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Precision NeuroNutrition: Toward Personalized Perioperative Care in Neurosurgery

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Abstract
Precision medicine has transformed modern neurosurgery through advances in molecular diagnostics, advanced imaging, artificial intelligence (AI), and individualized therapeutic strategies. In contrast, perioperative nutritional care remains largely based on standardized guidelines that inadequately address the biological heterogeneity of neurosurgical patients. Growing evidence indicates that nutritional status is a modifiable determinant of postoperative outcomes, yet conventional assessment often fails to capture interindividual differences in metabolism, inflammation, body composition, and physiological reserve. This mini-review introduces Precision NeuroNutrition as a conceptual framework for personalized perioperative nutritional care in neurosurgery. It summarizes current evidence on nutritional vulnerability in neurosurgical patients and highlights how body composition analysis, inflammatory and metabolic biomarkers, metabolic phenotyping, microbiome science, multi-omics, and AI may enable biologically informed nutritional assessment and intervention. Precision NeuroNutrition complements, rather than replaces, established evidence-based recommendations such as ESPEN and Enhanced Recovery After Surgery (ERAS) by integrating patient-specific biological, metabolic, and molecular characteristics into nutritional decision-making. Although implementation remains limited by challenges in standardization, validation, cost, and data integration, advances in systems biology and computational medicine offer new opportunities for adaptive nutritional strategies. Precision NeuroNutrition offers a promising roadmap for future research and personalized perioperative nutritional management in modern neurosurgery.
Keywords: Artificial Intelligence; Body Composition; Neurosurgery; Perioperative Nutrition; Precision Medicine; Precision NeuroNutrition; Precision Nutrition.

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Introduction

The emergence of precision medicine has fundamentally transformed modern healthcare by shifting clinical decision-making from standardized treatment algorithms toward individualized strategies based on patients' biological, molecular, and clinical characteristics.[1–4] In neurosurgery, this paradigm has been accelerated by advances in molecular diagnostics, genomic classification, radiomics, artificial intelligence (AI), machine learning, neuronavigation, and patient-specific surgical planning, substantially improving diagnostic accuracy, risk stratification, surgical precision, and personalized therapeutic decision-making across neuro-oncology, cerebrovascular, epilepsy, spinal, and functional neurosurgery.[1–5] Despite these advances, perioperative nutritional care has evolved more slowly. Current practice still relies largely on conventional nutritional screening, generalized estimates of energy and protein requirements, and guideline-based recommendations developed for heterogeneous surgical populations.[6–9] Although these approaches have improved perioperative nutritional management, they seldom account for the considerable biological heterogeneity of neurosurgical patients, including differences in inflammatory responses, metabolic demands, skeletal muscle reserve, immune competence, and treatment-related physiological stress. Nutritional status is increasingly recognized as a major and modifiable determinant of surgical outcomes. Malnutrition, sarcopenia, frailty, systemic inflammation, metabolic dysfunction, and micronutrient deficiencies are consistently associated with higher postoperative morbidity, impaired wound healing, prolonged intensive care unit (ICU) and hospital stay, delayed neurological recovery, and reduced survival.[6,7,10–17] Importantly, many of these factors are potentially reversible through early identification and individualized nutritional interventions. Nutritional vulnerability is particularly pronounced in neurosurgical patients. Individuals with malignant gliomas frequently develop cancer-associated cachexia, corticosteroid-

