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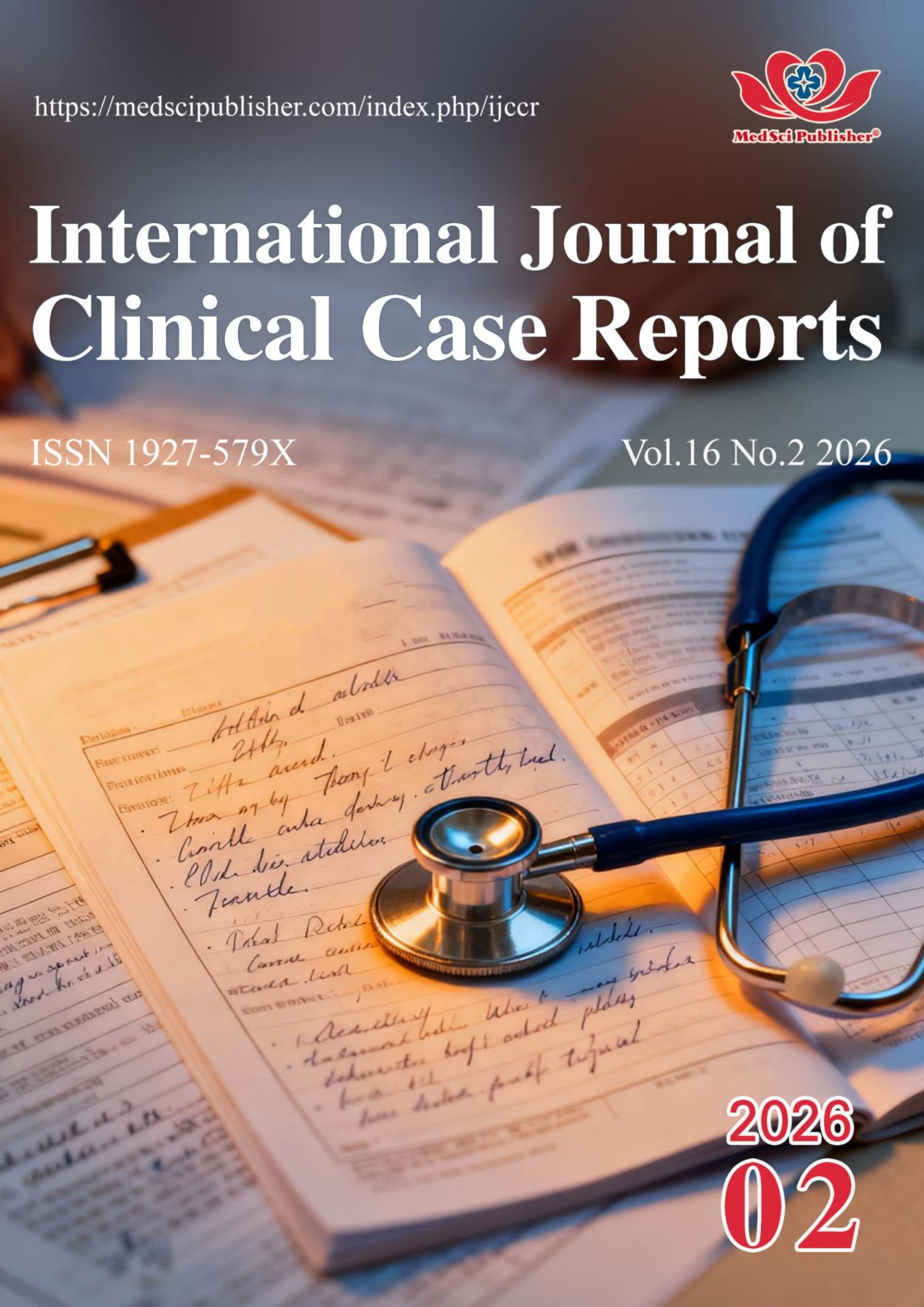

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Feature Review Open Access

Nursing-Sensitive Indicators and Quality Improvement for Inpatient Adverse Events Among Older Patients

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Abstract With the rapid aging of the population, older adults have become a major proportion of hospitalized patients, and their risk of experiencing adverse events during hospitalization is significantly higher than that of other age groups. Adverse events such as falls, pressure injuries, infections, delirium, and medication-related harm not only threaten patient safety but also contribute to prolonged hospital stays, functional decline, and increased mortality, with a substantial proportion considered preventable. Nursing care plays a critical role in both the occurrence and prevention of these events. Nursing-sensitive indicators (NSIs), which reflect changes in patient outcomes influenced by nursing structures, processes, and interventions, provide essential tools for evaluating nursing quality and supporting continuous quality improvement. Based on a comprehensive review of domestic and international literature, this article summarizes the epidemiological characteristics and major risk factors of adverse events among hospitalized older patients. It focuses on the conceptual foundations, key categories, and selection principles of nursing-sensitive indicators related to adverse events, and examines their current applications and limitations in nursing quality evaluation, risk surveillance, and quality improvement initiatives. The findings suggest that establishing an NSI-oriented quality management framework can facilitate early identification of risks and targeted nursing interventions for hospitalized older adults. Future efforts should prioritize the standardization, geriatric specificity, and digital integration of nursing-sensitive indicators to further enhance patient safety and nursing quality in geriatric inpatient care.

Keywords Older patients; Adverse events; Nursing-sensitive indicators; Nursing quality; Quality improvement

1 Introduction

With the accelerating process of population aging in China, older adults have become an important component of the hospitalized population. A large body of research indicates that, due to multiple factors such as age-related physiological decline, multimorbidity, frailty, complex treatment regimens, and geriatric syndromes, older patients face a significantly higher risk of experiencing adverse events (AEs) during hospitalization than other age groups. Systematic reviews show that in large general studies of adverse events, the incidence of AEs among hospitalized older medical patients is approximately 5%-6%; however, when geriatric syndromes such as falls, delirium, incontinence, and pressure injuries are included within the scope of adverse events, the incidence can be as high as 60%. Common hospital-associated adverse events include infections (e.g., pneumonia, urinary tract infections, sepsis, and wound infections), delirium, falls, pressure injuries, venous thromboembolism, and medication-related harm (Alotaibi et al., 2025). These adverse events not only pose direct threats to patient safety but also lead to prolonged hospital stays, increased healthcare resource utilization, functional decline, and even increased mortality risk. Importantly, a substantial proportion of these events are considered at least partially preventable.

Among the many influencing factors, nursing activities are closely associated with both the occurrence and prevention of adverse events in older hospitalized patients. Previous studies have shown that many adverse events occurring during hospitalization-particularly falls, pressure injuries, infections, medication-related harm, and delirium-are strongly associated with inadequate nursing assessment, insufficient ongoing monitoring, and

delayed interventions. This issue is especially prominent among older patients with cognitive impairment or dementia, who experience higher rates of preventable adverse events such as falls, delirium, and infections, and who often have longer hospital stays, higher readmission rates, and increased mortality risk (Catalán and Oliveira, 2025; Järbrink et al., 2025; Schouten et al., 2025). Collectively, this evidence highlights the central role of nursing safety in the inpatient management of older adults and underscores the need for more targeted indicator systems to systematically evaluate and continuously improve nursing quality and its relationship with adverse events.

Nursing-sensitive indicators (NSIs) are quantitative measures that directly or indirectly reflect the structure, processes, and outcomes of nursing care and are primarily influenced by nursing actions, thereby capturing changes in health status that can be modified by nursing practice. Concept analyses and systematic reviews consistently indicate that NSIs provide objective and comparable evidence for nursing quality monitoring, quality improvement, and organizational-level decision-making. Among hospitalized older patients, commonly used and representative nursing-sensitive indicators include fall rates, pressure injury rates, hospital-acquired infections, medication administration errors, length of stay, functional decline, and patient satisfaction (Goes et al., 2023; Wang et al., 2025). In long-term care and residential aged care settings, structured medication reviews, pain, dehydration, urinary tract infections, falls, behavioral symptoms, depression, weight loss, and decline in activities of daily living have been identified through Delphi studies and review research as priority nursing-sensitive quality indicators for frail older populations (Tevik et al., 2023). These indicators encompass key domains in which nursing practice has the greatest potential to prevent harm and maintain functional ability in older adults.

In recent years, nursing-sensitive indicators have increasingly become important tools for nursing quality evaluation and continuous quality improvement (QI) both nationally and internationally, and they have been widely applied in geriatric nursing. Existing evidence suggests that structured medication reviews, multifactorial fall risk assessment and prevention bundles, and enhanced identification interventions for adverse drug events-when implemented using nursing-sensitive indicators-can to some extent reduce the occurrence of specific types of adverse events or improve their detection. However, findings remain heterogeneous, and implementation is often challenged by insufficient integration and sustainability issues (Sultana et al., 2025). Moreover, current research on nursing-sensitive indicators is largely fragmented across different care settings and indicator types, and there remains a relative lack of systematic exploration of how to construct and apply comprehensive indicator sets to drive sustained improvements in nursing quality for hospitalized older patients (Tevik et al., 2023; Connolly et al., 2025).

