

Postoperative nutritional interventions and recovery: Molecular mechanisms, clinical outcomes, and ERAS-based practice

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Abstract

Nutritional interventions play a key role in enhancing postoperative recovery through anti-inflammatory, immunoregulatory, and metabolic effects. However, evidence across different nutrients and surgical settings remains heterogeneous. This review aimed to summarize both the molecular mechanisms and clinical outcomes of nutritional strategies supporting recovery after surgery. Relevant studies were identified through systematic searches of the PubMed, Web of Science, and Scopus databases from January 2000 to February 2025, including randomized controlled trials (RCTs), systematic reviews, and meta-analyses focusing on enteral nutrition, parenteral nutrition, and immunonutrition. Evidence from more than 50 clinical studies indicates that enteral immunonutrition (EIN) reduces postoperative infectious complications by approx. 30% and shortens hospital stay by 2–3 days. Early enteral feeding within 24–48 h improves gastrointestinal recovery and lowers overall morbidity. Omega-3-enriched nutrition modulates inflammatory and immune responses without increasing the risk of adverse events. Emerging technologies, such as nutrigenomics and digital monitoring, further enable individualized nutritional management. Nutritional interventions represent a promising nonpharmacological approach to optimizing postoperative recovery by integrating molecular insights with clinical practice. Standardization of protocols and long-term evaluation remain priorities for advancing evidence-based, personalized nutrition within Enhanced Recovery After Surgery (ERAS)-aligned surgical care.

Key words: postoperative care, nutritional support, Enhanced Recovery After Surgery (ERAS), immunonutrition, enteral nutrition

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Highlights

- Postoperative nutrition significantly improves surgical recovery, with enteral immunonutrition (EIN) reducing surgical site infections by approx. 30% and shortening hospital stay by 2–3 days.
- Early enteral nutrition initiated within 24–48 h enhances gastrointestinal recovery, reduces postoperative morbidity, and supports implementation of Enhanced Recovery After Surgery (ERAS) protocols.
- Omega-3 fatty acid–enriched postoperative nutrition modulates inflammation and immune function without increasing adverse events, supporting safe postoperative immune regulation.
- Personalized postoperative nutrition, supported by nutrigenomics and digital nutritional monitoring, enables evidence-based nutritional management to optimize surgical recovery.

Introduction

Postoperative recovery is a critical area in modern medicine that significantly impacts patient outcomes and quality of life (QoL). However, surgery induces a series of complex physiological and metabolic changes, including an acute inflammatory response, immunosuppression, delayed tissue repair, and disorders of energy metabolism.^{1,2} These factors collectively increase the risk of postoperative complications, such as infections, poor wound healing, and muscle atrophy, thereby delaying the recovery process.^{3–5} Therefore, identifying effective interventions to promote postoperative recovery has become a key focus of clinical research. In recent years, nutritional interventions have gained attention as an area of active research due to their noninvasive nature, cost-effectiveness, and multi-target effects.^{6–8}

Studies have demonstrated that specific nutrients, such as ω -3 fatty acids, glutamine, and vitamin D, play significant roles in suppressing postoperative inflammation, enhancing immune function, and promoting tissue repair.⁹ For instance, ω -3 fatty acids alleviate inflammatory responses by regulating the NF- κ B (nuclear factor kappa-light-chain-enhancer of activated B cells) signaling pathway,^{10,11} while glutamine has been shown to enhance T-cell activity and mitigate postoperative immunosuppression.¹² These molecular mechanisms provide a biological rationale for integrating nutritional strategies into perioperative management frameworks and guidelines, such as Enhanced Recovery After Surgery (ERAS) protocols and the European Society for Clinical Nutrition and Metabolism (ESPEN) guidelines. Moreover, an optimized combination of enteral nutrition (EN) and parenteral nutrition (PN) has been shown to significantly reduce postoperative complications.¹³ Despite the increasing number of related studies, notable gaps remain in our understanding of the specific molecular mechanisms, individual nutritional requirements, and standardized clinical intervention protocols. In clinical practice, nutritional interventions have been increasingly integrated into perioperative management for various surgical populations, including patients undergoing gastrointestinal, hepatobiliary, and

orthopedic procedures. The use of nutritional support within ERAS and ESPEN guideline frameworks has demonstrated measurable benefits in reducing complications, shortening hospital stays, and improving functional recovery. These frameworks emphasize early enteral feeding, immunonutrition, and metabolic optimization as essential components of postoperative care. Incorporating these clinical perspectives provides a practical foundation for understanding how molecular mechanisms translate into real-world recovery outcomes.

At present, the role of nutritional interventions in postoperative recovery lacks a comprehensive theoretical framework. On the one hand, the influence of different types of surgery and individual patient variability on nutritional needs requires further exploration. On the other hand, the precise pathways through which nutritional interventions regulate inflammation, immunity, and tissue repair at the molecular level remain inadequately understood. Additionally, many clinical studies lack long-term follow-up data, making it difficult to evaluate the long-term effects of nutritional interventions on recovery and QoL. Therefore, there is an urgent need to systematically integrate existing research findings to clarify the specific mechanisms and optimize nutritional intervention strategies.

Objectives

This work is a comprehensive narrative review that integrates molecular and clinical evidence on perioperative nutritional interventions, with the aim of informing clinical decision-making regarding the timing of EN and PN, the role of immunonutrition, and the use of ω -3-enriched formulas. First, it explores the molecular mechanisms by which nutritional interventions modulate inflammation, immune function, and tissue repair. Second, it reviews the clinical applications of nutritional interventions across various postoperative recovery contexts. Finally, it analyzes research challenges and future directions in this field, providing a scientific basis for optimizing postoperative recovery strategies.

Materials and methods

This review was conducted as a comprehensive narrative literature review. Relevant studies were identified through systematic searches of the PubMed, Web of Science, and Scopus databases for articles published between January 2000 and February 2025. The search strategy included combinations of the following terms: “postoperative recovery,” “nutritional intervention,” “enteral nutrition,” “parenteral nutrition,” “immunonutrition,” “ ω -3 fatty acids,” and “Enhanced Recovery After Surgery.”

Original research articles, randomized controlled trials (RCTs), systematic reviews, and meta-analyses focusing on the effects of perioperative nutritional interventions on postoperative outcomes were included. Non-English-language articles, animal studies, case reports, and conference abstracts were excluded. Each study was evaluated for methodological quality and relevance to clinical practice, and the findings were synthesized narratively according to the phase of care: preoperative, postoperative, and recovery.

Molecular mechanisms of nutritional interventions in postoperative recovery

Regulation of postoperative inflammatory responses by nutritional interventions

Control of acute postoperative inflammation

Postoperative inflammation is both a physiological response to surgical trauma and a critical phase of tissue repair.¹⁴ However, excessive or prolonged inflammation may cause secondary tissue damage, delay functional recovery, and contribute to postoperative complications. Research suggests that nutritional interventions can regulate

postoperative inflammation at the molecular level, thereby mitigating its adverse effects.¹⁵ Among these interventions, ω -3 fatty acids, a group of polyunsaturated fatty acids with anti-inflammatory properties, inhibit the production of proinflammatory cytokines, such as interleukin-6 (IL-6) and tumor necrosis factor alpha (TNF- α), by modulating the NF- κ B signaling pathway, thereby alleviating the inflammatory response. Additionally, ω -3 fatty acids can be converted into specialized lipid mediators, such as resolvins and protectins, which promote the resolution of inflammation and reduce inflammation-induced tissue damage.^{16,17} These mechanisms provide a theoretical basis for the nonpharmacological management of postoperative inflammation.

Alleviation of oxidative stress

Surgical trauma is often accompanied by increased oxidative stress, characterized by a marked increase in reactive oxygen species (ROS) production.¹⁸ Excessive ROS can compromise the integrity of cell membranes and cause oxidative damage to proteins and DNA, thereby exacerbating postoperative tissue injury and functional impairment.¹⁹ Therefore, controlling the level of oxidative stress is a critical step in promoting postoperative recovery. Antioxidants have been shown to exert significant protective effects by reducing oxidative stress. For example, vitamin C, a water-soluble antioxidant, directly scavenges ROS, prevents the propagation of free-radical chain reactions, and protects cells from oxidative damage.²⁰ Vitamin E, a fat-soluble antioxidant, is incorporated into cell membranes and stabilizes the lipid bilayer, thereby preventing lipid peroxidation.²¹ Furthermore, the synergistic action of these 2 vitamins can enhance antioxidant capacity and stabilize the postoperative tissue microenvironment. A recent study by Castillo et al.²² highlighted that the combined use of antioxidants may have a more pronounced effect on alleviating postoperative oxidative stress, offering new avenues for developing refined nutritional intervention strategies (Fig. 1).