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induced metabolic disturbances, chronic inflammation, and progressive nutritional deterioration.[15,17] Conversely, traumatic brain injury (TBI) induces profound hypermetabolism, accelerated protein catabolism, and markedly increased energy expenditure during the acute phase.[7,18] Older adults undergoing major spinal surgery commonly present with sarcopenia, frailty, vitamin D deficiency, and diminished physiological reserve, all of which adversely affect postoperative recovery.[11,16,19] Nevertheless, perioperative nutritional management remains largely uniform across these biologically distinct patient populations. Recent advances in precision nutrition offer an opportunity to address this gap. By integrating nutritional phenotyping with body composition analysis, inflammatory and metabolic biomarkers, multi-omics technologies, gut microbiome profiling, computational modeling, and AI, precision nutrition aims to deliver individualized nutritional interventions based on each patient's unique biological profile.[20,21] Although these concepts have gained increasing attention in oncology, cardiometabolic medicine, and critical care, their application in perioperative neurosurgery remains limited. In this mini review, we introduce Precision NeuroNutrition as a conceptual framework for personalized perioperative nutritional care in neurosurgery. We summarize current evidence regarding nutritional vulnerability in neurosurgical patients, discuss emerging technologies that may enable individualized nutritional management, highlight existing knowledge gaps, and outline future research priorities for integrating precision nutrition into contemporary neurosurgical practice.[1]

Nutritional Challenges in Neurosurgical Patients

Neurosurgical patients represent one of the most metabolically heterogeneous and nutritionally vulnerable surgical populations. The metabolic response to neurological disease is influenced by the underlying pathology, neuroendocrine activation, systemic inflammation, and the magnitude of surgical stress, resulting in substantial interindividual variability in nutritional requirements.[6,7,17] Consequently, patients with similar neurosurgical diagnoses may exhibit markedly different metabolic demands, inflammatory responses, and physiological resilience, underscoring the limitations of standardized perioperative nutritional strategies. Nutritional challenges also differ across neurosurgical diseases. Patients with malignant brain tumors frequently develop cancer-associated malnutrition, skeletal muscle wasting, chronic inflammation, corticosteroid-induced metabolic disturbances, and treatment-related nutritional deterioration, all of which may impair treatment tolerance and neurological recovery.[15,17,22] In contrast, severe TBI induces profound hypermetabolism, accelerated protein catabolism, negative nitrogen balance, and increased energy expenditure, making early nutritional support a cornerstone of neurocritical care.[7,18,23] Likewise, older adults undergoing major spinal surgery commonly present with sarcopenia, frailty, osteoporosis, and vitamin D deficiency, which are associated with postoperative complications, prolonged hospitalization, delayed functional recovery, and poorer long-term outcomes.[11,16,19,24] Despite these distinct metabolic phenotypes, perioperative nutritional management continues to rely largely on generalized recommendations for energy and protein delivery. Conventional nutritional screening identifies patients at risk of malnutrition but provides limited insight into the biological mechanisms underlying nutritional vulnerability or individual differences in metabolic adaptation to neurological disease and surgical stress.[6–10] As a result, patients with similar demographic characteristics or identical neurosurgical diagnoses may require fundamentally different nutritional strategies based on variations in inflammatory burden, skeletal muscle reserve, metabolic flexibility, immune competence, and physiological resilience. Emerging evidence supports moving beyond conventional malnutrition screening toward comprehensive nutritional phenotyping. Integrating body composition analysis, inflammatory and metabolic biomarkers, and precision nutrition approaches may enable perioperative nutritional management to be tailored to each patient's biological profile rather than relying solely on population-based recommendations.[6,10,11,20,21]

Precision NeuroNutrition: A Conceptual Framework for Personalized Perioperative Care