Against this backdrop, the present review focuses on nursing-sensitive indicators related to adverse events and nursing quality improvement during hospitalization of older patients. It systematically synthesizes the epidemiological characteristics and preventability evidence of adverse events among hospitalized older adults, with particular attention to high-risk factors such as frailty and cognitive impairment. It identifies key nursing-sensitive indicators closely associated with adverse events in older inpatients and elucidates their conceptual foundations and empirical evidence. Furthermore, it analyzes the current applications and limitations of nursing-sensitive indicators in geriatric nursing quality evaluation and quality improvement practices, and explores their application pathways and future directions in areas including falls, pressure injuries, infections, medication-related harm, functional decline, and patient experience. This review aims to provide evidence-based support and practical guidance for clinical nurses, nursing managers, and policymakers, to promote the standardized and systematic application of nursing-sensitive indicators in the quality management of inpatient geriatric nursing, ultimately improving patient safety and nursing quality for hospitalized older adults.

2 Characteristics of Adverse Events in Hospitalized Older Patients

2.1 Relationship between physiological and psychological characteristics and adverse events

Older patients commonly experience multisystem functional decline at the physiological level, which constitutes a fundamental internal basis for the occurrence of adverse events during hospitalization. Aging is frequently accompanied by frailty, multimorbidity, and polypharmacy, leading to reduced physiological reserve and increased vulnerability, thereby significantly elevating the risk of hospital-associated adverse events such as

healthcare-associated infections, delirium, falls, pressure injuries, and venous thromboembolism. Mechanistically, declines in sensory, neurological, and musculoskeletal function-including visual and auditory impairment, slowed reaction time, impaired balance, and reduced muscle strength-predispose patients to falls and bed-related injuries during mobility, transfers, and activities of daily living. Meanwhile, reduced skin elasticity, impaired local circulation, and malnutrition decrease tissue tolerance to pressure and shear, increasing the likelihood of pressure injury development (Alotaibi et al., 2025). In addition, age-related declines in hepatic and renal function and impaired homeostatic regulation may alter pharmacokinetics and pharmacodynamics, rendering standard treatments more likely to cause harm, particularly in the context of polypharmacy, and increasing the risk of adverse drug reactions (ADRs) and adverse drug events (ADEs). Systematic reviews indicate that the pooled incidence of in-hospital ADRs among older patients is approximately 16%-22%, with most being predictable, dose-related, and at least partially preventable; risk factors include polypharmacy, potentially inappropriate medications, and impaired renal or hepatic function.

Psychological and cognitive characteristics also exert a profound influence on the risk of adverse events. Cognitive impairment-including delirium, dementia, and mild cognitive impairment-is common among hospitalized older adults and is associated with a higher likelihood of adverse events, particularly when combined with a high burden of comorbidity. Studies suggest that in cognitively impaired patients, adverse events are more frequently linked to failures in nursing care, allied health management, and organizational processes, such as inadequate supervision, communication breakdowns, and poor care coordination (Schouten et al., 2025). Furthermore, hospitalization itself may initiate a cascade of "hospital-associated harms" that are not fully attributable to the primary illness: functional declines such as confusion, reduced oral intake, incontinence, and falls may trigger further invasive interventions (e.g., restraints, catheterization, enteral feeding), leading to downstream complications such as thromboembolism and infection. Emotional distress, sleep deprivation, sensory overstimulation or deprivation, and unfamiliar environments may exacerbate delirium and behavioral symptoms, thereby increasing the risk of falls, medication errors, and the use of high-risk psychoactive medications (Schattner, 2023).

2.2 Common types of adverse events during hospitalization and their causes

Hospitalized older patients experience a wide spectrum of adverse events, encompassing both traditional medical complications and geriatric syndromes such as falls, delirium, and pressure injuries, as well as infections, medication-related harm, and procedure- or intervention-related complications. Systematic reviews indicate that healthcare-associated infections, delirium, falls, pressure injuries, and venous thromboembolism constitute the most common adverse event profile. In acute geriatric wards, more than half of patients may experience at least one medical adverse event, with infections and delirium being particularly prevalent and often iatrogenic in nature (Alotaibi et al., 2025). Regarding medication safety, reviews suggest that approximately one in every five to six hospitalized older patients experiences an in-hospital adverse drug reaction, manifesting as fluid and electrolyte disturbances, gastrointestinal symptoms, renal impairment, hypotension, or delirium. Diuretics, antimicrobials, antithrombotic agents, and analgesics-particularly opioids and sedatives-are most frequently implicated (Cosgrave et al., 2025).

From an etiological perspective, adverse events typically arise at the intersection of patient vulnerability, care processes, and organizational systems. Patient-related factors such as frailty, advanced age, disease or injury severity, and multimorbidity independently increase the risk of unplanned adverse events, including infections, pressure injuries, malnutrition, and urinary retention (Alotaibi et al., 2025). Medication-related factors-such as polypharmacy, potentially inappropriate prescribing, prior fall history, and poor adherence-can further amplify ADE and ADR risk in the absence of adequate medication review and monitoring (Wang et al., 2025). Organizational factors include missed nursing care, staffing shortages, inadequate monitoring, and failures in care coordination. Particularly among cognitively impaired patients, adverse events are more frequently attributable to nursing and organizational causes and are considered highly preventable (Schouten et al., 2025; Järbrink et al., 2025). Additionally, hospitalization-related stressors-such as restricted mobility, invasive devices, sleep deprivation, and unnecessary tests or procedures-may precipitate delirium, deconditioning, and falls, increasing the risk of post-discharge complications (Schattner, 2023).

2.3 Impact of adverse events on prognosis and nursing quality in older patients

The occurrence of adverse events during hospitalization has a substantial negative impact on outcomes in older patients and is closely associated with prolonged length of stay, functional decline, and increased mortality risk. Prospective studies indicate that older patients experiencing medical adverse events have nearly double the length of hospital stay and significantly higher in-hospital mortality; even after adjustment for disease severity and functional status, adverse events are associated with an approximately threefold increase in mortality risk. Review studies further suggest that adverse events often trigger unnecessary interventions and complications, resulting in marked prolongation of hospitalization, with rates of functional disability or death ranging from 5% to 27% among injured older patients. Among geriatric trauma patients, the incidence of nursing-sensitive adverse events is approximately 30% and is associated with significantly longer hospital stays (17 days vs. 6 days), greater frailty, and higher injury severity, underscoring their prognostic significance (Järbrink et al., 2025). Hospitalizations related to ADEs in older adults are also associated with higher healthcare costs and increased need for post-discharge care, such as institutional placement or home care services (Cosgrave et al., 2025).

From a nursing quality perspective, adverse events serve both as critical signals of suboptimal nursing care and as factors that further consume nursing resources and strain healthcare systems. Falls, pressure injuries, infections, malnutrition, bladder overdistension, delirium, and adverse drug reactions are all classic nursing-sensitive outcomes, closely linked to the quality of nursing assessment, ongoing surveillance, timely intervention, and care coordination (Alotaibi et al., 2025; Järbrink et al., 2025). High adverse event rates often indicate missed or delayed nursing care, insufficient implementation of preventive measures, and inadequate medication management. This pattern is particularly evident among cognitively impaired patients, in whom nursing- and organization-related adverse events account for a larger proportion, revealing gaps in individualized supervision, communication, and environmental adaptation (Schouten et al., 2025). Conversely, strengthened nursing interventions-such as comprehensive geriatric assessment, proactive pharmacovigilance, early mobilization, and seamless care transitions-have the potential to reduce adverse events, improve functional trajectories, lower readmission risk, and enhance patient satisfaction (Schattner, 2023).

3 Nursing-Sensitive Indicators Related to Adverse Events in Older Patients

3.1 Concept of nursing-sensitive indicators and principles for indicator selection

Nursing-sensitive indicators (NSIs) refer to changes in health status or care processes that can be directly influenced by nursing care, and they constitute a core foundation for monitoring nursing quality and performance. Within Donabedian's "structure-process-outcome" framework, NSIs typically span three dimensions: structural indicators (e.g., nurse staffing levels and skill mix), process indicators (e.g., risk assessment, ongoing monitoring, patient education, nursing communication, and care coordination), and outcome indicators (e.g., falls, pressure injuries, infections, satisfaction, and functional decline) (Baillie et al., 2025). Compared with broader quality indicators, the defining feature of NSIs is that there is an empirically supported association between nursing inputs and patient outcomes, and the indicator content explicitly targets professional nursing practice, thereby enabling a more precise estimation of nursing's independent contribution to patient outcomes. Accordingly, in the inpatient geriatric context, NSIs are not only used to describe the level of adverse event occurrence but, more importantly, to use quantitative evidence to elucidate the pathways through which nursing interventions contribute to risk control and functional preservation, providing actionable levers for quality improvement.

