially mitigate ocular effects. Daily or overnight LBNP use reduced choroidal engorgement and optic disc changes with minimal adverse events. Table 2 summarizes the primary studies that evaluated causes, risk factors, and countermeasures related to SANS. SANS functional impacts were identified, including reduced contrast sensitivity, stereoacuity changes, and peripheral vision changes. Post-flight, there were temporary refractive changes, optic disc changes, and possible risk for chronic ocular conditions such as cataracts and glaucoma-like optic neuropathies. The results support that SANS is multifactorial and includes cephalad fluid shifts, changes in intracranial pressure, vascular changes, orbital anatomy, and environmental stress.

Table 2: Summary of Key Studies Investigating Mechanisms, Risk Factors, and Countermeasures for Spaceflight-Associated Neuro-Ocular Syndrome (SANS)

Title	Author Details	Purpose	Result	Conclusion
Understanding the relationship between intracranial pressure and spaceflight-associated neuro-ocular syndrome (SANS): a systematic review	Rodrigues *et al.*, 2025	To complete a systematic review of the processes linking intracranial pressure (ICP) and cerebrospinal fluid (CSF) dynamics to SANS development	Reviewed 20 studies; two main theories found: (1) mild ICP elevation from CSF shifts; (2) CSF compartmentalization/ optic nerve sheath pressure independent of ICP. Environmental factors (radiation, CO_2, exercise) also relevant	ICP variation alone does not explain SANS. Likely a multifactorial syndrome involving ICP, CSF compartmentalization, venous/glymphatic systems, and spaceflight stressors
Self-Generated Lower Body Negative Pressure Exercise, a Low-Power Countermeasure for Deep-Space Missions	Velichala *et al.*, 2024	To test a self-generated LBNP device as an alternative countermeasure for fluid shift	Feasible low-resource countermeasure; reduces IJV CSA (right) but slightly less effective than traditional LBNP. More study required before operational use	SELF-LBNP is feasible and produces similar physiological responses to traditional LBNP, though slightly less effective on the left IJV. Device needs optimization (seal, body-type fit) and further testing
Ocular perfusion pressure is not reduced in response to lower body negative pressure	Hall *et al.*, 2024	To assess effect of graded LBNP on IOP, MAP, and OPP in supine and head-down tilt	LBNP reduces IOP but may not lower (and can raise) OPP under HDT conditions—implying limited efficacy of LBNP alone to prevent SANS if OPP is a causal factor. More work needed (different protocols/durations/postures)	Although LBNP reduces IOP, it does not reliably reduce OPP across postures; in 15° HDT, OPP actually increased. Therefore, LBNP may not reduce the ocular perfusion component hypothesized in SANS pathogenesis; posture and dose matter
Sleep deprivation and glymphatic system dysfunction as a risk factor for SANS during long-duration spaceflight	Joshua & Rosenberg, 2024	To explore potential etiologies of SANS and link with the glymphatic system	Conceptual synthesis: GS impairment is a plausible shared mechanism linking macro (fluid/pressure) and micro (barrier/ inflammatory) factors in SANS. Recommends targeted research on GS markers and interventions	Glymphatic system dysfunction (PVS enlargement, impaired CSF/ISF clearance) may be a common downstream pathway in SANS development; targeting GS function could open new countermeasure avenues
Ocular Deformations in Spaceflight-Associated Neuro-Ocular Syndrome and Idiopathic Intracranial Hypertension	Sibony *et al.*, 2023	To investigate ocular distortions in SANS and idiopathic intracranial hypertension (IIH) to determine if elevated intracranial pressure is the sole cause of SANS-related findings	SANS showed mild, bidirectional deformations and significantly less retinal nerve fiber layer thickening compared to IIH, which had large anterior deformations and severe disc edema	Ocular changes in SANS differ significantly from IIH, suggesting SANS is not solely due to elevated ICP but likely involves multiple factors and distinct biomechanical mechanisms