The marked biological heterogeneity among neurosurgical patients highlights the need for a paradigm that extends beyond conventional nutritional support. We propose Precision NeuroNutrition as a conceptual framework that integrates precision medicine with evidence-based clinical nutrition to deliver individualized perioperative nutritional care. Rather than considering nutrition as supportive therapy alone, this approach recognizes nutritional management as an active therapeutic strategy capable of modulating inflammation, metabolism, immune function, tissue repair, and neurological recovery.[6,7,25,26] Precision NeuroNutrition integrates nutritional phenotyping with body composition analysis, inflammatory and metabolic biomarkers, advanced imaging, multi-omics technologies, AI, and patient-specific clinical characteristics to individualize nutritional interventions according to biological profile, metabolic demands, disease characteristics, and anticipated response to surgical stress.[25,26] Importantly, Precision NeuroNutrition complements rather than replaces current ESPEN and ERAS recommendations. Existing guidelines provide the foundation for evidence-based perioperative nutritional care through standardized nutritional screening, optimized energy and protein delivery, and multidisciplinary management.[6–9,13] However, because they are designed for heterogeneous surgical populations, they cannot fully account for the biological variability observed in neurosurgical patients. Precision NeuroNutrition extends these recommendations by incorporating individualized biological information into nutritional decision-making [25,26]. A central feature of this framework is nutritional phenotyping, which integrates body composition, inflammatory activity, metabolic status, functional reserve, and molecular characteristics to define each patient's metabolic resilience and nutritional vulnerability. Consequently, patients with similar demographic characteristics or identical neurosurgical diagnoses may require fundamentally different nutritional strategies despite comparable clinical presentations.[10,11,25,26] From a systems medicine perspective, Precision NeuroNutrition represents the convergence of nutritional science, neuroscience, computational biology, and precision medicine. By integrating multimodal biological data with continuous clinical assessment, this framework may improve patient stratification, facilitate earlier identification of nutritional risk, personalize perioperative interventions, and ultimately enhance neurological recovery and long-term functional outcomes.[1–4,25–29]

Core Components of Precision NeuroNutrition

Body Composition: Beyond Conventional Nutritional Assessment

Body composition analysis is a cornerstone of Precision NeuroNutrition, shifting perioperative nutritional assessment beyond conventional anthropometric measures. Traditional indices, including body weight, body mass index (BMI), and serum proteins, often fail to identify clinically relevant reductions in skeletal muscle mass and quality, particularly in patients with obesity, edema, or fluid imbalance.[10,11] Routine CT and MRI provide an opportunity for opportunistic assessment of skeletal muscle quantity, muscle quality, and adipose tissue distribution without additional imaging, enabling objective detection of sarcopenia and myosteatosis.[22,30] These imaging-derived biomarkers have consistently been associated with postoperative complications, prolonged hospitalization, impaired functional recovery, treatment intolerance, and mortality across surgical populations, offering a more accurate estimate of physiological reserve than conventional nutritional screening alone.[11,22,30–32] This approach may be particularly valuable in neurosurgical patients, in whom metabolic deterioration frequently precedes measurable weight loss. Patients with malignant brain tumors, traumatic brain injury, hydrocephalus, and degenerative spinal disorders may experience progressive skeletal muscle depletion despite apparently preserved anthropometric indices, while corticosteroid therapy, immobility, and chronic neuroinflammation further accelerate muscle wasting.[15–19,22] Within the Precision NeuroNutrition framework, body composition should therefore be regarded as a dynamic biological biomarker rather than a simple nutritional parameter. Integrating CT- or MRI-derived body composition into routine preoperative assessment, together with emerging automated image analysis and AI-based quantification, may improve perioperative risk stratification and facilitate individualized nutritional interventions [4,30,33].

Inflammatory and Metabolic Biomarkers: Toward Biological Phenotyping

Inflammation is a key biological mechanism linking neurological injury with metabolic dysfunction, immune dysregulation, and adverse postoperative outcomes. Unlike many other surgical specialties, conditions such as malignant brain tumors, traumatic brain injury (TBI), intracerebral hemorrhage, and major spinal surgery trigger complex neuroinflammatory responses that alter cytokine production, oxidative stress, protein metabolism, and immune regulation, thereby influencing nutritional status and neurological recovery.[7,17,18] Traditional nutritional assessment has relied on serum biomarkers such as albumin and prealbumin; however, these markers are strongly influenced by inflammation and acute illness and therefore inadequately reflect nutritional status.[6,7,10,17] Consequently, modern nutritional assessment is shifting toward multidimensional biological profiling that integrates inflammatory and metabolic information. Several biomarkers, including C-reactive protein (CRP), interleukin-6 (IL-6), Prognostic Nutritional Index (PNI), Controlling Nutritional Status (CONUT) score, Geriatric Nutritional Risk Index (GNRI), and the CRP-to-albumin ratio, have demonstrated prognostic value in patients with brain tumors and spinal disorders, where they are associated with postoperative complications, prolonged hospitalization, and survival.[17,24,25,34] Within the Precision NeuroNutrition framework, these biomarkers should be interpreted collectively rather than individually. Integrating inflammatory biomarkers with body composition, metabolic characteristics, and clinical variables enables more accurate nutritional phenotyping, facilitating earlier identification of high-risk patients and more individualized perioperative nutritional strategies. Future integration of longitudinal biomarker data with imaging, physiological monitoring, and AI may further transform inflammatory biomarkers from static prognostic indicators into dynamic clinical decision-support tools capable of continuously adapting nutritional management throughout the perioperative course.[20,21,30,31,35]