Selection of NSIs in geriatric care should follow principles of scientific rigor, relevance, and feasibility, while ensuring that indicators are truly "nursing-sensitive." International and national experiences in indicator development emphasize that NSIs should: (1) be clearly and modifiably influenced by nursing; (2) focus on high-incidence or high-risk problems; (3) sensitively discriminate differences in nursing quality; and (4) have reliable, standardized data sources and operational definitions that support continuous measurement and inter-institutional comparison (Tevik et al., 2023). Delphi studies further propose that indicator selection should incorporate clinical relevance, modifiability by nursing, alignment with professional standards, and potential value for benchmarking and quality improvement. For hospitalized older adults, indicator selection should also reflect a risk-oriented and population-specific approach: priority should be given to indicators that capture key geriatric

characteristics such as frailty, cognitive impairment, mobility limitation, and functional decline, and risk stratification and risk adjustment should be incorporated based on illness severity and nursing dependency to enhance interpretability and managerial utility (Connolly et al., 2025).

3.2 Key nursing-sensitive indicators closely related to adverse events in older patients

In older populations, NSIs largely concentrate on nursing-sensitive adverse events and functional outcomes that are closely tied to nursing surveillance, prevention, and coordination. Major reviews and concept analyses repeatedly identify the most commonly used core NSIs in inpatient settings as falls, pressure injuries, healthcare-associated infections, medication administration errors, length of stay, and patient satisfaction. Among these, fall rates reflect the combined effectiveness of nursing practice in risk assessment, environmental management, rounds and observation, medication-risk identification, and safety education. Continuous monitoring of fall incidence and injury severity helps identify high-risk subgroups and time periods and evaluate the implementation of multifactorial prevention bundles. Similarly, pressure injury incidence and the proportion of newly acquired pressure injuries are important indicators of geriatric nursing quality because they are strongly associated with nursing processes such as repositioning, skin assessment, pressure-relieving interventions, and nutritional support. Linking outcome indicators with process indicators (e.g., repositioning adherence rates and completion rates of pressure injury risk assessment) enables a more comprehensive evaluation of intervention effectiveness.

In response to the risk profile of older adults, contextualized studies have further expanded the scope of inpatient NSIs to include delirium, frailty, functional decline, malnutrition, bladder overdistension, and readmission, given their high prevalence and substantial preventability under high-quality nursing care (Connolly et al., 2025). For example, in older surgical patients, frailty is significantly associated with the incidence of nursing-sensitive indicators such as in-hospital falls, delirium, pneumonia, and pressure injuries, suggesting that integrating “frailty assessment + NSI monitoring” may trigger earlier individualized preventive nursing care. In older trauma patients, nursing-sensitive adverse events (e.g., healthcare-associated infections, pressure injuries, malnutrition, and urinary retention) occur frequently and are significantly associated with advanced age, frailty, greater injury severity, and longer length of stay, further indicating that these indicators are highly sensitive to nursing care processes (Järbrink et al., 2025).

In addition, in long-term care and residential aged care settings, consensus studies emphasize prioritizing systematic medication review, pressure injuries, pain, dehydration, urinary tract infections, fecal impaction, behavioral symptoms, depression, weight loss, decline in activities of daily living (ADL), falls, and restraint use as nursing-sensitive quality indicators for frail older residents (Tevik et al., 2023). Community nursing and home-care research further highlights that “positive outcomes” such as autonomy, participation in decision-making, level of activity participation, quality of end-of-life care, and adherence to care are also important nursing-sensitive outcomes, moving beyond single adverse events to capture older patients’ overall experience and benefits from care (Goes et al., 2023). Overall, constructing multi-indicator portfolios helps more comprehensively cover the risk and outcome spectra of hospitalized older patients and jointly incorporate adverse event prevention and functional preservation into the nursing quality evaluation framework (Gormley et al., 2024).

3.3 Value of nursing-sensitive indicators for risk early warning and quality management

NSIs have important value for early warning of adverse event risks in older patients by translating patterns of nursing-sensitive adverse events into actionable risk signals. Indicators such as falls, pressure injuries, delirium, pneumonia, urinary tract infections, malnutrition, and bladder overdistension can conceptually be regarded as manifestations of “failure to maintain,” signaling potential missed nursing care, insufficient allocation of nursing resources, or deterioration of the care environment; thus, they can be used to identify high-risk subgroups and trigger preventive measures in advance (Järbrink et al., 2025; McCauley et al., 2025). For example, when a ward shows an abnormal increase in fall rates or unplanned device removal, or when process indicators (e.g., completion of risk assessment and adherence to prevention bundles) decline, root-cause analysis and targeted interventions can be initiated, enabling a shift from “post-event response” to “pre-event prevention”.

At the level of nursing quality management, NSIs provide a structured framework for planning, implementing, and evaluating continuous quality improvement (QI). National and institutional practices show that developing nursing process indicators and indicator systems tailored to older-adult services can send "strong signals" regarding improvement priorities, guiding intervention design, staff training, and resource allocation (Baillie et al., 2025). Long-term care facilities and national indicator programs further demonstrate that consensus-based NSI portfolios covering medication review, pressure injury prevention, infection, pain, hydration, function, and social participation not only support inter-institutional benchmarking and system-level improvement, but also expose methodological and feasibility challenges in indicator development and implementation (Tevik et al., 2023). Therefore, NSI-driven quality management should not remain at the level of outcome reporting; rather, it should be integrated with governance structures (e.g., quality committees and risk management teams) and action mechanisms (feedback-review-improvement) to establish a sustainable closed-loop management cycle (Mohan et al., 2024) (Table 1).

4 Nursing Quality Analysis Based on Nursing-Sensitive Indicators

4.1 Data collection and analytical methods for nursing-sensitive indicators

Data collection for nursing-sensitive indicators (NSIs) constitutes the foundation of nursing quality analysis, and its scientific rigor and standardization directly determine the credibility and applicability of analytical findings. In the context of inpatient care for older adults, NSI data are typically derived from multiple sources, including nursing documentation and electronic health records (EHRs), adverse event/near-miss reporting systems, clinical quality registries, and standardized assessment tools. The literature indicates that retrospective medical record review remains an important approach for identifying nursing-sensitive adverse events (NSAEs). In particular, trigger tool-guided chart reviews enable systematic identification of events such as infections, pressure injuries, bladder overdistension, and malnutrition, and can be used to calculate incidence rates and compare vulnerability profiles between patients with and without events (Järbrink et al., 2025). At the macro level, regional or national quality registries allow for long-term, structured data accumulation. For example, Sweden's Senior Alert continuously collects risk assessments and follow-up outcomes related to pressure injuries, malnutrition, falls, and oral health, providing a robust basis for inter-institutional benchmarking and longitudinal trend analysis. In both acute and long-term care settings, standardized outcome assessment tools (e.g., functional status or symptom scales) have demonstrated good reliability and sensitivity to change when routinely used by nurses, supporting nurse-led routine NSI data collection.

To ensure comparability across time periods, wards, and institutions, standardized indicator definitions, numerator and denominator rules, event adjudication criteria, and data dictionaries should be established at the organizational or system level. In addition, training nurses on indicator concepts and reporting standards is essential to reduce bias arising from subjective interpretation. With regard to incident reporting, studies suggest that punitive climates and fear of blame may lead to underreporting and undermine the value of data for learning and improvement; therefore, fostering a non-punitive reporting culture should be incorporated into data quality assurance systems (Huang et al., 2025; Wang et al., 2025).

Analytically, a stepwise approach combining descriptive epidemiology, multivariable modeling, and benchmarking enables progression "from description to explanation." Descriptive statistics are used to present incidence rates, distributions, and trends of events such as falls, pressure injuries, infections, medication errors, and bladder overdistension, with stratification by age, frailty status, disease or injury severity, and care setting to identify risk clustering and vulnerable subgroups (Järbrink et al., 2025). Multivariable models (e.g., logistic or Cox regression) further identify patient- and institution-level predictors of serious adverse events and explore associations between NSIs and staffing levels or organizational characteristics, thereby providing more explanatory evidence for management decision-making. Importantly, cross-sectional nurse survey studies have linked missed or unfinished nursing care with increased frequencies of medication dosing errors, hospital-acquired infections, and injurious falls, demonstrating that process gaps can be quantified through NSIs and used to target quality improvement interventions.