Optic nerve sheath diameter and spaceflight: defining shortcomings and future directions	Fall *et al.*, 2022	Review ONSD use in spaceflight and analogs	ONSD increased in astronauts and analogs but was variable due to inconsistent methods	ONSD is a promising tool for monitoring spaceflight-associated neuro-ocular syndrome (SANS), but standardization in imaging, measurement, and reporting is necessary to improve reliability and comparability
Effect of Nightly Lower Body Negative Pressure on Choroid Engorgement in a Model of Spaceflight-Associated Neuro-ocular Syndrome	Hearon *et al.*, 2022	To test whether nightly LBNP during 3 days of supine bed rest reduces choroid remodeling and maintains hemodynamic stability	Ten participants completed; nightly LBNP induced footward fluid shift (↓ central venous pressure), attenuated increases in choroid area and volume, and caused no adverse hemodynamic events	Nightly LBNP during sleep is safe, feasible, and partially effective in reducing ocular changes linked to SANS; supports its potential as a countermeasure in space missions
Noninvasive Indicators of Intracranial Pressure Before, During, and After Long-Duration Spaceflight	Jasien *et al.*, 2022	To assess intracranial pressure (ICP) using noninvasive indicators before, during, and after long-duration spaceflight, and to evaluate whether lower body negative pressure (LBNP) can reduce ICP	Noninvasive ICP indicators during spaceflight were not elevated compared to Earth's seated posture. Acute LBNP application did not significantly change indicators of ICP	It is possible for intracranial pressure to stay stable across extended spaceflight. During weightlessness, LBNP did not have a significant effect on readings for intracranial pressure
Eye changes in space: New insights into clinical aspects, pathogenesis, and prevention	Händel *et al.*, 2021	To provide an overview of current research on ocular alterations in spaceflight-associated neuro-ocular syndrome (SANS) and highlight relevance for terrestrial ophthalmology	Causes of ocular changes in space remain unclear; possible factors include intracranial pressure increase, fluid shifts, hypercapnia, and genetics. Terrestrial analogue model (−6° head-down tilt) and countermeasures (e.g., intermittent artificial gravity) are under investigation	Bed rest studies will yield important insights for both space and terrestrial research; clinical ophthalmology can benefit from space research findings
Intraocular pressure and choroidal thickness respond differently to lower body negative pressure during spaceflight	Greenwald *et al.*, 2021	To test whether acute application of lower body negative pressure (LBNP) can counteract headward fluid shift and modify intraocular pressure (IOP) and choroidal thickness during spaceflight	Spaceflight elevated IOP by 1.3 mmHg compared to preflight seated values. Acute LBNP reduced IOP to seated posture levels. Choroidal thickness increased by 35 µm during spaceflight compared with preflight seated posture, but LBNP did not reduce choroidal thickness.	Acute LBNP reduces the weightlessness-induced increase in IOP, suggesting potential as a countermeasure. However, choroidal engorgement was not reversed, likely reflecting changes secondary to chronic cerebral venous congestion in spaceflight
Daily generation of a footward fluid shift attenuates ocular changes associated with head-down tilt bed rest	Lawley *et al.*, 2020	To identify early ocular changes during simulated microgravity (HDT bed rest) and test if daily lower body negative pressure (LBNP) can attenuate them	OCT and ultrasound showed increased choroidal area, volume, and optic nerve sheath diameter during HDT. Daily 8-h LBNP reduced choroidal engorgement by ~40% and lessened optic changes	Low-level daily LBNP is an effective countermeasure to reduce early ocular remodeling and could help prevent SANS in astronauts

Association of Exercise and Swimming Goggles With Modulation of Cerebro-ocular Hemodynamics and Pressures in a Model of Spaceflight-Associated Neuro-ocular Syndrome	Scott *et al.*, 2019	To examine whether exercise (aerobic, resistance, high-intensity) or artificially increasing IOP with swimming goggles modulates cerebro-ocular hemodynamic and pressure changes during head-down tilt (HDT), a spaceflight analogue	In 20 healthy men, HDT increased IOP, jugular venous pressure (JVP), and decreased translaminar pressure gradient (TLPG). Exercise during HDT decreased IOP and TLPG compared with HDT rest. Wearing swimming goggles increased IOP and TLPG in both supine and HDT conditions	Exercise reduced IOP and TLPG, while swimming goggles increased IOP and TLPG. Modestly increasing IOP with goggles may help mitigate SANS; further evaluation in spaceflight is needed to confirm safety and efficacy