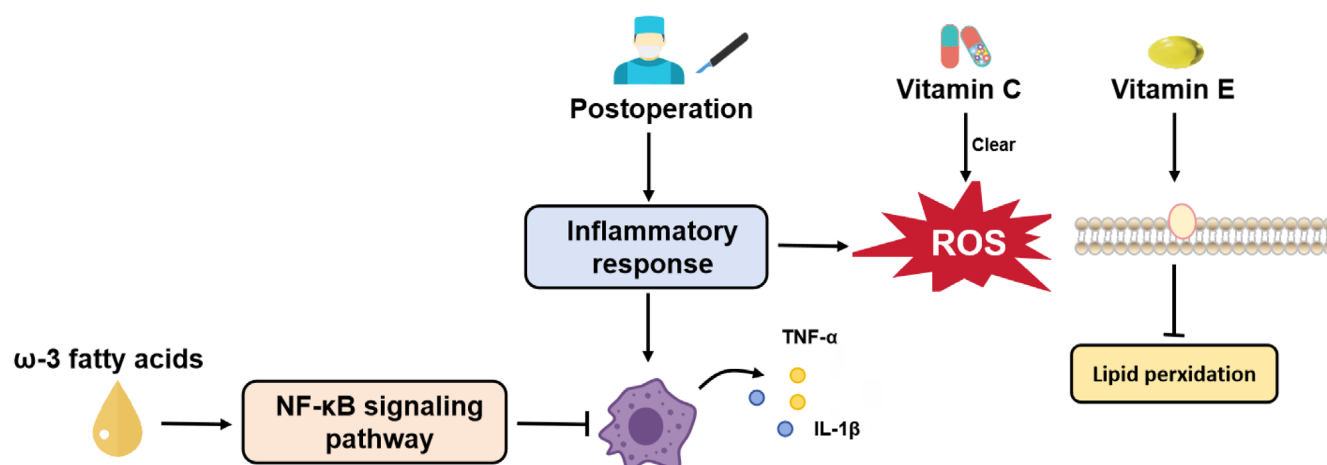


Fig. 1. Antioxidant mechanisms of nutritional interventions in postoperative recovery

Modulation of postoperative immune function by nutritional interventions improvement of postoperative immunosuppression

The physiological stress response triggered by surgery often leads to an immunosuppressive state, particularly in the early postoperative phase. This immunosuppression not only reduces the body's ability to combat infection but also increases the risk of postoperative complications, such as sepsis and wound infections. Nutritional intervention is regarded as a potentially effective strategy for addressing this issue. Glutamine, the most abundant free amino acid in the human body, plays a crucial role in maintaining normal immune function.^{23,24} Studies have shown that postoperative glutamine supplementation significantly enhances T-cell proliferation and increases the activity of natural killer (NK) cells.²⁵ These effects are particularly important during postoperative recovery, as T cells and NK cells are essential for defense against pathogenic infections. Additionally, glutamine promotes repair of the intestinal mucosal barrier, indirectly improving systemic immune function and reducing the incidence of postoperative bacterial translocation.^{26,27} These findings suggest that glutamine is a multifunctional immunonutrient with substantial benefits for postoperative recovery.

Gut microbiota regulation and immune recovery

Surgical stress and postoperative antibiotic use often disrupt the balance of the gut microbiota, resulting in a reduction in beneficial bacteria, such as *Lactobacillus* and *Bifidobacterium*, and overgrowth of opportunistic pathogens.²⁸ Dysbiosis of the gut microbiota may further suppress host immune function and increase the risk of postoperative infections. Therefore, restoring gut microbiota balance through nutritional interventions is a critical strategy for promoting immune recovery after surgery. Probiotics and dietary fiber have been widely studied and used to modulate the gut microbiota. Probiotics restore immune homeostasis by competitively excluding pathogenic bacteria and modulating gut immune responses.^{29,30} Moreover, dietary fiber is fermented in the gut to produce short-chain fatty acids (SCFAs), such as acetate, propionate, and butyrate.^{31,32} Short-chain fatty acids serve as the primary energy source for intestinal epithelial cells and activate immune-related pathways, including those mediated by G-protein-coupled receptors 41 and 43 (GPR41/43), thereby promoting anti-inflammatory responses and enhancing systemic immune function.³³ For instance, butyrate enhances the function of regulatory T cells (Tregs), alleviating postoperative inflammation and ameliorating immunosuppression.³⁴ Recently, Trone et al. demonstrated

that the combined use of probiotics and dietary fiber may have a synergistic effect, thereby optimizing postoperative immune regulation strategies.³⁵ This finding provides new avenues for developing precise nutritional intervention plans for postoperative recovery.

The role of nutrition in supporting postoperative tissue repair and regeneration

Effects of proteins and amino acids on postoperative wound healing

Tissue repair after surgery is a critical component of the recovery process and is highly dependent on an adequate supply of protein and amino acids. Surgical trauma induces a hypermetabolic state characterized by increased protein degradation and a heightened demand for protein synthesis. Adequate protein intake provides essential substrates for new tissue formation, supports collagen synthesis, and promotes cell proliferation. Leucine, an essential amino acid, is particularly important for postoperative recovery. According to Holowaty et al., leucine accelerates muscle and wound repair by activating the mTOR signaling pathway, thereby promoting protein synthesis.³⁶ Additionally, leucine stimulates fibroblast activity and enhances collagen matrix production, which is vital for wound healing.³⁷ Other branched-chain amino acids (BCAAs), such as valine and isoleucine, also play supportive roles in cell repair and regulation of inflammation. Postoperative patients often experience impaired protein synthesis or excessive protein catabolism; therefore, supplementation with high-protein diets or specific amino acid formulations can effectively promote wound healing, shorten recovery time, and reduce the incidence of postoperative complications.

Promotion of angiogenesis and tissue regeneration by micronutrients

Micronutrients play a crucial role in tissue repair after surgery. Zinc and copper are essential cofactors for numerous enzymes involved in collagen cross-linking and metabolic regulation. Zinc enhances extracellular matrix (ECM) remodeling by activating metalloproteinases and promotes fibroblast and keratinocyte activity, thereby expediting wound closure.³⁸ Copper plays a unique role in angiogenesis, acting as a critical regulator of vascular endothelial growth factor (VEGF) signaling pathways, thereby improving blood supply to the wound, facilitating nutrient and oxygen delivery, and creating optimal conditions for tissue regeneration.³⁹ Vitamin C, an essential cofactor in collagen synthesis, aids in converting procollagen into mature collagen, enhancing the strength

and elasticity of wound tissue. Vitamin A regulates epithelial cell proliferation and differentiation and plays a key role in wound epithelialization. The synergistic effects of multiple micronutrients provide comprehensive support for tissue repair and angiogenesis. Clinical studies have demonstrated that postoperative supplementation with a combination of micronutrients significantly improves the quality of wound healing and reduces the risk of infection.⁴⁰ These findings provide a solid basis for developing micronutrient supplementation protocols tailored to postoperative patients. According to the ESPEN micronutrient guideline,⁴¹ the recommended supplementation ranges are as follows: zinc, 3 mg/day intravenously (i.v.; up to 12 mg/day in loss states and 30 mg/day in major burns); copper, 0.3 mg/day in PN (1 mg/day in EN; 4 mg/day i.v. in severe deficiency); vitamin C, 100 mg/day (rising to 200 mg/day in chronic oxidative stress and 2 g/day i.v. during critical illness); and vitamin E, 100 mg/day for deficiency repletion. These ranges reflect the evidence-based safety levels summarized by ESPEN and should be adjusted according to individual clinical conditions.