Metabolic Phenotyping: Individualizing Nutritional Therapy

Metabolic phenotyping is another key component of Precision NeuroNutrition. Although perioperative nutritional therapy is traditionally guided by predictive equations and standardized recommendations, neurosurgical patients exhibit substantial variability in resting energy expenditure, substrate utilization, insulin sensitivity, protein turnover, and lipid metabolism, leading to heterogeneous responses to similar nutritional regimens [7,26,27]. This variability is particularly evident in neurocritical care. Following TBI, subarachnoid hemorrhage, or major intracranial surgery, metabolic demands evolve dynamically according to injury severity, inflammation, neuroendocrine responses, infection, sedation, and rehabilitation, limiting the accuracy of static predictive equations and emphasizing the need for repeated metabolic assessment.[7,18,26,27] Indirect calorimetry remains the reference standard for measuring resting energy expenditure in critically ill patients, while metabolomics provides comprehensive characterization of disease-specific metabolic pathways. Together, these technologies enable patient-specific assessment of energy metabolism rather than reliance on population-based estimates [26,27,36,37]. Within the Precision

NeuroNutrition framework, metabolic phenotyping extends beyond accurate caloric estimation to support individualized energy and protein delivery, lipid composition, micronutrient supplementation, and nutritional timing according to each patient's evolving metabolic profile. Integration of metabolic monitoring with body composition, inflammatory biomarkers, and AI may further enable adaptive nutritional strategies that continuously refine nutritional prescriptions throughout the perioperative course, representing a major step toward precision perioperative care.[20,21,30,31,38]

Systems Biology: Integrating the Microbiome and Multi-omics

A defining feature of Precision NeuroNutrition is its systems biology perspective, recognizing that perioperative nutritional status results from dynamic interactions among host metabolism, immune responses, the gut microbiome, and molecular networks rather than isolated nutritional variables [20,21,29–31]. This approach extends conventional nutritional assessment toward comprehensive biological phenotyping to support individualized perioperative care. The microbiota–gut–brain axis has emerged as an important regulator of neuroinflammation, immune homeostasis, blood–brain barrier integrity, and neurotransmitter signaling [28]. Neurosurgical patients are particularly vulnerable to microbiome disruption because of perioperative antibiotics, corticosteroids, prolonged fasting, critical illness, and altered enteral nutrition. Although clinical evidence remains limited, microbiome-targeted interventions including dietary modification, probiotics, prebiotics, and synbiotics represent promising strategies for future personalized nutritional care.[28,35,39] Complementing microbiome research, multi-omics technologies including genomics, transcriptomics, proteomics, metabolomics, lipidomics, and epigenomics have revealed considerable biological heterogeneity among patients with similar neurosurgical diseases.[29,31] Integrating these datasets with nutritional phenotyping may improve patient stratification and facilitate mechanism-based nutritional interventions tailored to individual biological profiles rather than diagnosis alone.[20,21,29,31,40] Although widespread clinical implementation remains limited by cost, standardization, and data integration, continuing advances in systems biology and computational medicine are expected to accelerate the translation of microbiome and multi-omics research into precision perioperative neurosurgical nutrition.