3.1. Comparative Interpretation of Study Methodology

The sensitivity, duration, and accuracy of outcomes regarding study designs and imaging approaches were highly variable in the papers we discussed. Although we considered comparatively calibrated parameters, ground-based analogs, like head-down-tilt studies, did not achieve precision for anything longer than moderately long-term exposure. Although the in-flight studies did not achieve a high degree of image similarity and often used a smaller sample, they had ecological validity in the field. Multiple reasons for the variation in reported optic nerve and choroid outcomes are likely due to some of the methodological differences. This comparison highlights the need for standardization in imaging and consistent inclusion criteria in the next study of SANS.

4. Discussion

This section looks into the underlying mechanisms and contributing factors that impact intracranial pressure (ICP) and fluid dynamics, as well as the glymphatic system and other physiological pathways at play. It also describes gaps in current knowledge and future opportunities related to ocular health optimization in spaceflight or environments meant to emulate spaceflight conditions. Spaceflight-Associated Neuro-Ocular Syndrome (SANS) is a multifactorial syndrome resulting from complex interactions with physiology and the environment, including microgravity effects on humans during long-duration spaceflight. The current body of evidence provides a multidimensional understanding of spaceflight-associated neuro-ocular syndrome (SANS), with an emphasis on the interaction between intracranial pressure (ICP), cerebrospinal fluid (CSF) dynamics, ocular physiology, and environmental stresses, especially during long-duration spaceflight. Early concepts, especially some of the first reports on SANS, placed exclusive emphasis on increased intracranial pressure as the reason for SANS; however, subsequent investigations indicate a much more complex pathophysiology. Rodrigues *et al.* (2025) and Sibony *et al.* (2023) indicated that increased intracranial pressure alone, especially a modest ICP rise, does not account for the types of visual changes associated with SANS. SANS presents with modest bi-directional ocular deformities and moderate optic nerve head thickening, which contrasts with what we see in idiopathic intracranial hypertension, where we see extreme anterior deformations of the optic nerve head and severe swelling. These data suggest that there is a complex pathophysiology involving compartmentalized cerebrospinal fluid dynamics and altered venous and glymphatic fluid flow, as well as additional fluid changes and environmental stresses (e.g., hypercapnia, radiation) encountered during spaceflight.

The glymphatic system has quite recently been suggested to play a possible role in SANS. Venegas and Rosenberg (2024) have argued that sleep deprivation and impaired glymphatic clearance may link macro-level changes in fluid and pressure to micro-level processes of neuroinflammation. If perivascular space clearance mechanisms are failing, it could represent a downstream convergence of multiple stressors, which may unlock new strategies to countermeasure SANS symptoms. Previous research by Händel *et al.* (2021) and Fall *et al.* (2022) recommended developing commonly recognized technologies for monitoring and the potential value of optic nerve sheath diameter as a relevant, easy, and noninvasive metric; however, differences in methodology have limited the ability to directly compare the results of studies across each research group. Several studies have evaluated lower body negative pressure (LBNP) for treatment of visual abnormalities associated with SANS. Both acute and repetitive LBNP applications demonstrated a reduction in intraocular pressure (IOP) and the potential to suppress choroidal volume increases and optic nerve sheath diameter (Lawley *et al.*, 2020; Greenwald *et al.*, 2021; Hearon *et al.*, 2022). However, LBNP alone did not demonstrate the ability to fully restore ocular perfusion pressure (Hall *et al.*, 2024) or completely reverse choroidal thickening (Greenwald *et al.*, 2021), indicating dose, position, and length of exposure limitations. While self-sustaining LBNP devices offer low-power alternatives for missions in deep space (Velichala *et al.*, 2024), additional development is required with regard to the efficacy and stability of the body seal and body type compatibility.

Additionally, the literature has explored further interventions. When subjects engage in exercise during head-down tilt (HDT), intraocular pressure (IOP) decreases and translaminar pressure differential is positively reduced. Conversely, IOP can be artificially elevated with the use of swimming goggles and will alter cerebro-ocular hemodynamics (Scott *et al.*, 2019). These results suggest that regulated changes in fluid, combined with active physiological involvement, may serve as additional protective factors.