The role of nutritional interventions in postoperative metabolic balance

Regulation of postoperative metabolic disorders

Surgical trauma triggers a series of metabolic responses, placing patients in a stress state characterized by an increased metabolic rate, catabolism, and insulin resistance. Without timely intervention, this state can exacerbate protein degradation, muscle loss, immune dysfunction, and delayed tissue repair, thereby prolonging postoperative recovery. Nutritional interventions play a pivotal role in managing postoperative metabolic disturbances. Certain nutrients have shown promising effects on metabolic regulation after surgery. For instance, BCAAs, such as leucine, valine, and isoleucine, not only serve as direct substrates for protein synthesis but also activate the mTOR signaling pathway to reduce protein breakdown, thereby facilitating muscle and tissue repair. Furthermore, BCAAs improve insulin sensitivity, stabilize blood glucose levels, and mitigate the hypercatabolic state associated with postoperative stress. Lipid emulsions, a key component of PN, provide an alternative energy source and reduce reliance on glucose metabolism, thereby significantly improving postoperative metabolic disturbances. A study by Klek indicates that lipid emulsions containing ω -3 fatty acids exhibit anti-inflammatory properties, further promoting metabolic stability.⁴²

Optimization of postoperative energy metabolism

During postoperative recovery, patients often have increased energy requirements. However, traditional high-carbohydrate diets may lead to hyperglycemia, thereby increasing the risk of infections and other complications. Identifying efficient and metabolically favorable energy sources has become a focus of nutritional interventions. Medium-chain triglycerides (MCTs) have attracted attention because of their unique metabolic properties. Unlike long-chain fatty acids, MCTs are rapidly absorbed and metabolized directly in the liver to generate ketone bodies, thereby providing an efficient energy source for patients. Ketone bodies serve as an alternative energy substrate to glucose, offering anti-inflammatory and antioxidant benefits that help alleviate postoperative inflammation and improve cellular function. Additionally, ketone metabolism does not significantly elevate blood glucose levels, thereby helping to avoid complications associated with high-carbohydrate diets, such as hyperglycemia. Studies suggest that incorporating MCTs into postoperative nutritional regimens or using ketogenic diets to modulate energy metabolism can significantly accelerate recovery, reduce postoperative fatigue, and improve overall QoL.⁴³ These findings provide important support for the precise management of energy metabolism during postoperative recovery.

Clinical applications of nutritional interventions in postoperative practice assessment of nutritional needs

Evaluation of preoperative nutritional status

Preoperative nutritional status is a critical factor influencing postoperative recovery outcomes. Malnourished patients are at higher risk of postoperative complications, including delayed wound healing, increased infection rates, and prolonged hospital stays. Therefore, a comprehensive assessment of nutritional status before surgery is essential for designing effective nutritional intervention plans. Common parameters used to evaluate nutritional risk include body mass index (BMI), serum albumin concentration, and lymphocyte count. Patients with a BMI below 18.5 kg/m or a serum albumin concentration below 30 g/L are typically considered malnourished. Additionally, tools such as the Subjective Global Assessment (SGA) and Nutritional Risk Screening 2002 (NRS-2002) are widely used to identify patients at high nutritional risk. These tools integrate patient history, physical examination findings,

and laboratory indicators to provide an objective basis for preoperative nutritional intervention decisions. Early intervention is particularly important for patients at risk of malnutrition. In summary, preoperative nutritional support significantly improves immune function and the capacity for recovery while reducing postoperative complications.

Personalized nutritional intervention strategies

Nutritional needs during postoperative recovery vary depending on individual patient characteristics and the type of surgery performed. Personalized nutritional intervention strategies should take into account factors such as nutritional status, basal metabolic rate, the severity of surgical trauma, and the risk of postoperative complications. For patients undergoing digestive system surgery, postoperative EN is often prioritized to support recovery of gastrointestinal function, given the direct impact of such procedures on food intake and nutrient absorption. For patients unable to tolerate EN, PN is necessary to provide essential energy and nutrients. In patients undergoing cancer surgery, among whom preoperative malnutrition is often highly prevalent, high-protein, high-calorie dietary interventions are particularly critical. Personalized interventions must also align with individual metabolic characteristics. For example, diabetic patients should follow low-sugar, high-fiber diets to control blood glucose fluctuations, while patients with obesity need to meet postoperative energy demands without excessive fat intake. Emerging precision nutrition approaches, such as those based on genomic and metabolomic data, also offer new insights into postoperative nutritional management. In summary, comprehensive preoperative nutritional assessment and personalized intervention strategies are key to optimizing postoperative recovery outcomes and providing patients with more scientifically grounded and effective therapeutic support.

Nutritional interventions in preoperative, postoperative, and recovery phases

Preoperative nutritional interventions

Preoperative nutritional status is crucial for postoperative recovery. Adequate preoperative nutritional reserves enhance the body's ability to cope with surgical trauma and reduce the incidence of postoperative complications. Nutritional interventions are particularly important for malnourished patients. High-protein, high-calorie diets are typically recommended preoperatively to enhance energy reserves and the capacity for protein synthesis. Protein

intake is central to preoperative nutritional interventions, as it supports immune function and provides essential substrates for tissue repair and cell proliferation. For patients requiring additional support, specialized medical nutrition formulas, such as immune-enhancing nutritional supplements, may be introduced. These products are rich in ω -3 fatty acids, glutamine, and antioxidants, which can effectively reduce postoperative inflammation and promote immune recovery. Studies have shown that the longer high-risk patients receive preoperative nutritional support, the more pronounced the effects of the intervention.⁶ Preoperative nutritional support for 7–14 days is generally recommended to sufficiently improve nutritional status and enhance postoperative resilience.

Postoperative nutritional support

Postoperative patients have significantly increased nutritional requirements due to trauma, inflammation, and metabolic disturbances. However, in the early postoperative period, patients often face challenges such as loss of appetite and reduced digestive and absorptive capacity, making the choice of nutritional support method crucial. Enteral nutrition is generally the preferred method of postoperative nutritional support, as it not only provides sufficient energy and nutrients but also helps maintain intestinal mucosal barrier function, thereby reducing the risk of bacterial translocation and infection.⁴⁴ The earlier EN is initiated, the better the recovery outcomes for patients. For patients with temporarily impaired gastrointestinal function or those unable to tolerate EN, PN is used to meet nutritional requirements. Parenteral nutrition provides necessary energy and nutrients directly via intravenous administration; however, long-term PN use may increase the risk of infection and metabolic disturbances.⁴⁵ Therefore, transition to EN as early as possible is recommended. Modern postoperative nutritional support also emphasizes immune-enhancing nutrients, such as glutamine, arginine, and ω -3 fatty acids. These nutrients regulate inflammatory responses, enhance immune function, and promote tissue repair, thereby accelerating postoperative recovery.

Nutritional management during the recovery phase

Nutritional management during the recovery phase is crucial for sustaining postoperative recovery outcomes and improving patients' QoL. While short-term postoperative nutritional support focuses on meeting basic needs, medium- to long-term management emphasizes the optimization of dietary composition and metabolic status. During recovery, patients should gradually resume a regular diet while ensuring sufficient protein and energy intake to maintain muscle mass and support tissue repair. Diets rich in vitamins and minerals can enhance immune function and improve overall health. Additionally, targeted