Table 1 Core nursing-sensitive indicators (NSIs) for hospitalized older adults

Domain	Core NSI Indicator	Indicator Description	Modifiable Nursing Targets	Data Source	Recommended Metric
Structure	Geriatric-trained nurse staffing ratio	Proportion of nurses with geriatric care qualifications	Nurse staffing and competency management	Human resources system	Percentage (%)
	Nursing staff training coverage	Completion of geriatric and safety-related training	Continuing education and skill development	Training management records	Compliance rate (%)
	Availability of fall- and pressure-injury-prevention equipment	Adequacy and accessibility of protective equipment	Equipment allocation and maintenance	Nursing management records	Availability rate (%)
Process	Fall risk assessment compliance	Completion of standardized fall risk assessments	Risk screening and ongoing reassessment	Electronic medical records	Compliance rate (%)
	Pressure injury risk assessment compliance	Use of tools such as the Braden scale	Early identification of high-risk patients	Electronic medical records (EMR)	Compliance rate (%)
	Appropriate restraint use compliance	Adherence to indications and protocols for restraints	Alternatives to restraints and monitoring	Nursing documentation	Compliance rate (%)
	Medication administration safety compliance	Double-checking and safe administration of high-risk medications	Medication verification and patient education	Electronic medical records (EMR)	Compliance rate (%)
Outcome	In-hospital fall incidence rate	Falls occurring during hospitalization	Environmental safety and nursing surveillanc	Adverse event reporting system	Incidence per 1000 patient-days
	Hospital-acquired pressure injury incidence rate	New pressure injuries developed during hospitalization	Repositioning and skin care interventions	Adverse event reporting system	Incidence per 1 000 patient-days
	Nursing-related infection rate	Infections associated with nursing procedures	Aseptic technique and device care	Infection control system	Incidence per 1000 patient-days
	Overall nursing adverse event rate	Falls, pressure injuries, medication errors, etc	Comprehensive nursing quality improvement	Adverse event reporting system	Incidence per 1 000 patient-days

Meanwhile, national indicator programs that monitor long-term trends and conduct inter-institutional benchmarking can identify quality improvement priorities and research gaps, offering macro-level evidence to support sustained improvement efforts. With advances in information technology, multidimensional data integration and visualization have become increasingly important tools in nursing quality management. Embedding NSIs into information systems and applying statistical process control (SPC) methods (e.g., control charts) for real-time or periodic monitoring facilitates early detection of abnormal variation, triggers root cause analysis, and supports evidence-based decision-making, thereby promoting a shift from “outcome reporting” to “process governance” in quality management (Figure 1).

4.2 Current status of nursing quality and adverse event occurrence in hospitalized older patients

Existing research and quality monitoring evidence indicate that preventable nursing-sensitive adverse events remain common among hospitalized older adults, with substantial variation across wards and institutions, reflecting persistent gaps in nursing quality. In studies of geriatric trauma patients, approximately 30% experienced at least one nursing-sensitive adverse event, most commonly healthcare-associated infections (19%), bladder overdistension (11%), pressure injuries (6%), and malnutrition (5%). Patients who experienced events were older, frailer, more severely injured, and had nearly threefold longer hospital stays than those without events

(Järbrink et al., 2025). Systematic reviews of hospitalized older medical patients report adverse event rates of approximately 5%-6% in large chart review studies; however, when geriatric syndromes such as falls, delirium, and incontinence are included, incidence rates rise to as high as 60%, suggesting that both traditional complications and geriatric syndromes are important reflections of inadequate nursing quality. In nursing homes and skilled nursing facilities, more than one-third of residents or admissions are affected by adverse events such as falls, pressure injuries, medication errors, and acute infections, with particularly high rates during high-risk periods (e.g., early rehabilitation phases or pandemic conditions).

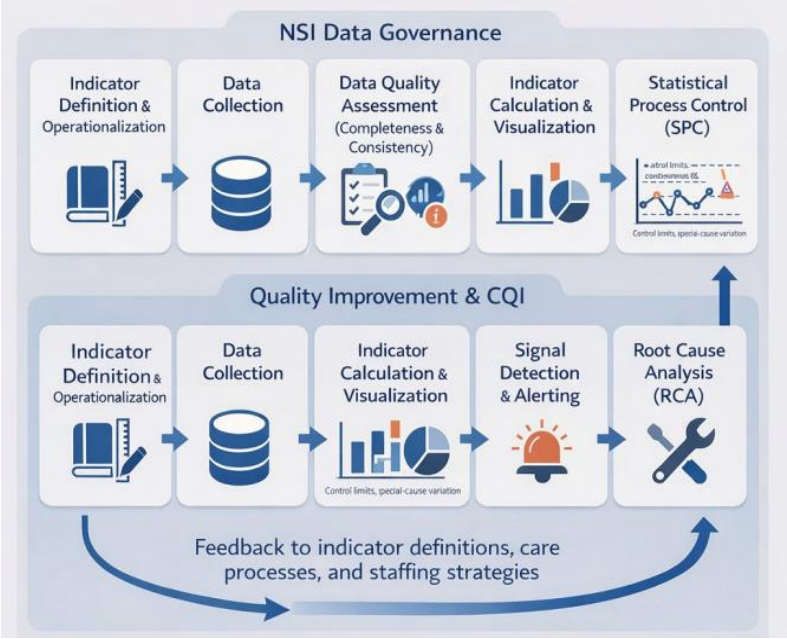

Figure 1 NSI data-to-action loop for quality improvement in geriatric inpatient care

NSI-based evaluations also reveal variability in nursing performance and the problem of "incomplete monitoring." A large U.S. hospital survey showed that key nursing activities such as patient education, discharge preparation, and care planning were frequently left unfinished; higher levels of missed nursing care were associated with increased rates of medication errors, hospital-acquired infections, and injurious falls, indicating that process-level nursing gaps translate into measurable safety outcomes. In long-term care settings, serious adverse events are often concentrated in medication errors, falls, delayed or inappropriate interventions, and missed care, and are closely associated with inadequate staff competence, incomplete documentation, and deficiencies in teamwork and communication. Moreover, national-level NSI trend analyses suggest that routine monitoring covers only a small fraction of potential indicators, that mental health-related indicators are frequently absent, and that post-complication mortality has increased over time-implying that current monitoring systems may capture only part of the nursing quality landscape in geriatric care.

4.3 Major problems and weak points in nursing practice

At the level of nursing practice, NSI-based analyses consistently expose key vulnerabilities, including missed or delayed nursing care, underreporting of events, and deficiencies in competence and documentation. In hospital settings, higher levels of unfinished nursing tasks-often driven by workload pressures and staffing constraints-are directly associated with increased rates of medication errors, infections, and injurious falls, indicating that monitoring- and prevention-intensive nursing activities are not being reliably delivered. Retrospective studies and incident reports from long-term care facilities further show that serious adverse events are frequently linked to delayed or inappropriate interventions and missed care, with contributing factors including insufficient geriatric assessment and medication management skills, incomplete or missing documentation, weak teamwork, and poor communication. In addition, fear of blame and punitive responses may drive underreporting of events, undermining organizational learning and system-level quality improvement (Huang et al., 2025; Wang et al., 2025).

A second prominent issue concerns the limited alignment between existing indicator systems and the complex needs of older patients. Review studies highlight that inconsistent NSI definitions, heterogeneous data collection methods, and insufficient evidence of "nursing sensitivity" for some commonly used indicators constrain effective benchmarking and interpretation in geriatric populations. National NSI programs often prioritize a small set of complications while inadequately covering cognitive, psychosocial, and functional outcomes-dimensions that are central to safety and experience in older adults. Furthermore, research on care transitions suggests that adverse events occurring after discharge to nursing facilities are poorly explained by existing institution-level quality scores, implying that critical nursing processes and contextual factors are not fully captured by current quality measurement tools. Overall, although NSIs are powerful management instruments, their potential remains constrained by measurement gaps, reporting culture barriers, and the lack of geriatric-specific, practice-oriented indicators and a supportive safety culture.

5 Development and Implementation of Nursing Quality Improvement Interventions

5.1 Establishing an NSI-oriented quality management mechanism

Building a nursing quality management mechanism centered on nursing-sensitive indicators (NSIs) represents a key pathway for driving continuous improvement in adverse events among hospitalized older patients. Concept analyses and studies on indicator application indicate that, for NSIs to fulfill a true governance function, they must be supported by standardized definitions, robust health information systems, and formal reporting linkages to management, thereby enabling routine extraction of nursing performance data, trend analysis, and cross-ward or cross-institutional comparison. In terms of indicator configuration, research from long-term care and residential aged care settings internationally suggests that structured NSI portfolios-such as falls, pressure injuries, infections, dehydration, medication-related problems, pain, and functional decline-can highlight high-risk domains and guide prioritization of quality improvement efforts, demonstrating strong transferability and governance potential (Tevik et al., 2023; Caughey et al., 2025). Accordingly, in the hospital geriatric inpatient context, it is recommended that NSIs closely related to patient safety be incorporated into nursing quality management systems, with explicit definitions, numerators and denominators, data sources, and evaluation cycles specified. This enables the formation of institutionalized and auditable management processes and supports continuous improvement through a closed-loop cycle of "indicator monitoring-problem identification-intervention implementation-outcome evaluation".