5. Knowledge Gaps and Future Implications

Although new mechanical data are emerging in the literature, meaningful gaps in knowledge still exist. Noninvasive intracranial pressure indicators do not often show a meaningful measured increase during prolonged spaceflight (Jasien *et al.*, 2022), warranting the interpretation that we use intracranial pressure measurements solely to quantify SANS risk. The ground-based analogs (head-down tilt and other bed rest studies) that offer valuable insight and understanding are still a part of the research process and developing the countermeasures of this knowledge base as evidenced before (Händel *et al.*, 2021). The evidence examined indicates that preventing SANS requires a multifactorial approach, including daily LBNP, planned activity, sleep management, and intervention to support glymphatic clearance. Operational planning for long-duration missions should include individualized fluid-shift management and continuous eye monitoring. SANS research findings may also help to improve terrestrial ophthalmology, particularly in those with chronic ocular changes resulting from fluid shifts and ICP-independent optic nerve illnesses.

6. Limitations and Research Gaps in SANS Assessment Technologies

Although there have been notable improvements in the imaging technologies that are currently available to evaluate SANS, all methods still have limitations. Cross-study comparisons become increasingly challenging due to inter-device variability; OCT is operator-dependent, ultrasonography allows for real-time measurement but lacks spatial resolution to detect minor changes in the retina or choroid, and fundus photography lacks depth/volumetric data but can show the presence and persistence of optic disc edema; and there is a lack of consistent calibration for the terrestrial systems that are used to assess SANS, and this complicates meaning longitudinally. Resolving the options to create a standardized approach to imaging SANS would assist in solving confounding effects noted between the studies, especially when prior SANS results may have been impacted by differences in the imaging accuracy or time of measure. Thus, a future direction of study should be focused on the development of portable, microgravity-validated automated imaging devices. The subsequent incorporation of artificial intelligence for fully automated segmentation and standardization of data sharing and format would increase the repeatability of testing and improve the assessment of structures with progressive SANS.

In summary, SANS occurs as a function of ICP, CSF compartmentalization and dynamics, venous and glymphatic fluid shifts and dynamics, and spaceflight-associated stresses. Even though LBNP and exercise have shown promise at decreasing ocular impacts, an approach that addresses and optimizes multiple pathways, including glymphatic function, may be necessary to prevent or reduce SANS. Future studies should focus on customizability of acronyms for standardized assessment, appropriate individualization of interventions, and identification of novel biomarkers to fully understand and address this condition. Several studies have observed ocular changes after spaceflight or in simulated microgravity settings. Ng *et al.* (2025) reported optic disc edema in over 45% of subjects in a 6° head-down tilt bed rest protocol, with choroidal changes and increased retinal thickness. Aleci and Dutto (2025) also observed changes to the posterior segment following flight, including optic disc edema, globe flattening, and choroidal folds. Pardon *et al.* (2022) also reviewed astronauts and noted unilateral or bilateral optic disc edema, globe flattening, chorioretinal folds, hyperopic shifts, and sometimes cotton-wool spots. Lee *et al.* (2020) reported optic disc edema, reduced near visual acuity, and changes in the intraocular pressure–intracranial pressure relationship in microgravity and head-down bed rest conditions. Williams *et al.* (2019) demonstrated significant retinal remodeling, edema, and changes to the neuroimmune state in a simulated microgravity environment with animals. Taken together, these studies indicate that both real microgravity and simulated microgravity can produce significant anatomical and functional changes in ocular structures, including optic disc edema and changes to the posterior segment. Table 3 summarizes the experimental conditions and associated ocular changes from various studies, providing a brief comparative review of the evidence for microgravity-induced ocular changes.