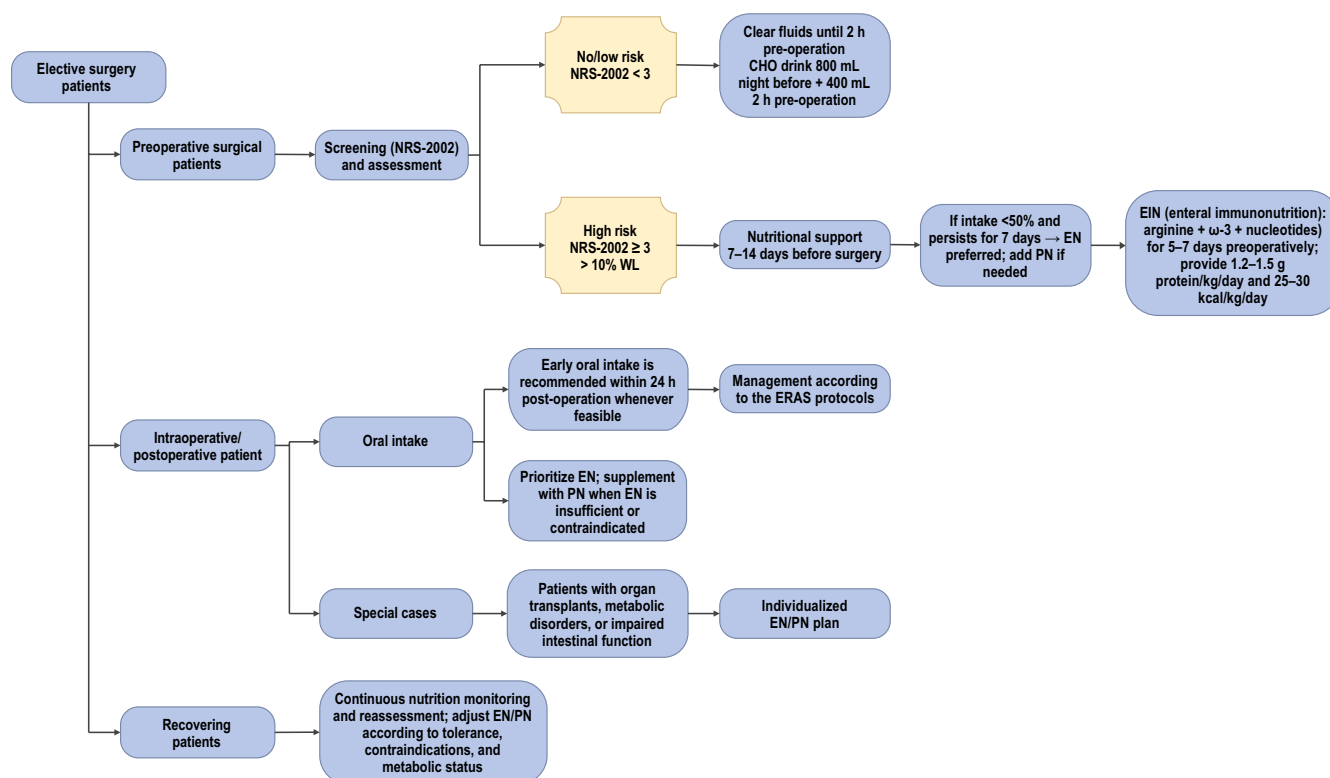


Fig. 2. Enhanced Recovery After Surgery (ERAS)-aligned perioperative nutritional management pathway

EN – enteral nutrition; PN – parenteral nutrition.

dietary supplementation is recommended to address potential postoperative nutrient deficiencies, including deficiencies in iron, zinc, and vitamin D. For postoperative patients with chronic diseases, such as diabetes or obesity, nutritional management during recovery must take their specific conditions into account and include individualized interventions. For instance, diabetic patients should strictly control carbohydrate intake, while patients with obesity should reduce total energy intake without compromising nutritional requirements. Wobith et al. highlighted that systematic nutritional management can significantly improve long-term recovery outcomes, including shorter recovery time, reduced recurrence rates, and better QoL.⁴⁶ Therefore, nutritional interventions during the recovery phase should be an integral component of postoperative care (Fig. 2).

Clinical research and efficacy analysis

Summary of clinical research findings

In recent years, clinical research into nutritional interventions for postoperative recovery has increased significantly, with substantial progress achieved, particularly through RCTs. Numerous studies have demonstrated the efficacy of various nutritional interventions in promoting postoperative recovery, providing robust evidence for

their use in clinical practice. An RCT involving patients undergoing abdominal surgery demonstrated that, compared with traditional postoperative dietary management, enteral immunonutrition (EIN) significantly reduced postoperative infection and complication rates and shortened hospital stays; however, EIN had no effect on noninfectious complications (Table 1).^{47–50} Another study found that a 2-week preoperative diet incorporating immune-enhancing formulas resulted in greater preoperative weight loss, reduced postoperative pain, and lower C-reactive protein (CRP) and liver enzyme levels compared with high-protein formulas or standard diets (Table 2).^{51–55} A prospective clinical trial reported that lipid emulsions containing ω-3 polyunsaturated fatty acids (PUFAs), administered to patients after liver resection, effectively controlled inflammation, preserved liver function, and reduced complication rates and length of hospital stay (Table 3).^{56–59} Collectively, these studies consistently support the positive impact of systematic nutritional interventions on postoperative recovery.

Efficacy evaluation metrics

Several key metrics are used to evaluate the effectiveness of nutritional interventions, including postoperative infection and complication rates. Postoperative patients often face an increased risk of infection due to reduced immune function, and nutritional interventions play a crucial role in mitigating this risk by improving immune function and reducing inflammation. For example, appropriate

Table 1. Effects of enteral immunonutrition (EIN) in gastrointestinal surgery

Population (n)	Formula (main nutrients)	Timing/duration	Main outcomes	Effect size (95% CI/p-value)	Quality/remarks	Reference
3,692 GI cancer patients (35 RCTs)	arginine + ω -3 PUFAs + nucleotides	perioperative period (5–7 days before and after surgery)	overall and infectious complications, LOS, mortality	overall RR = 0.79 ($p < 0.001$); infectious RR = 0.66 ($p < 0.001$); LOS MD = -2.36 days (95% CI: -3.76 to -0.97); no difference in non-infectious complications or mortality	high-quality meta-analysis; no increase in EN-related events	47
3,793 GI cancer patients (37 RCTs)	arginine + ω -3 PUFAs $\pm$ RNA	preoperative period (5–7 days) + post-operation (5–7 days)	infectious complications, SSI, anastomotic leak, LOS	infection OR = 0.58 (95% CI: 0.47–0.72); SSI OR = 0.65 (95% CI: 0.52–0.81); anastomotic leak OR = 0.67 (95% CI: 0.47–0.93); LOS MD = -1.94 days (95% CI: -3.00 to -0.87)	significant benefit with pre-/peri-operative IMN; no increase in adverse events	48
1,269 patients (13 RCTs)	arginine + RNA + ω -3 PUFAs	perioperative period (5–7 days before and after surgery)	infectious complications, LOS, immune function	infection OR = 0.41 ($p < 0.001$); LOS WMD = -3.48 ($p < 0.001$); $\uparrow$ CD4 (WMD = 11.39, $p < 0.001$); $\downarrow$ IL-6 (WMD = -201.83, $p < 0.001$)	no difference in mortality; improved immune parameters; no serious adverse events	49
705 hepatectomy patients (9 RCTs)	arginine + ω -3 PUFAs + nucleotides	postoperative period (7 days)	liver function, inflammatory markers, immune parameters, GI recovery	first flatus MD = -14.60 h (95% CI: -16.06 to -13.15, $p < 0.001$); ALT MD = -22.26 (95% CI: -28.42 to -16.10); IL-6 MD = -46.29 (95% CI: -50.24 to -42.34); IgG MD = 1.52 (95% CI: 1.22–1.82)	safe and effective; improved liver function, reduced inflammation, and enhanced immune recovery	50

EIN – enteral immunonutrition; GI – gastrointestinal; RCTs – randomized controlled trials; PUFAs – polyunsaturated fatty acids; RNA – ribonucleic acid; LOS – length of hospital stay; RR – relative risk; OR – odds ratio; MD – mean difference; WMD – weighted mean difference; 95% CI – 95% confidence interval; EN – enteral nutrition; IMN – immunonutrition; SSI – surgical site infection; CD4 – cluster of differentiation 4 (CD4⁺ T lymphocytes); IL-6 – interleukin-6; ALT – alanine aminotransferase; IgG – immunoglobulin G.

Table 2. Early enteral nutrition (EEN) across different surgical procedures

Timing of EEN and comparator	Main outcomes	Adverse events / safety	References
EEN $\leq$ 24 h vs delayed feeding $>$ 48 h	infectious complications reduced (RR = 0.50, 95% CI: 0.38–0.67; $p < 0.01$); earlier first bowel movement (MD = -4.10 h, 95% CI: -5.38 to -2.82)	improved albumin; no increase in leak or mortality	51
Early supplemental PN (E-SPN $\leq$ 24–48 h) vs EN, L-SPN, or TPN	reduced overall adverse events (OR = 3.02, 95% CI: 1.81–5.02); infectious events (OR = 3.12, 95% CI: 1.59–6.15); non-infectious events (OR = 2.47, 95% CI: 1.14–5.34); shorter time to resumption of flatus (SMD = 0.98, 95% CI: 0.59–1.36)	no safety concerns reported	52
EN $\leq$ 24 h vs standard management $\geq$ 72 h	major complications 19.2% vs 10.2% ($p = 0.030$); infectious events ($p = 0.047$); shorter LOS ($p < 0.001$)	safe and effective; reduced ICU mortality ($p = 0.018$)	53
EEN (immunonutrition $\leq$ 24 h) vs standard diet	infectious events 7.4% vs 20% ($p < 0.05$); anastomotic leak 3.7 % vs 7.3% ($p < 0.05$); LOS 12.7 $\pm$ 2.3 vs 15.9 $\pm$ 3.4 days ($p = 0.029$)	improved cellular immunity; no difference in mortality	54
EN $\leq$ 48 h vs $>$ 48 h	28-day mortality 25.5% vs 50.0% ($p < 0.001$); mechanical ventilation 66.5% vs 80.6% ($p = 0.007$); ICU LOS 13.07 $\pm$ 16.44 vs 16.23 $\pm$ 13.57 days ($p < 0.001$); surgical subgroup: HR = 1.85 (95% CI: 1.02–3.35, $p = 0.043$)	early feeding lowered mortality and shortened ICU stay; no safety issues identified	55

EEN – early enteral nutrition; EN – enteral nutrition; PN – parenteral nutrition; E-SPN – early supplemental parenteral nutrition; L-SPN – late supplemental parenteral nutrition; TPN – total parenteral nutrition; RR – relative risk; OR – odds ratio; MD – mean difference; SMD – standardized mean difference; 95% CI – 95% confidence interval; LOS – length of hospital stay; ICU – intensive care unit; HR –hazard ratio.

supplementation with immune-enhancing nutrients, such as glutamine and ω -3 fatty acids, significantly reduces the incidence of surgical site infections and pneumonia, as well as severe complications, such as sepsis. Therefore, nutritional interventions are an indispensable adjunctive strategy for reducing postoperative infection rates.