With respect to governance structures and operational mechanisms, a mature NSI-oriented system also requires scientifically grounded indicator selection, risk adjustment, and root cause analysis (RCA) processes. Reviews of quality improvement in long-term care note that existing indicators often emphasize safety and effectiveness but may insufficiently capture the breadth of older adults' needs; therefore, expert consensus methods are needed to optimize indicator sensitivity and interpretability (Caughey et al., 2025). Modified Delphi studies demonstrate that expert panels comprising clinicians, researchers, and family members or caregivers can help prioritize indicators that are genuinely nursing-sensitive, high-incidence or high-risk, and responsive to changes in nursing quality (Tevik et al., 2023). In parallel, governance structures such as multidisciplinary quality committees and dedicated risk management or infection control leads should be established to interpret NSI trends, organize RCAs, and ensure that evidence is translated into revisions of nursing workflows, staffing decisions, and targeted quality improvement (QI) initiatives, rather than remaining at the level of passive reporting.

Informatics support is a critical enabler of effective NSI-oriented management. Embedding NSIs within electronic health record systems and deploying visual dashboards can facilitate real-time or periodic monitoring of adverse events in older patients, enable inter-institutional benchmarking, and provide transparent feedback, thereby reducing bias associated with manual data collection and improving data usability (Caughey et al., 2025). In management practice, NSI results can be integrated into unit-level goal management, with regular feedback to nursing teams on trends and benchmarking positions, and intensified monitoring and resource allocation for high-risk units or indicators to enhance the precision and efficiency of improvement efforts (Tevik et al., 2023).

5.2 Nursing interventions and preventive measures targeting major adverse events

NSI-based analyses help delineate the most common and modifiable adverse event profiles in older patients and guide the implementation of stratified, individualized prevention strategies. Evidence indicates that key nursing-sensitive issues requiring focused attention in older populations include infections, pressure injuries, bladder overdistension, malnutrition, delirium, falls, and medication-related harm (Järbrink et al., 2025; Koehl, 2023). Using falls as an example, nursing interventions should emphasize dynamic assessment at admission and throughout hospitalization, optimization of environmental safety and care coordination, appropriate use of assistive devices, and enhanced monitoring of medication-related risks. Concurrently, patient and family education and caregiver guidance should be strengthened to improve risk recognition, ensuring that process measures are traceable and auditable. In long-term care settings, multifactorial fall prevention programs-including exercise and balance training, environmental modification, medication review (especially psychoactive medications), management of orthostatic hypotension, and foot and footwear assessment-are recommended to reduce fall and fracture risk. However, studies also indicate that without deeper organizational transformation, quantifiable effects may be limited, underscoring the importance of using NSIs such as fall rates as feedback triggers to iteratively refine interventions.

Pressure injury prevention should be guided by outcome indicators such as pressure injury incidence and the proportion of newly acquired pressure injuries, and linked with process indicators including completion of skin risk assessments, adherence to repositioning schedules, and utilization of pressure-relieving devices to form executable nursing care pathways. Research shows that nursing-sensitive problems such as pressure injuries, malnutrition, and infections are not uncommon among older trauma patients, highlighting the central role of systematic risk assessment, early mobilization, skin care, elimination management, and nutritional support as core nursing responsibilities (Järbrink et al., 2025). Systematic reviews further indicate that ward-level, multicomponent interventions targeting “mobility-nutrition-cognitive engagement,” when combined with evidence implementation frameworks and adapted to local barriers, can improve mobility and functional outcomes, increase nutritional intake, and reduce delirium-thereby achieving a bundled reduction in multiple geriatric nursing-sensitive complications. Perioperative nursing studies also demonstrate that targeted interventions-such as temperature management, pain and anxiety control, close monitoring, and effective communication-can reduce emergence agitation and related complications in older surgical patients while improving satisfaction, suggesting that strengthening care processes can translate into improved outcomes (Hu and Peng, 2025).

Medication safety represents a critical NSI domain requiring focused governance. Reviews and clinical recommendations emphasize that pharmacist- or physician-led medication reviews, geriatric-friendly order sets, and team-based optimization of high-risk prescriptions can reduce the risk of adverse drug events (ADEs); however, effects on “hard outcomes” (e.g., hospitalization and mortality) are inconsistent, highlighting the importance of implementation quality, interprofessional collaboration, and integration with nursing monitoring processes (Koehl, 2023). Building on this foundation, events such as unplanned device removal and catheter-associated infections should be addressed through process optimization and behavioral standardization: strengthening assessment of cognitive and delirium risk and caregiver strategies, standardizing restraint use, refining protocols for catheter fixation and maintenance, and reducing medication errors through double checks, smart medication alerts, and closed-loop medication administration systems to achieve multi-point risk reduction.

5.3 Strengthening nursing staff training and risk management in geriatric care

Nursing staff competence and organizational risk management capacity are critical determinants of adverse events in older patients, and systematic development should target vulnerabilities identified through NSIs. Randomized controlled studies show that safety culture training programs in intensive care settings can significantly improve nurses’ safety knowledge, attitudes, practices, and perceptions of the work environment, indicating that the “safety culture-behavior-outcome” chain can be activated through training (Shoukr et al., 2025). Studies in geriatric specialty hospitals further demonstrate that patient safety competence and clinical experience are important predictors of safe nursing behaviors, underscoring the need for targeted training in patient safety competencies and retention of experienced nursing staff. In long-term care facilities, qualitative interview studies suggest that

training in risk assessment, early warning strategies, family communication, and comprehensive preventive measures serves as a key mediator in translating risk recognition into actual reductions in adverse events. Accordingly, an "indicator-driven training prescription" is recommended: NSI trends related to falls, pressure injuries, infections, and medication-related events should be used as signals to precisely target training topics; case reviews and simulation-based exercises can enhance team capabilities in recognition, communication, and response, and training effectiveness should be continuously tracked through process NSIs (e.g., screening completion rates and bundle adherence) (Shoukr et al., 2025).

In terms of risk management, adverse event reporting, analysis, and feedback mechanisms should be strengthened, and a non-punitive safety culture fostered to reduce underreporting and enhance organizational learning. In long-term care settings, nurses often face strategic dilemmas between person-centered care and risk control and express concerns about legal and personal consequences, highlighting the need for clear policies, procedures, and decision-support tools to enable negotiated approaches to risk management (Behrens et al., 2023). Risk management guidelines and practical experience emphasize the establishment of infection prevention leads, multidisciplinary safety committees, structured surveillance programs, and regular case reviews to address systemic threats such as infection outbreaks, aspiration, falls, or clusters of pressure injuries. Moreover, the "failure to maintain" theory underscores that risk management systems must explicitly protect and invest in fundamental nursing care-mobility, hydration, nutrition, skin care, and communication-to prevent the escalation of latent nursing rationing into increased rates of urinary tract infections, pneumonia, pressure injuries, and delirium. This provides a theoretical basis for incorporating fundamental care process indicators into NSI frameworks (Figure 2).

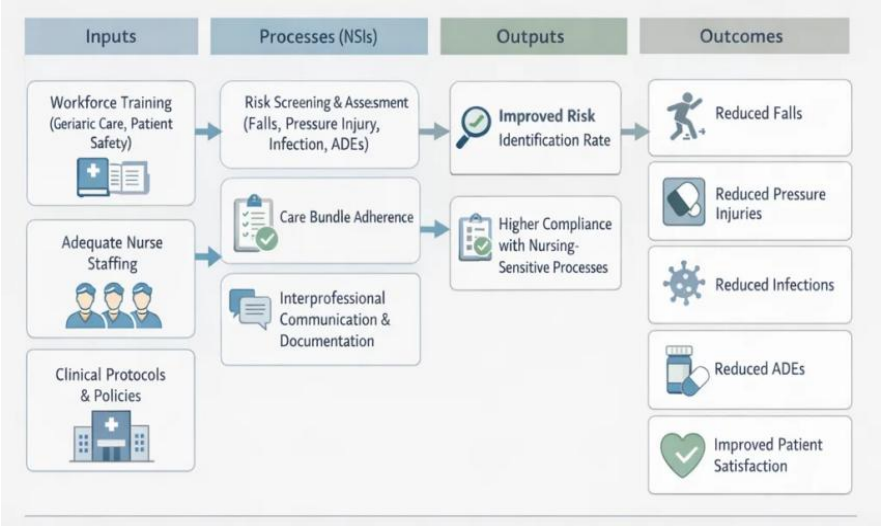

Figure 2 Nursing workforce inputs, process NSIs, and patient safety outcomes in geriatric inpatient care

At the same time, attention should be paid to nursing workload and psychological well-being, with appropriate staffing and process redesign implemented to mitigate the negative effects of burnout on care quality. Integrating staff training, risk governance, and NSI monitoring into a unified "learning system" can facilitate a shift from experience-driven practice to data-driven, continuously learning care models, thereby promoting sustained improvements in safety and quality of nursing care for hospitalized older patients (Shoukr et al., 2025).