Table 3: Comparative Findings from Published Reports on Spaceflight and Head-Down Tilt–Induced Ocular Changes

Published Reports	Condition	Symptoms
Ng *et al.*, 2025	Strict 6° head-down tilt bed rest analog	Optic disc edema developed in ~45 % participants, choroidal changes, increased retinal thickness
Aleci & Dutto, 2025	Posterior segment changes post-flight	Optic disc edema, globe flattening, choroidal folds
Pardon *et al.*, 2022	Review – SANS in astronauts	Unilateral/bilateral optic disc edema, globe flattening, choroidal & retinal folds, hyperopic refractive shifts, cotton-wool spots
Lee *et al.*, 2020	Review of microgravity effects on eye / head-down bed rest models	Optic disc edema, reduction in near visual acuity, changes in intraocular pressure / IOP vs ICP dynamics
Williams *et al.*, 2019	Simulated microgravity (animal model)	Pronounced ocular structural changes in animals: retinal remodeling, edema, changes in neuroimmune response

7. Conclusion

Although acknowledging that differences in study design, imaging technology, and subject selection may influence the strength and consistency of reported effects, the present review describes the available evidence. This review emphasizes optometry's unique contribution to the diagnosis, monitoring, and modulation of visual changes associated with microgravity. It represents the first conceptual synthesis of optometric, neuro-ocular, and imaging perspectives into a single framework. The reviewed literature confirms that spaceflight-associated neuro-ocular syndrome (SANS) is a multifactorial phenomenon resulting from complex interactions involving intracranial pressure, cephalad fluid shifts, vascular changes, orbital anatomical factors, and the effects of environmental stressors such as radiation and CO_2. The major visual symptoms include optic disc edema, globe flattening, choroidal folds, and hyperopic refractive shifts, which pose substantial risks to astronaut health and mission effectiveness. Although previously reported interventions, including LBNP, artificial gravity, and fluid-shifting garments, have had some limited success in mitigating SANS, none of these have completely prevented SANS. Non-invasive imaging with the use of AI will be an important tool for detecting and monitoring SANS risk. Thus, optometry is critical to the screening, assessment, and management of astronaut vision.

Future studies should seek to create standardized diagnostic frameworks, particularly for imaging methods such as OCT and optic nerve sheath diameter (ONSD), which would provide a uniform approach to evaluating SANS. These studies should have longitudinal designs to establish an understanding of the neuropathological progression and recovery of ocular changes following flight. Studying systemic processes such as glymphatic dysfunction and orbital fat mechanics may reveal other possible treatment targets. Countermeasures will need to be optimized using a combined approach that includes LBNP, artificial gravity, posture adjustments, and exercise strategies. Advances in portable tele-optometry devices, along with robust and AI-driven predictive models, will improve the delivery of in-flight ocular care. Ultimately, the translation of principles from spaceflight studies to terrestrial ocular disease states, such as idiopathic intracranial hypertension, glaucoma, and myopia, will augment the clinical relevance of these studies.

Abbreviations

SANS: Spaceflight-Associated Neuro-Ocular Syndrome; **ICP**: Intracranial Pressure; **IOP**: Intraocular Pressure; **IIH**: Idiopathic Intracranial Hypertension; **CSF**: Cerebrospinal Fluid; **ISF**: Interstitial Fluid; **GS**: Glymphatic System; **ODE**: Optic Disc Edema; **ONSD**: Optic Nerve Sheath Diameter; **OPP**: Ocular Perfusion Pressure; **JVP**: Jugular Venous Pressure; **TLPG**: Translaminar Pressure Gradient; **TRT**: Total Retinal Thickness; **RNFL**: Retinal Nerve Fiber Layer; **OCT**: Optical Coherence Tomography; **EDI-OCT**: Enhanced Depth Imaging Optical Coherence Tomography; **MRI**: Magnetic Resonance Imaging; **AI**: Artificial Intelligence; **CNN**: Convolutional Neural Network; **HDT-BR**: Head-Down Tilt Bed Rest; **AG**: Artificial Gravity; **LBNP**: Lower Body Negative Pressure; **ISS**: International Space Station; **SELF-LBNP**: Self-Generated Lower Body Negative Pressure.

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Ethical Approvals

No ethical approvals were required for this study.

Declarations

The authors declare that they have followed all ethical standards in conducting this research. All data supporting the findings are available within the manuscript

Conflict of Interest

The authors declare no conflict of interest related to this study.

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