In addition to infection rates, the duration of hospital stay and healthcare costs are important parameters for assessing the impact of nutritional interventions. The length of hospital stay is closely related to the rate of postoperative

recovery, and appropriate postoperative nutritional support has been shown to significantly shorten hospitalization. For instance, in patients undergoing surgery for gastrointestinal malignancies, early initiation of EN improved recovery efficiency, reduced postoperative complications, and decreased healthcare resource utilization.⁵⁴ Furthermore, such interventions can lower overall medical expenses, underscoring their value from an economic perspective. Nutritional interventions therefore help balance improved recovery efficiency with reduced financial burden.

Table 3. Clinical effects of ω -3 fatty acid–enriched EN or PN in postoperative and critically ill patients

Population (n)	Intervention (ω -3 dose and route)	Control	Main outcomes	Key results (effect size/p-value)	Safety	References
Gastric cancer patients undergoing Roux-en-Y reconstruction (n = 210; retrospective cohort)	PN with ω -3 fish oil emulsion 0.2 g/kg/day	standard PN	incidence of DGE; LOS; symptom score	DGE significantly lower (4.3% vs 15.5%, $p = 0.005$); shorter LOS (10 vs 13 days, $p < 0.001$); ω -3 an independent protective factor (OR = 0.32, 95% CI: 0.11–0.96, $p = 0.042$)	no adverse events reported	56
Gastric cancer patients after radical gastrectomy (n = 120, RCT)	EN + PN enriched with n-3 PUFA (postoperative days 1–5)	EN + PN without n-3 PUFA	immune and inflammatory markers (LYM, CD3 ⁺ , CD4 ⁺ , CD8 ⁺ , CD4 ⁺ /CD8 ⁺ , CRP, IL-6, TNF- α); nutritional status; complications	immune and nutritional indices $\uparrow$; CRP, IL-6, TNF- α $\downarrow$ ($p < 0.05$); complication rate 7% vs 20%; earlier first flatus / defecation	well tolerated; no differences in readmission or reoperation	57
Liver transplant recipients (n = 98, RCT)	PN containing ω -3 PUFA for 7 days post-operation	standard PN or oral diet	ALT, prealbumin (PAB), infection rate, LOS	ALT and PAB significantly improved ($p < 0.05$); infectious morbidity reduced; LOS shortened compared with PN group	no serious adverse effects	58
Mechanically ventilated ICU patients (n = 100, RCT, double-blind)	combined EN + supplemental PN enriched with ω -3 PUFA for ≤ 28 days	EN + PN without ω -3 PUFA	change in PaO ₂ /FiO ₂ (from day 1 to day 4); ICU outcomes; catecholamine-free days	no difference in PaO ₂ /FiO ₂ (-1.3 ± 83.7 vs 13.3 ± 86.1 , $p = 0.780$); more catecholamine-free days (~ 4 days, $p = 0.048$); higher EN tolerance at day 6 (51.0% vs 29.8%, $p = 0.034$)	safe; no ω -3-related adverse events	59

PN – parenteral nutrition; EN – enteral nutrition; PUFA – polyunsaturated fatty acid; DGE – delayed gastric emptying; LOS – length of hospital stay; OR – odds ratio; 95% CI – 95% confidence interval; RCT – randomized controlled trial; LYM – lymphocyte count; CD3⁺ – cluster of differentiation 3-positive T lymphocytes; CD4⁺ – cluster of differentiation 4-positive T lymphocytes; CD8⁺ – cluster of differentiation 8-positive T lymphocytes; CRP – C-reactive protein; IL-6 – interleukin-6; TNF- α – tumor necrosis factor alpha; ALT – alanine aminotransferase; PAB – prealbumin; ICU – intensive care unit.

Functional recovery metrics reflect improvements in patients' overall physical performance after surgery. These metrics include muscle strength, mobility, and the ability to perform activities of daily living, which are often key goals of postoperative recovery. Surgical trauma and postoperative inflammation can increase protein catabolism, whereas nutritional interventions that support protein synthesis and tissue repair can accelerate functional recovery. For example, adequate protein and amino acid supplementation in the early postoperative phase significantly improved muscle strength, which is critical for long-term recovery and improved QoL.⁶⁰

Finally, QoL scores serve as a comprehensive measure of postoperative recovery outcomes. These scores assess not only physical function but also psychological well-being and social participation, with commonly used tools including the 36-Item Short Form Health Survey (SF-36) and the EuroQol 5-Dimension Questionnaire (EQ-5D). Comprehensive nutritional interventions combining protein, micronutrients, and immune-enhancing nutrients significantly improve QoL, particularly by enhancing psychological wellbeing and restoring social engagement. These effects extend beyond the early recovery phase and can profoundly influence long-term patient outcomes. Thus, QoL scores are an indispensable component when evaluating the effectiveness of nutritional interventions.

Integrating these evaluation metrics allows clinical research to comprehensively reflect the practical effects

of nutritional interventions across multiple dimensions. This approach not only provides a scientific foundation for developing more precise and effective intervention plans but also offers new directions for optimizing postoperative nutritional support strategies.

Technologies and emerging trends in nutritional interventions

Nutrigenomics and personalized nutritional interventions

With the rapid development of omics technologies, nutrigenomics offers new tools for exploring personalized nutritional interventions. By integrating data from genomics, transcriptomics, metabolomics, and microbiomics, nutrigenomics reveals interindividual differences in nutrient requirements and metabolic responses, thereby enabling precision nutritional strategies. For instance, genomic data can identify genetic variations in key metabolic pathways and predict an individual's capacity to metabolize specific nutrients. Metabolomics enables real-time monitoring of postoperative patients' metabolic status, providing dynamic feedback for optimizing nutritional plans. Research indicates substantial potential for precision nutritional interventions in postoperative recovery. For example,

supplementation with specific micronutrients, such as folic acid or vitamin D, in patients with certain genetic variants can effectively improve postoperative immune and metabolic function.⁶¹ Additionally, dietary interventions targeting the gut microbiota, informed by microbiomics data, have been shown to significantly alleviate postoperative inflammation and improve immune function.^{62,63} These findings highlight that nutrigenomics provides a solid scientific foundation for developing personalized nutritional intervention strategies.

Development of novel nutritional formulations

Traditional postoperative nutritional support has primarily focused on meeting basic energy and nutrient requirements. However, recent advances in novel nutritional formulations have emphasized functionality and specificity. For instance, immune-enhancing formulas enriched with glutamine, arginine, and ω -3 fatty acids can effectively lower the risk of postoperative complications by modulating inflammatory responses and enhancing immune function. Nutritional formulations containing antioxidants, such as vitamins C and E, are intended to reduce oxidative damage, thereby promoting tissue repair. Functional foods and supplements derived from natural products are emerging as new areas of focus in postoperative recovery. For example, plant-derived polyphenols, which exhibit anti-inflammatory and antioxidant properties,⁶⁴ have been used to mitigate postoperative inflammatory responses. Similarly, the combined use of probiotics and prebiotics can optimize the balance of the gut microbiota, further enhancing postoperative immune recovery and metabolic regulation.⁶⁵ In the future, the development of novel nutritional formulations will increasingly focus on personalized approaches tailored to specific types of surgery and patient characteristics.