6 Evaluation of Quality Improvement Effects

6.1 Changes in nursing-sensitive indicators before and after quality improvement

Systematic comparison of nursing-sensitive indicators (NSIs) before and after the implementation of quality improvement (QI) initiatives is a core component of evaluating intervention effectiveness. Longitudinal analyses of key outcome indicators-such as fall rates, pressure injury incidence, unplanned device removal, and medication error rates-can directly illustrate trajectories of change in nursing quality. From a broader NSI framework, however, structural indicators (e.g., staff qualifications and training coverage) and process indicators (e.g.,

screening rates and adherence to preventive measures) often improve earlier than outcome indicators, forming an early "evidence chain" that signals the occurrence of improvement. For example, a pilot study in an intensive care unit used standardized nursing-sensitive quality indicators (staff qualifications, life-support certification, continuing education hours, and patient satisfaction) to evaluate QI effects. Following implementation, the validity rates of basic and advanced life support certification and continuing education hours increased significantly, alongside marked improvements in patient satisfaction with pain management, nursing care, and overall care, indicating that structural and process indicators are highly responsive to QI interventions. In geriatric specialty nursing, models such as "high-quality nursing" or "seamless care" have likewise been associated with higher nursing quality scores (service capacity, procedural compliance, humanistic care, and health education) and improvements in functional and psychosocial outcomes, further supporting the logical chain of "strengthened nursing processes→improved outcomes" (Zuo et al., 2023; Liu, 2025; Wei et al., 2025).

Beyond traditional manual audits, digital quality assessment and nursing informatics tools have enhanced the sensitivity and sustainability of NSIs for QI evaluation. An automated quality assessment system for pressure injury management in older adults demonstrated high concordance between its quality scores and expert nurse judgments, while significantly reducing assessment time, thereby supporting long-term tracking of guideline adherence as a process NSI. In critical care settings, systematic reviews indicate that nursing informatics interventions (e.g., electronic health records, decision support, and telemedicine) are associated with higher risk screening completion rates, improved adherence to pressure injury and fall prevention bundles, and greater process consistency. These findings mechanistically illustrate how "information-enabled process control" can optimize nursing process indicators upstream of adverse event occurrence. Accordingly, evaluation of QI effects should link changes in outcome indicators with concurrent improvements in structural and process indicators to avoid overinterpretation based solely on outcome fluctuations (Shi et al., 2025).

6.2 Changes in the incidence of adverse events during hospitalization of older patients

The ultimate goal of nursing QI is to reduce both the incidence and severity of adverse events during hospitalization of older patients. Comparing pre- and post-QI rates of falls, pressure injuries, catheter-related adverse events, aspiration, and other safety outcomes allows validation of intervention effectiveness at the patient safety endpoint level. Existing evidence suggests that targeted QI initiatives can reduce overall adverse event rates or alter their occurrence patterns to some extent; however, effects vary depending on care settings, implementation intensity, and patients' structural vulnerability (Järbrink et al., 2025). A national longitudinal chart review study, after adjusting for case mix, found that the incidence of adverse events among acutely admitted older patients declined from 10.7% to approximately 7.2% between 2008 and 2016, with many events being medication-related. This improvement likely reflects system-level patient safety initiatives and strengthened nursing surveillance and standardized care processes. Among older patients with coronary heart disease, "seamless care" models significantly reduced adverse event rates while improving angina control and quality of life; similarly, in older patients undergoing cataract surgery, high-quality nursing interventions were associated with fewer postoperative complications and improved recovery trajectories (Zuo et al., 2023; Wei et al., 2025).

It should be emphasized, however, that risk does not "automatically disappear" with QI and that residual risk concentration and pattern shifts may occur. In studies of older trauma patients, the incidence of nursing-sensitive adverse events (e.g., infections, pressure injuries, bladder overdistension, and malnutrition) remained at approximately 30% and was strongly associated with greater frailty, injury severity, and longer hospital stays, suggesting that structural vulnerability may partially offset QI gains (Järbrink et al., 2025). Moreover, longitudinal data indicate that although overall adverse event rates declined, the proportion of events deemed preventable did not continue to decrease and even increased in later periods. This finding suggests that, against a backdrop of increasing disease complexity and healthcare congestion, there may be substantial remaining scope to prevent residual events through improved care. Registry data likewise indicate that burdens of falls, pressure injuries, and weight loss persist across care settings; even with risk registration and preventive care in place, adverse events are not fully eliminated.

6.3 Integrated evaluation of nursing quality and patient safety

In evaluating the effects of QI in geriatric nursing, reliance on a single NSI or adverse event rate is insufficient to capture overall improvements in nursing quality and potential trade-offs. Concept analyses and reviews consistently emphasize the integration of structural indicators (e.g., nursing hours, staffing mix, competency levels), process indicators (e.g., risk assessment, adherence to preventive measures, humanistic communication, medication safety practices), and outcome indicators (e.g., falls, pressure injuries, infections, delirium, length of stay, readmission rates, satisfaction, and quality of life) within Donabedian's structure-process-outcome framework to form a multidimensional evaluation model (Connolly et al., 2025). In studies of "high-quality" or "seamless" nursing care for older patients, combined evaluation of clinical outcomes (complications, functional status, symptom control) with patient satisfaction and quality of life provides a more comprehensive reflection of the clinical and managerial value of improvements than reliance on event rates alone (Zuo et al., 2023; Liu, 2025; Wei et al., 2025).

At the same time, evaluation frameworks should incorporate mechanistic and mediating indicators to explain why improvements or rebounds occur. Emerging evidence highlights the critical role of safety culture, humanistic care, and informatics support in nursing quality evaluation. Safety culture training has been shown to significantly enhance nurses' safety knowledge, attitudes, and practices; such intermediate outcomes are believed to contribute to long-term reductions in adverse events. Qualitative studies of humanistic geriatric nursing grounded in three-dimensional quality structure theory identify communication, individualized needs assessment, prevention in high-risk situations, and medication safety as key nursing process domains, with satisfaction and adverse event rates serving as important endpoint indicators (Yuan et al., 2025). Informatics-focused reviews further demonstrate that enhanced documentation and decision support are associated with reductions in pressure injuries and medication errors, shorter lengths of stay, and improved adherence to preventive care, supporting a testable pathway of "informatics→process control → outcome improvement" (Shi et al., 2025). Therefore, robust evaluation of QI in inpatient geriatric nursing should adopt a triangulation approach combining NSI trajectories, adverse event incidence, and functional or patient-reported outcomes (PROs), with explicit assessment of mediating mechanisms such as safety culture and guideline adherence (Shoukr et al., 2025).

7 Managing Adverse Events in Older Patients Based on Nursing-Sensitive Indicators

7.1 Significance of nursing-sensitive indicators in managing adverse events in older patients

From the perspective of nursing-sensitive indicators (NSIs), this study systematically discusses pathways for monitoring adverse events during hospitalization and for improving quality among older patients, further underscoring the central role of NSIs in geriatric safety management. NSIs capture changes in health status that are directly influenced by nursing care and are considered foundational tools for monitoring and managing adverse events in high-risk populations. Within Donabedian's structure-process-outcome framework, NSIs link nursing structures and processes (e.g., staffing levels, skill mix, and guideline adherence) with outcomes such as falls, pressure injuries, infections, delirium, length of stay, readmission, functional decline, and satisfaction-outcomes that are highly prevalent among hospitalized older adults. Therefore, compared with traditional evaluation approaches focused primarily on medical outcomes, NSIs more directly reflect how nursing behaviors and care processes influence adverse event occurrence, thereby revealing nursing's independent contribution to patient safety.

More importantly, NSIs can support a shift in adverse event management for older patients from "post-event response" to "pre-event prevention." Research in acute geriatric care shows that outcome or quality indicators centered on geriatric syndromes and functional status help identify key points requiring targeted nursing interventions, thereby preventing complications and functional loss (Martin-Khan et al., 2024). Among frail older surgical patients, indicators such as falls, pressure injuries, delirium, pneumonia, and mortality show clustered distributions, suggesting that NSIs are not merely "outcome statistics" but also "risk markers" for identifying high-risk subgroups and promoting proactive, individualized nursing models. At the system level, trend data from regional or national programs can reveal deficiencies in functional outcomes and complication-related mortality, providing evidence to support policymaking, staffing allocation, and practice priorities in services for older adults.

7.2 Effectiveness of quality improvement measures and practical experience

Overall evidence suggests that NSI-oriented quality improvement (QI) can strengthen nursing processes and reduce risk, and is particularly suitable for geriatric service areas where risks are highly concentrated. Geriatric-specific nursing process indicators developed through Delphi consensus provide nurses with a clear framework for measuring core care processes (assessment, person-centered care planning, and risk prevention) and for indicating key areas in urgent need of improvement. In long-term care and community settings, NSI-based quality indicator systems and operational manuals have improved assessment consistency and supported more standardized evaluation of adverse outcomes; however, social and psychosocial dimensions remain difficult to quantify, reflecting the problem of "measurability bias" within indicator systems (Kawase et al., 2025).