Artificial Intelligence and Digital Health: Translating Biological Complexity into Clinical Decision-Making

The successful implementation of Precision NeuroNutrition depends on integrating large volumes of biological and clinical data into individualized nutritional decisions. Artificial intelligence provides the computational framework to combine multimodal information, including neuroimaging, body composition, laboratory biomarkers, physiological monitoring, electronic health records, and multi-omics data, thereby supporting personalized perioperative nutritional management.[1,3,4,29–31] Machine learning models have already demonstrated promising performance in predicting postoperative complications, functional recovery, and survival in neurosurgical patients. Incorporating nutritional variables into these models may further improve perioperative risk stratification and identify patients most likely to benefit from targeted nutritional interventions.[1–4,30,31,41] Beyond prediction, AI enables adaptive nutritional management by continuously integrating changes in inflammatory biomarkers, energy expenditure, body composition, glycemic control, and organ function. This dynamic approach allows nutritional therapy to evolve alongside the patient's metabolic and physiological status rather than relying on fixed perioperative protocols. Recent advances in digital health, including wearable sensors, remote monitoring, and patient-reported outcome platforms, extend nutritional assessment beyond hospitalization and support continuous evaluation during rehabilitation. Among these innovations, digital twins offer promise by integrating longitudinal clinical, imaging, physiological, and molecular data to simulate disease progression and predict responses to nutritional interventions before clinical deterioration occurs.[32,33,42] Importantly, AI is intended to complement, not replace, clinical expertise. By integrating complex biological information beyond the capacity of conventional assessment, AI has the potential to unify nutritional phenotyping, body composition, inflammatory biomarkers, metabolic profiling, microbiome analysis, and multi-omics into a comprehensive precision nutrition ecosystem for neurosurgical care.[20,21,29–33]

Challenges and Future Directions

Despite increasing interest in precision medicine and personalized nutrition, translating Precision NeuroNutrition into routine neurosurgical practice remains challenging. Current evidence largely focuses on isolated nutritional factors, including malnutrition, sarcopenia, inflammatory biomarkers, vitamin D, immunonutrition, and ketogenic therapies, rather than integrated biology-driven nutritional strategies.[6,7,10,11,15–17,24,25,35] Consequently, high-quality evidence supporting comprehensive nutritional phenotyping and individualized nutritional interventions in neurosurgery remains limited. Several barriers must be addressed before widespread clinical implementation. Standardized frameworks integrating body composition, inflammatory and metabolic biomarkers, microbiome profiling, and multi-omics are still lacking, while many emerging technologies remain costly, technically demanding, and difficult to standardize across centers [20,21,29–33]. Future research should prioritize prospective multicenter studies to validate nutritional phenotypes, identify clinically relevant biomarker panels, and evaluate AI-assisted decision-support systems that can dynamically adapt nutritional therapy throughout the perioperative period.[41,43] Equally important, successful implementation will require close collaboration among neurosurgeons, neurointensivists, neuro-oncologists, clinical nutrition specialists, radiologists, rehabilitation physicians, molecular scientists, bioinformaticians, and data scientists. Importantly, Precision NeuroNutrition is intended to complement, not replace, current ESPEN and ERAS recommendations by integrating patient-specific biological, metabolic, and molecular information into evidence-based perioperative nutritional care.[6–9,20,21,44]

Conclusion

Precision medicine has transformed modern neurosurgery, yet perioperative nutritional care remains largely standardized despite the marked biological heterogeneity of neurosurgical patients. Precision NeuroNutrition provides a conceptual framework that integrates nutritional phenotyping, body composition, inflammatory and metabolic biomarkers, microbiome science, multi-omics, and AI to support individualized perioperative nutritional care. Rather than replacing established ESPEN and ERAS recommendations, this approach seeks to extend them by incorporating patient-specific biological information into nutritional decision-making. Although substantial challenges related to validation, standardization, and implementation remain, advances in computational medicine and systems biology provide new opportunities for precision nutritional management. Future multidisciplinary studies should determine whether biologically guided nutritional strategies can improve neurological recovery, postoperative outcomes, and long-term quality of life. Precision NeuroNutrition therefore represents a promising roadmap toward predictive, adaptive, and personalized perioperative nutritional care in neurosurgery.

Ethical consideration

None.

Competing Interests

The authors declare no conflict of interest.

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