Digital technology in nutritional management

Digital technologies are revolutionizing postoperative nutritional management by enabling real-time monitoring and targeted interventions through wearable devices and artificial intelligence (AI). Wearable devices continuously monitor physiological parameters, such as body weight, temperature, heart rate, and activity levels, providing important reference data for adjusting nutritional support during recovery. For example, changes in body weight and fluid status can be used to assess hydration and energy balance, helping optimize nutritional support plans. AI technologies use big-data analytics to predict postoperative nutritional requirements and assess the risk of potential complications. AI models based on pre- and postoperative data can generate personalized nutritional recommendations, including energy intake, macronutrient ratios, and specific micronutrient supplementation.

Furthermore, smartphone applications and telemedicine platforms facilitate seamless communication between patients and healthcare teams, enhancing adherence to nutritional interventions and improving their effectiveness. As digital technologies continue to evolve, integrated nutritional management systems combining AI, the Internet of Things (IoT), and smart sensors are expected to be applied more widely in postoperative recovery. This technology-driven approach not only improves the precision and efficiency of interventions but also provides patients with higher-quality, personalized care.

Current status and challenges

Limitations of molecular mechanism research

Despite significant progress in understanding the molecular mechanisms underlying nutritional interventions, many unresolved issues remain. Current research primarily focuses on the effects of individual nutrients, such as glutamine or ω -3 fatty acids, with limited exploration of interactions among multiple nutrients and their combined impact on postoperative recovery. Additionally, most studies rely on *in vitro* experiments or animal models, leaving the applicability of their results to postoperative recovery in humans uncertain. For instance, the influence of different types of surgery and interindividual variability on molecular pathways remains unclear, hindering the translation of research findings into clinical practice. Moreover, studies at the molecular level often overlook the complex relationship between nutritional interventions and patients' overall physiological status. Postoperative inflammation and immune regulation involve intricate interactions among multiple signaling pathways, and the ways in which nutrients dynamically modulate these pathways to promote recovery remain inadequately understood. Future research should adopt systems biology approaches and integrate multi-omics technologies, such as metabolomics, proteomics, and transcriptomics, to comprehensively elucidate the mechanisms of nutritional interventions.

Challenges in clinical practice

In clinical practice, balancing the need for standardized nutritional intervention protocols with the demand for individualized care remains a major challenge. Although unified clinical nutrition guidelines, such as the ESPEN Practical Guideline for Clinical Nutrition in Surgery,⁴¹ are available, variation in their adoption and adherence across institutions remains a major obstacle. This lack of standardization not only limits the comparability of research outcomes but also reduces the efficiency of clinical implementation. On the other hand, postoperative nutritional needs vary significantly among individuals due to factors

such as age, basal metabolic status, and type of surgery, which influence specific nutrient requirements. Achieving personalized nutritional support within a standardized framework remains an unresolved issue.

Additionally, adherence to postoperative nutritional interventions poses a challenge in clinical settings. Some patients may find it difficult to fully comply with nutritional plans because of postoperative discomfort, psychological stress, or financial constraints, thereby limiting the effectiveness of interventions. Future clinical studies should focus on strategies to improve adherence and satisfaction, such as psychological support, digital technologies, and telemedicine.

Moreover, the quality and applicability of existing evidence vary across types of surgery. Parenteral nutrition may increase the risk of catheter-related infection and metabolic complications, while excessive micronutrient supplementation, such as zinc, copper, or antioxidants, can cause toxicity. The optimal dose and duration of immunonutrition remain uncertain. Larger, well-designed trials are needed to improve the quality of evidence and guide safe, standardized practice.

Future research directions

Integration of multidisciplinary research strategies

Research on nutritional interventions in postoperative recovery should emphasize multidisciplinary collaboration and integration, particularly by bridging basic research and clinical application. Multi-omics technologies, such as genomics, metabolomics, and microbiomics, offer powerful tools for analyzing the dynamic effects of nutritional interventions. For example, metabolomics can help identify metabolic changes in postoperative patients and clarify which nutrients play key roles in repair and recovery, while microbiomics can reveal how the gut microbiota regulate immune function and support strategies involving probiotics and dietary fiber. Systems biology methods can integrate these omics data to construct comprehensive models of nutritional metabolic networks, providing insights into the multilayered regulatory effects of nutritional interventions at the molecular level. Such approaches not only clarify complex mechanisms but also provide theoretical support for developing precise and individualized intervention strategies. Future research should also focus on dynamically monitoring postoperative metabolic states and integrating omics technologies to optimize intervention strategies, thereby enabling real-time, precision nutritional support.

Strengthening cross-disciplinary collaboration

Advancing the research and application of nutritional interventions requires combining expertise from clinical

nutrition, surgery, immunology, and data science to develop innovative and effective strategies. Surgery provides the clinical context and identifies the need for nutritional interventions, while clinical nutrition enables the design of scientifically sound dietary and nutritional support plans based on postoperative conditions. Immunology research sheds light on how specific nutrients regulate inflammation and immune responses, offering new insights into the prevention of postoperative infections and complications. Furthermore, data science and AI play critical roles in optimizing intervention plans. Nutritional models based on big-data analytics can predict postoperative recovery trajectories in different patients and generate personalized nutritional recommendations. For example, AI algorithms can dynamically adjust the energy and nutrient composition of nutritional formulas based on pre- and postoperative physiological parameters, thereby improving the precision of interventions. Future research should emphasize cross-disciplinary collaboration and the joint development of digital nutrition management platforms that enhance patient adherence and improve the overall effectiveness of postoperative interventions.

Limitations of the study

This review has several limitations. The included studies vary in terms of types of surgery, nutritional protocols, and outcome measures, which introduces heterogeneity and limits direct comparability. Some sections rely on mechanistic or observational data rather than randomized evidence, and no quantitative meta-analysis was conducted. These factors should be considered when interpreting the findings. Future large-scale, standardized RCTs are needed to validate the conclusions and strengthen the evidence base.

Conclusions

Nutritional interventions play an important role in postoperative recovery by reducing inflammation, enhancing immune function, promoting tissue repair, and optimizing metabolic balance. Existing studies suggest that nutritional interventions may help shorten recovery time, reduce complications, and improve patients' QoL. However, current research on nutritional interventions has several limitations, including an incomplete understanding of molecular mechanisms, a lack of standardized intervention protocols, and insufficient integration of individualized needs into clinical practice. Further high-quality, multidisciplinary research is needed to address these gaps. By integrating cutting-edge technologies, such as nutrigenomics, metabolomics, and microbiomics, future studies will be able to reveal the mechanisms of nutritional interventions more comprehensively and provide scientific evidence for precision nutritional support. In clinical practice, developing

more systematic and standardized postoperative nutritional management guidelines, together with individualized plans, will help optimize patient outcomes. This approach not only enhances the effectiveness of interventions but also advances the field of postoperative recovery, benefiting a broader range of patients. In summary, nutritional interventions represent a promising strategy for supporting postoperative recovery. Continued research and implementation will further improve patient outcomes and promote integration between medicine and nutritional science.

Use of AI and AI-assisted technologies

Not applicable.