Practical experience indicates that the effects of QI depend on multifactorial synergy. First, a clear "goal-accountability-feedback" chain can increase nurses' engagement and the consistency of implementation. Second, using both process and outcome indicators allows timely identification of workflow gaps and iterative adjustment of strategies before outcome indicators show significant changes. Reviews of QI in nursing homes further suggest that multifaceted strategies (education and training, audit-and-feedback, and teamwork interventions) often improve documentation quality, adherence to pressure injury and fall prevention, and pain management outcomes. However, improvements in resident-level "hard outcomes" are less stable and rarely sustained over the long term, implying that implementation intensity, organizational support, and intervention sustainability may be key limiting factors.

Regarding informatics and transparency, embedding NSIs into routine information systems and publicly reporting them can enhance transparency, promote inter-facility benchmarking, and sustain managerial attention to safety and functional outcomes for older patients. In addition, incorporating patient satisfaction as a nursing-related indicator-linked to functional status and quality of life-illustrates how subjective experiences of older patients can be integrated into indicator systems, expanding evaluation from "event control" to "perceived benefit" in a way that aligns more closely with person-centered geriatric care goals (Goes et al., 2023). Across acute care, long-term care, and transitional care, NSIs are increasingly being used to design and evaluate interventions targeting preventable harm. By matching assessment, monitoring, and prevention bundles to identified risk profiles, more precise interventions can be achieved (Järbrink et al., 2025; Feng et al., 2024).

7.3 Limitations of existing evidence and future directions for improvement

Despite the considerable potential of NSIs and related QI initiatives, existing evidence still shows substantial conceptual, methodological, and implementation-level limitations. Multiple reviews consistently note that there is a lack of consensus regarding NSI definitions; indicator systems vary widely across countries and care environments; and empirical evidence is inconsistent as to whether many commonly used indicators are truly "nursing-sensitive," limiting benchmarking interpretation and cross-institutional transferability. Moreover, many indicator systems were originally developed for acute care or nursing homes and do not fully reflect the complex needs of older patients (e.g., cognition, autonomy, care transitions, and social participation). As a result, key domains of geriatric safety may be underestimated or not measured at all. Reliability studies also suggest that agreement for physical health outcome indicators is often acceptable, whereas measurement performance for social and psychosocial items is weaker, indicating that tool refinement and staff training remain necessary (Kawase et al., 2025).

From the standpoint of QI study design, the evidence base remains fragmented and methodologically limited, particularly in nursing homes and community care, where robust experimental or long-term longitudinal studies are scarce and evidence for sustained resident outcome improvements is limited. Reviews focusing on nursing-sensitive outcomes in general practice nurses or community nurses highlight gaps in outcome reporting, high heterogeneity of interventions, and uncertainty regarding which outcomes most sensitively reflect nursing effects in older populations. Data infrastructure also poses barriers: free-text documentation and performance systems oriented toward acute care limit standardized collection and longitudinal tracking of NSIs during care transitions and across the continuum of care (Cowdell et al., 2025).

Future improvements should focus on four directions. First, advance the standardization and refinement of geriatric-relevant NSIs by incorporating functional status, frailty, autonomy, care transitions, and patient-reported outcomes, and develop and validate these indicators with the participation of older patients and caregivers (Connolly et al., 2025). Second, strengthen methodological rigor by conducting multicenter studies, extending follow-up, and clarifying causal relationships among NSI changes, nurse-led interventions, and "hard outcomes" (adverse events, function, mortality, and quality of life) (Martin-Khan et al., 2024). Third, build integrated digital platforms that embed NSIs into electronic health records and dashboards across hospitals, home care, and residential aged care settings to support real-time monitoring, benchmarking, and feedback. Fourth, apply implementation science methods to enhance implementation fidelity, sustainability, and staff engagement in NSI-driven QI projects, thereby moving geriatric nursing from isolated initiatives toward a continuously learning system (Cowdell et al., 2025; Wells et al., 2025).

8 Conclusions and Future Directions

Synthesizing evidence across multiple care contexts-including acute care, long-term care, and community care-demonstrates that nursing-sensitive indicators (NSIs) provide a feasible and essential measurement foundation for nurse-led quality improvement, and serve as key tools for demonstrating nursing's independent contribution to patient outcomes, particularly among older populations. Existing concept analyses and systematic reviews consistently confirm that indicators such as falls, pressure injuries, infections, functional decline, mortality, and patient satisfaction reflect changes in health status that are directly influenced by nursing structures (e.g., staffing levels and nursing hours) and nursing processes (e.g., risk assessment, preventive measures, health education, and care coordination), thereby constituting core "quantifiable interfaces" for nursing quality evaluation and improvement. Accordingly, in the management of adverse events among hospitalized older patients, continuous monitoring and analysis of key NSIs-such as falls, pressure injuries, unplanned device removal, and medication-related problems-enable more accurate identification of nursing-related risks, more robust evaluation of intervention effects, and the provision of traceable and benchmarkable quantitative evidence to support quality improvement.

When NSIs are incorporated into organizational governance as standardized "nursing quality-sensitive indicators," pilot studies and regional or national benchmarking programs indicate that capacities for adverse event surveillance are enhanced; relationships between nursing workforce capacity and preventable complications become clearer; and alignment between nursing workflows and clinical guidelines is easier to monitor and correct . National registry and benchmarking studies further suggest that indicators such as falls and pressure injuries can function as critical levers for nursing quality benchmarking, enabling identification of high-risk wards and prioritization of improvement efforts. Although evidence regarding causal effects of NSIs on all outcomes remains heterogeneous and inconsistent, overall findings demonstrate that NSIs help institutions identify high-risk areas, conduct ward-level benchmarking, and prioritize interventions, thereby reducing nursing-sensitive adverse events and supporting functional preservation in older adults. Importantly, integrating structural, process, and outcome NSIs into an "indicator portfolio" facilitates a more comprehensive nursing quality evaluation framework and promotes a transition in quality management from "outcome appraisal" toward closed-loop governance characterized by "process improvement plus outcome verification".

NSI-based quality improvement practices offer direct implications for enhancing nursing safety among hospitalized older patients. First, adverse event prevention should be shifted "upstream" by embedding dynamic risk assessment, individualized intervention, and reassessment into routine workflows, and by incorporating high-priority risk domains into bedside rounds and nursing bundles. Consensus-based indicator systems from nursing homes, long-term care, and acute hospitals have identified key geriatric nursing risks-including systematic medication review, pressure injuries, pain, dehydration, urinary tract infections, falls, functional decline, and opportunities for engagement in meaningful activities-which should constitute core target domains for harm prevention in hospitalized older patients. In practice, embedding these indicators into admission assessments, interdisciplinary care plans, and ward-level dashboards can help nurses anticipate geriatric syndrome risks and continuously monitor whether safety initiatives are effectively reducing harm.

Indicator-driven improvement must be grounded in high-quality data. Reliability studies of quality indicators show that clear operational definitions, structured assessment manuals, and informatics support (e.g., mobile nursing systems) significantly enhance data quality and facilitate seamless integration of risk screening, ongoing monitoring, and documentation into daily nursing workflows. This implies that nursing managers should prioritize organizational capabilities such as standardized indicator definitions, automated data capture, and visualized feedback, rather than using NSIs solely for outcome reporting or performance appraisal.

Transparent reporting and benchmarking mechanisms can strengthen managerial attention and drive resource allocation. Experiences from regional and national NSI programs indicate that transparent reporting of falls, pressure injuries, and complication-related mortality can prompt leadership engagement, targeted resource investment, and focused training-particularly in settings with high concentrations of adverse events, such as geriatric psychiatry and intensive care units. Therefore, improving nursing safety for hospitalized older patients requires not only bedside-level interventions but also coordinated organizational governance, resource commitment, and informatics infrastructure.

Looking ahead, NSIs are expected to evolve from static monitoring tools into dynamic quality improvement engines spanning the continuum of geriatric care. Recent studies advocate expanding indicator systems beyond traditional safety events to include autonomy, participation in decision-making, quality of end-of-life care, social participation, and patient-reported outcomes (PROs), thereby enabling NSIs to more comprehensively reflect the person-centered values of geriatric nursing. Concurrently, methodological advances-such as Delphi consensus methods, theory-driven frameworks, cross-national scoping reviews, and stakeholder engagement-are laying the groundwork for developing more standardized, geriatric-specific indicator portfolios and supporting localized development and validation across diverse contexts, including low- and middle-income countries.