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References

- Margraf A, Ludwig N, Zarbock A, Rossaint J. Systemic inflammatory response syndrome after surgery: Mechanisms and protection. *Anesth Analg*. 2020;131(6):1693–1707. doi:10.1213/ANE.0000000000005175
- Cao S, Tang J, Fei M, et al. Identification of potential hub genes linked to immune and metabolic alterations in postoperative systemic inflammatory dysregulation. *Front Immunol*. 2023;14:1238774. doi:10.3389/fimmu.2023.1238774
- World Health Organization (WHO). *Global Guidelines for the Prevention of Surgical Site Infection*. 2nd ed. Geneva, Switzerland: World Health Organization (WHO); 2018. ISBN:978-92-4-155047-5.
- Allegranzi B, Zayed B, Bischoff P, et al. New WHO recommendations on intraoperative and postoperative measures for surgical site infection prevention: An evidence-based global perspective. *Lancet Infect Dis*. 2016;16(12):e288–e303. doi:10.1016/S1473-3099(16)30402-9
- Javed H, Olanrewaju OA, Ansah Owusu F, et al. Challenges and solutions in postoperative complications: A narrative review in general surgery. *Cureus*. 2023;15(12):e50942. doi:10.7759/cureus.50942
- Martínez-Ortega AJ, Piñar-Gutiérrez A, Serrano-Aguayo P, et al. Perioperative nutritional support: A review of current literature. *Nutrients*. 2022;14(8):1601. doi:10.3390/nu14081601
- Adiamah A, Skořepa P, Weimann A, Lobo DN. The impact of preoperative immune modulating nutrition on outcomes in patients undergoing surgery for gastrointestinal cancer: A systematic review and meta-analysis. *Ann Surg*. 2019;270(2):247–256. doi:10.1097/SLA.0000000000003256
- Piekarska B, Prusisz M, Włodarczyk M, et al. The impact of preoperative and postoperative nutritional interventions on treatment outcomes and quality of life in colorectal cancer patients: A comprehensive review. *Medicina (Kaunas)*. 2024;60(10):1587. doi:10.3390/medicina60101587
- Kirsch R, Brown C, Stroud A, Rosenthal M, Martindale R, Kavalukas S. Macronutrients, micronutrients, and integrative medical products in wound healing. *Curr Surg Rep*. 2023;11(9):216–224. doi:10.1007/s40137-023-00364-x
- Chen X, Wu S, Chen C, et al. Omega-3 polyunsaturated fatty acid supplementation attenuates microglial-induced inflammation by inhibiting the HMGB1/TLR4/NF- κ B pathway following experimental traumatic brain injury. *J Neuroinflammation*. 2017;14(1):143. doi:10.1186/s12974-017-0917-3
- Zgórzńska E, Stulczewski D, Dziedzic B, Su KP, Walczewska A. Docosahexaenoic fatty acid reduces the pro-inflammatory response induced by IL-1 β in astrocytes through inhibition of NF- κ B and AP-1 transcription factor activation. *BMC Neurosci*. 2021;22(1):4. doi:10.1186/s12868-021-00611-w
- Lorenz KJ, Schallert R, Daniel V. Immunonutrition: The influence of early postoperative glutamine supplementation in enteral/parenteral nutrition on immune response, wound healing and length of hospital stay in multiple trauma patients and patients after extensive surgery. *GMS Interdiscip Plast Reconstr Surg DGPW*. 2015;4:Doc15. doi:10.3205/IPRS000074
- McClave SA, Taylor BE, Martindale RG, et al; Society of Critical Care Medicine; American Society for Parenteral and Enteral Nutrition. Guidelines for the Provision and Assessment of Nutrition Support Therapy in the Adult Critically Ill Patient: Society of Critical Care Medicine (SCCM) and American Society for Parenteral and Enteral Nutrition (ASPEN). *JPEN J Parenter Enteral Nutr*. 2016;40(2):159–211. doi:10.1177/0148607115621863
- Bain CR, Myles PS, Corcoran T, Dieleman JM. Postoperative systemic inflammatory dysregulation and corticosteroids: A narrative review. *Anaesthesia*. 2023;78(3):356–370. doi:10.1111/anae.15896
- Wunderle C, Stumpf F, Schuetz P. Inflammation and response to nutrition interventions. *JPEN J Parenter Enteral Nutr*. 2024;48(1):27–36. doi:10.1002/jpen.2534
- Carracedo M, Artiaç G, Arnardottir H, Bäck M. The resolution of inflammation through omega-3 fatty acids in atherosclerosis, intimal hyperplasia, and vascular calcification. *Semin Immunopathol*. 2019;41(6):757–766. doi:10.1007/s00281-019-00767-y
- Abdolmaleki F, Kovanen PT, Mardani R, Gheibi-hayat SM, Bo S, Sahebkar A. Resolvins: Emerging players in autoimmune and inflammatory diseases. *Clinic Rev Allerg Immunol*. 2020;58(1):82–91. doi:10.1007/s12016-019-08754-9
- Oldman AH, Martin DS, Feelisch M, Grocott MPW, Cumpstey AF. Effects of perioperative oxygen concentration on oxidative stress in adult surgical patients: A systematic review. *Br J Anaesth*. 2021;126(3):622–632. doi:10.1016/j.bja.2020.09.050
- Hong Y, Boiti A, Vallone D, Foulkes NS. Reactive oxygen species signaling and oxidative stress: Transcriptional regulation and evolution. *Antioxidants (Basel)*. 2024;13(3):312. doi:10.3390/antiox13030312
- Zhitkovich A. Nuclear and cytoplasmic functions of vitamin C. *Chem Res Toxicol*. 2020;33(10):2515–2526. doi:10.1021/acs.chemrestox.0c00348
- Kamal-Eldin A. Antioxidative activity of vitamin E. In: Weber P, Birringer M, Blumberg JB, Eggersdorfer M, Frank J, eds. *Vitamin E in Human Health*. Cham, Switzerland: Springer International Publishing; 2019:19–30. doi:10.1007/978-3-030-05315-4_3
- Castillo R, Rodrigo R, Perez F, et al. Antioxidant therapy reduces oxidative and inflammatory tissue damage in patients subjected to cardiac surgery with extracorporeal circulation. *Basic Clin Pharmacol Toxicol*. 2011;108(4):256–262. doi:10.1111/j.1742-7843.2010.00651.x
- Cruzat V, Macedo Rogero M, Noel Keane K, Curi R, Newsholme P. Glutamine: Metabolism and immune function, supplementation and clinical translation. *Nutrients*. 2018;10(11):1564. doi:10.3390/nu10111564
- de Oliveira DC, da Silva Lima F, Sartori T, Santos ACA, Rogero MM, Fock RA. Glutamine metabolism and its effects on immune response: Molecular mechanism and gene expression. *Nutrire*. 2016;41(1):14. doi:10.1186/s41110-016-0016-8
- Kuhn KS, Muscaritoli M, Wischmeyer P, Stehle P. Glutamine as indispensable nutrient in oncology: Experimental and clinical evidence. *Eur J Nutr*. 2010;49(4):197–210. doi:10.1007/s00394-009-0082-2
- Wang B, Wu G, Zhou Z, et al. Glutamine and intestinal barrier function. *Amino Acids*. 2015;47(10):2143–2154. doi:10.1007/s00726-014-1773-4
- Tang G, Pi F, Qiu YH, Wei ZQ. Postoperative parenteral glutamine supplementation improves the short-term outcomes in patients undergoing colorectal cancer surgery: A propensity score matching study. *Front Nutr*. 2023;10:1040893. doi:10.3389/fnut.2023.1040893
- Lederer AK, Pisarski P, Kousoulas L, Fichtner-Feigl S, Hess C, Huber R. Postoperative changes of the microbiome: Are surgical complications related to the gut flora? A systematic review. *BMC Surg*. 2017;17(1):125. doi:10.1186/s12893-017-0325-8
- Gunaswetha K, Sujatha E, Anusha K, et al. Understanding the probiotics and mechanism of immunomodulation interactions with the gut-related immune system. In: Veera Bramhachari P, ed. *Human Microbiome in Health, Disease, and Therapy*. Singapore: Springer Nature Singapore; 2023:67–79. doi:10.1007/978-981-99-5114-7_4
- La Fata G, Weber P, Mohajeri MH. Probiotics and the gut immune system: Indirect regulation. *Probiotics Antimicrob Proteins*. 2018;10(1):11–21. doi:10.1007/s12602-017-9322-6

31. Facchin S, Bertin L, Bonazzi E, et al. Short-chain fatty acids and human health: From metabolic pathways to current therapeutic implications. *Life (Basel)*. 2024;14(5):559. doi:10.3390/life14050559
32. Frolova MS, Suvorova IA, Iablokov SN, Petrov SN, Rodionov DA. Genomic reconstruction of short-chain fatty acid production by the human gut microbiota. *Front Mol Biosci*. 2022;9:949563. doi:10.3389/fmolb.2022.949563
33. Sun M, Wu W, Liu Z, Cong Y. Microbiota metabolite short chain fatty acids, GPCR, and inflammatory bowel diseases. *J Gastroenterol*. 2017;52(1):1–8. doi:10.1007/s00535-016-1242-9
34. Karim MdR, Iqbal S, Mohammad S, et al. Butyrate's (a short-chain fatty acid) microbial synthesis, absorption, and preventive roles against colorectal and lung cancer. *Arch Microbiol*. 2024;206(4):137. doi:10.1007/s00203-024-03834-7
35. Trone K, Rahman S, Green CH, Venegas C, Martindale R, Stroud A. Synbiotics and surgery: Can prebiotics and probiotics affect inflammatory surgical outcomes? *Curr Nutr Rep*. 2023;12(2):238–246. doi:10.1007/s13668-023-00464-1
36. Holowaty MNH, Lees MJ, Abou Sawan S, et al. Leucine ingestion promotes mTOR translocation to the periphery and enhances total and peripheral RPS6 phosphorylation in human skeletal muscle. *Amino Acids*. 2023;55(2):253–261. doi:10.1007/s00726-022-03221-w
37. Mariggiò MA, Cassano A, Vinella A, et al. Enhancement of fibroblast proliferation, collagen biosynthesis and production of growth factors as a result of combining sodium hyaluronate and aminoacids. *Int J Immunopathol Pharmacol*. 2009;22(2):485–492. doi:10.1177/039463200902200225
38. Lansdown ABG, Mirastschijski U, Stubbs N, Scanlon E, Ågren MS. Zinc in wound healing: Theoretical, experimental, and clinical aspects. *Wound Repair Regen*. 2007;15(1):2–16. doi:10.1111/j.1524-475X.2006.00179.x
39. Gérard C, Bordeleau LJ, Barralet J, Doillon CJ. The stimulation of angiogenesis and collagen deposition by copper. *Biomaterials*. 2010;31(5):824–831. doi:10.1016/j.biomaterials.2009.10.009
40. Weimann A, Braga M, Carli F, et al. ESPEN practical guideline: Clinical nutrition in surgery. *Clin Nutr*. 2021;40(7):4745–4761. doi:10.1016/j.clnu.2021.03.031
41. Berger MM, Shenkin A, Schweinlin A, et al. ESPEN micronutrient guideline [published correction appears in: *Clin Nutr*. 2024;43(4):1024. doi:10.1016/j.clnu.2024.03.004]. *Clin Nutr*. 2022;41(6):1357–1424. doi:10.1016/j.clnu.2022.02.015
42. Klek S. Omega-3 fatty acids in modern parenteral nutrition: A review of the current evidence. *J Clin Med*. 2016;5(3):34. doi:10.3390/jcm5030034
43. Kang CM, Yun B, Kim M, et al. Postoperative serum metabolites of patients on a low carbohydrate ketogenic diet after pancreatectomy for pancreaticobiliary cancer: A nontargeted metabolomics pilot study. *Sci Rep*. 2019;9(1):16820. doi:10.1038/s41598-019-53287-y
44. Hu Q, Ren H, Hong Z, et al. Early enteral nutrition preserves intestinal barrier function through reducing the formation of neutrophil extracellular traps (NETs) in critically ill surgical patients. *Oxid Med Cell Longev*. 2020;2020:8815655. doi:10.1155/2020/8815655
45. Wanchoo J. Monitoring and complications of total parenteral nutrition. In: Prabhakar H, Tandon MS, Kapoor I, Mahajan C, eds. *Transfusion Practice in Clinical Neurosciences*. Singapore: Springer Nature Singapore; 2022:585–595. doi:10.1007/978-981-19-0954-2_49
46. Wobith M, Weimann A. Postoperative nutrition management: Who needs what? *Visc Med*. 2022;38(5):354–362. doi:10.1159/000526665
47. Shen J, Dai S, Li Z, et al. Effect of enteral immunonutrition in patients undergoing surgery for gastrointestinal cancer: An updated systematic review and meta-analysis. *Front Nutr*. 2022;9:941975. doi:10.3389/fnut.2022.941975
48. Khan A, Wong J, Riedel B, et al. The impact of peri-operative enteral immunonutrition on post-operative complications in gastrointestinal cancer surgery: A meta-analysis. *Ann Surg Oncol*. 2023;30(6):3619–3631. doi:10.1245/s10434-023-13265-1
49. Zheng Y, Li F, Qi B, et al. Application of perioperative immunonutrition for gastrointestinal surgery: A meta-analysis of randomized controlled trials. *Asia Pac J Clin Nutr*. 2007;16(Suppl 1):253–257. PMID:17392114.
50. Chen X, Wang D, Liang S, Yang J, Li K. Effect of enteral ecoimmunonutrition support for patients undergoing hepatectomy: A meta-analysis of randomized controlled trials. *Eur J Clin Nutr*. 2022;76(8):1133–1141. doi:10.1038/s41430-022-01073-x
51. Shu XL, Kang K, Gu LJ, Zhang YS. Effect of early enteral nutrition on patients with digestive tract surgery: A meta-analysis of randomized controlled trials. *Exp Ther Med*. 2016;12(4):2136–2144. doi:10.3892/etm.2016.3559
52. Wang T, Huang J, Shang Z, et al. Efficacy and safety of nutrition therapy for patients undergoing abdominal surgery: A systematic review and network meta-analysis. *Eur J Clin Nutr*. 2025;79(11):1078–1086. doi:10.1038/s41430-025-01637-7
53. Martos-Benítez FD, Gutiérrez-Noyola A, Soto-García A, González-Martínez I, Betancourt-Plaza I. Program of gastrointestinal rehabilitation and early postoperative enteral nutrition: A prospective study. *Updates Surg*. 2018;70(1):105–112. doi:10.1007/s13304-018-0514-8
54. Marano L, Porfidia R, Pezzella M, et al. Clinical and immunological impact of early postoperative enteral immunonutrition after total gastrectomy in gastric cancer patients: A prospective randomized study. *Ann Surg Oncol*. 2013;20(12):3912–3918. doi:10.1245/s10434-013-3088-1
55. Hadi V, Amiri Khosroshahi R, Imani H, et al. Impact of early versus delayed enteral nutrition on ICU outcomes: A comparative study on mortality, ventilator dependence, and length of stay. *Eur J Med Res*. 2025;30(1):315. doi:10.1186/s40001-025-02579-3
56. Jing S, Chen H, Bao L, et al. Effects of perioperative ω -3 fish oil fat emulsion on postoperative gastric emptying function following Roux-en-Y reconstruction for gastric cancer. *J Gastrointest Surg*. 2025;29(7):102066. doi:10.1016/j.gassur.2025.102066
57. Yang J, Zhang X, Li K, et al. Effects of EN combined with PN enriched with n-3 polyunsaturated fatty acids on immune related indicators and early rehabilitation of patients with gastric cancer: A randomized controlled trial. *Clin Nutr*. 2022;41(6):1163–1170. doi:10.1016/j.clnu.2022.03.018
58. Zhu X, Wu Y, Qiu Y, Jiang C, Ding Y. Effects of ω -3 fish oil lipid emulsion combined with parenteral nutrition on patients undergoing liver transplantation. *JPN J Parenter Enteral Nutr*. 2013;37(1):68–74. doi:10.1177/0148607112440120
59. Singer P, Bendavid I, Mesilati-Stahy R, et al. Enteral and supplemental parenteral nutrition enriched with omega-3 polyunsaturated fatty acids in intensive care patients: A randomized, controlled, double-blind clinical trial. *Clin Nutr*. 2021;40(5):2544–2554. doi:10.1016/j.clnu.2021.03.034
60. Hirsch KR, Wolfe RR, Ferrando AA. Pre- and post-surgical nutrition for preservation of muscle mass, strength, and functionality following orthopedic surgery. *Nutrients*. 2021;13(5):1675. doi:10.3390/nu13051675
61. Usategui-Martín R, De Luis-Román DA, Fernández-Gómez JM, Ruiz-Mambrilla M, Pérez-Castrillón JL. Vitamin D receptor (VDR) gene polymorphisms modify the response to vitamin D supplementation: A systematic review and meta-analysis. *Nutrients*. 2022;14(2):360. doi:10.3390/nu14020360
62. Bilal M, Ashraf S, Zhao X. Dietary component-induced inflammation and its amelioration by prebiotics, probiotics, and synbiotics. *Front Nutr*. 2022;9:931458. doi:10.3389/fnut.2022.931458
63. Paudel D, Nair DVT, Joseph G, Castro R, Tiwari AK, Singh V. Gastrointestinal microbiota-directed nutritional and therapeutic interventions for inflammatory bowel disease: Opportunities and challenges. *Gastroenterol Rep (Oxf)*. 2023;12:goae033. doi:10.1093/gastro/goae033
64. Chen H, Li Y, Wang J, et al. Plant polyphenols attenuate DSS-induced ulcerative colitis in mice via antioxidation, anti-inflammation and microbiota regulation. *Int J Mol Sci*. 2023;24(13):10828. doi:10.3390/ijms241310828
65. Kim YT, Mills DA. Exploring the gut microbiome: Probiotics, prebiotics, synbiotics, and postbiotics as key players in human health and disease improvement. *Food Sci Biotechnol*. 2024;33(9):2065–2080. doi:10.1007/s10068-024-01620-1