Digitalization and intelligent technologies will further amplify the value of NSIs. Integrating NSIs into electronic health records, mobile nursing information systems, and national quality registries has the potential to enable real-time feedback, predictive analytics for identifying high-risk older patients, and the creation of learning networks for sharing effective nursing practices across institutions. At the same time, the risk of “indicator narrowing” must be acknowledged. Scholars emphasize the need to further clarify indicator definitions, strengthen the evidence base for indicators that are truly nursing-sensitive, and ensure that indicator sets capture the breadth of nursing practice rather than focusing solely on adverse events. Accordingly, future priorities lie in advancing standardization and digital embedding while simultaneously integrating person-centered geriatric values-such as function, participation, and autonomy-into indicator systems, thereby achieving sustained improvement toward the dual goals of safety and functional preservation.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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The Impact of High-Intensity Interval Training (HIIT) on Endurance and Speed in Adolescent Athletes

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Abstract High-Intensity Interval Training (HIIT) has emerged as a highly efficient conditioning method in athletic performance development. While HIIT has been widely studied in adults, limited research has investigated its effects on adolescent athletes, a population undergoing critical physical and physiological development. The purpose of this study was to examine the impact of an 8-week HIIT program on endurance and speed performance in adolescent athletes. Forty male and female athletes (age 14~17) were randomly assigned to either a HIIT group (n=20) or a control group performing traditional endurance and sprint training (n=20). Endurance was assessed using VO_2 max testing, and speed was evaluated through a 30-meter sprint test. Following the intervention, the HIIT group demonstrated a significant improvement in VO_2 max (10.8% increase, $p<0.01$) and 30-meter sprint times (8% improvement, $p<0.05$), whereas the control group showed only marginal gains (3.1% and 1.2%, respectively,). These findings suggest that HIIT provides superior benefits for improving both aerobic capacity and speed compared to traditional training methods in adolescent athletes. The study highlights the potential of HIIT as a time-efficient and effective training strategy for youth sports performance.

Keywords HIIT; Adolescent; Endurance; Speed; Sports training

1 Introduction

In the area of sports science, High-Intensity Interval Training (HIIT) is widely known as a quick and effective way to get in shape. HIIT usually includes short, intense workouts that are done over and over again, with recovery times that can be either passive (rest) or active (low-intensity activity). HIIT is different from traditional endurance training, which is usually done at a moderate level for long periods of time. It causes big changes in the body in shorter amounts of time, which makes it very appealing in both sports and clinical settings (Buchheit and Laursen, 2013).

One of the most important developmental phases for athletes is adolescence. Significant physiological, hormonal, and neuromuscular changes occur in young athletes between the ages of 13 and 18, which affects their potential for performance as well as their response to training. Long-term impacts on sports performance and potential career paths could result from training treatments implemented during this time (Bishop et al., 2011). There is a lack of evidence-based guidelines for adolescent athletes because the majority of HIIT research has been done on adults, despite its significance.

The fundamental elements of athletic performance in a variety of sports disciplines are speed and endurance. The ability of the circulatory and muscular systems to maintain extended exercise is reflected in endurance capacity, which is commonly assessed by maximal oxygen uptake (VO_2 max). It is commonly acknowledged that one of the best indicators of aerobic performance is VO_2 max (Bauer et al., 2022).Enhancing endurance capacity in teenagers not only improves performance but also has long-term health benefits, such as lowering the risk of obesity and cardiovascular disease (Milanović et al., 2015; Deng and Wang, 2024)

On the other hand, in sports like rugby, football, basketball, and track and field, speed is a key component. When playing games that require rapid accelerations, direction changes, or pursuit, even minor gains in sprint

performance might give an advantage over other players. Plyometrics, resisted sprinting, and high-intensity exercise are examples of neuromuscular training stimuli that have a particularly strong effect on speed development in young athletes (Rumpf et al., 2016).

Given the significance of both speed and endurance, coaches of adolescent athletes face the difficulty of finding training strategies that concurrently improve these abilities without overtaxing or exhausting young athletes.

Improvements in VO_2 max, mitochondrial density, capillarization, and glycolytic enzyme activity are just a few of the positive adaptations that HIIT has been demonstrated to produce (Hanafi and Hasanuddin, 2022; Michailidis et al., 2023). Furthermore, it has been shown that sprint-based HIIT therapies are effective in enhancing running economy and neuromuscular power, two factors that directly influence speed performance. Crucially, HIIT workouts are typically shorter than conventional training sessions, which lowers the time commitment overall and may lessen the likelihood of overuse issues (Laursen and Jenkins, 2002; Men et al., 2023).

Adolescent athletes may benefit from HIIT in other ways. Time management is especially important for young people who have to juggle social, athletic, and academic obligations. Furthermore, HIIT protocols' intensity and diversity may enhance motivation and enjoyment, two factors that are critical for young populations' long-term adherence (Helgerud et al., 2007). The safety and suitability of HIIT for teenagers are still up for debate, though, especially in light of the risks of overtraining, musculoskeletal strains, and cardiovascular stress. As a result, carefully crafted methods that are appropriate for adolescents' developmental stage are needed (Logan et al., 2014; Hottenrott et al., 2022).

Although HIIT has been shown to be beneficial for adults, its effects on teenage athletes have not been well studied in many controlled experiments. The few studies that do exist have frequently concentrated on sprint ability or endurance results separately, failing to take into account how HIIT affects both performance metrics (Rønnestad et al., 2015). Additionally, the findings' generalisability has been hampered by methodological flaws such varied training methods, limited sample sizes, and a lack of suitable control groups.

This gap in the literature is of particular importance not only for sports performance but also for adolescent health and clinical outcomes. High-intensity interval training (HIIT) is increasingly being implemented in youth training programs by coaches and practitioners; however, its effectiveness and safety in this population remain insufficiently established. Beyond performance enhancement, HIIT has the potential to improve cardiopulmonary fitness, which is a key indicator of overall health and a protective factor against future cardiovascular disease in adolescents (Armstrong and Barker, 2011; Costigan et al., 2015). Additionally, appropriately designed HIIT protocols may contribute to improved neuromuscular control and reduced risk of sports-related injuries (Rumpf et al., 2016). Therefore, a systematic investigation comparing HIIT with conventional training methods in adolescent athletes is warranted to better understand its role in both performance development and health promotion.

Therefore, more experimental studies are necessary to clarify how HIIT affects young athletes' development of endurance and speed. This study looked at how an eight-week HIIT intervention affected adolescent athletes' VO_2 max and 30 m sprint performance in comparison to a control group that received conventional training. It was predicted, based on previous studies, that the HIIT group would outperform the control group in terms of VO_2 max and sprint performance.

2 Methods

2.1 Study design

This study employed a randomized controlled trial design with pre- and post-intervention testing. Participants were randomly allocated to either:

1 HIIT Group (n=20): Completed an 8-week high-intensity interval training program in addition to their regular sport-specific training.

2 Control Group (n=20): Completed an 8-week traditional endurance and sprint training program alongside their regular sport-specific training.

Both groups trained three times per week under supervision by certified strength and conditioning coaches. Testing occurred one week before (baseline) and one week after the intervention.

2.2 Participants

Forty adolescent athletes (22 males, 18 females) aged 14-17 years were recruited from local sports academies (soccer, basketball, athletics, and rugby). Inclusion criteria were:

Minimum 2 years of organized sports participation.

Currently training at least 3 times per week.

Medical clearance for high-intensity exercise.

Exclusion criteria included: history of cardiovascular or respiratory disease, musculoskeletal injuries within the past 6 months, or participation in structured HIIT programs in the previous 3 months.

Parental consent and athlete assent were obtained in compliance with ethical guidelines for research involving minors.

2.3 Training interventions

2.3.1 HIIT training program

The HIIT protocol was designed to progressively increase intensity and volume over 8 weeks as shown in Table 1. Training sessions lasted 25-30 minutes, excluding warm-up and cool-down.

Table 1 Training Regime for 8 weeks

Week	Frequency	Work Interval	Reps	Recovery	Mode
1-2	3×/week	15 sec @ 90% HRmax	10	45 sec jog	Running-based sprints
3-4	3×/week	20 sec @ 90-92% HRmax	12	40 sec jog	Running-based sprints
5-6	3×/week	25 sec @ 92-94% HRmax	14	35 sec jog	Shuttle sprints+hill sprints
7-8	3×/week	30 sec @ 94-95% HRmax	16	30 sec jog	Sprint repeats+resisted runs

Warm-Up (10 minutes): Dynamic stretches, mobility drills, and light jogging.

Main Set: Short, maximal or near-maximal efforts (85-95% HRmax) interspersed with active recovery periods.

Cool-Down (5 minutes): Static stretching and light jogging.

Intensity monitored using heart rate monitors and rate of perceived exertion (RPE≥8/10).

Progressive overload (more resistance, shorter rest periods, and longer work) increased the weekly load.

Average session duration: ~25-30 minutes (excluding warm-up/cool-down).

2.3.2 Control training program

The control group performed traditional training consisting of moderate-intensity continuous running (65-75% HRmax) and short sprint efforts (6-8×60 m), reflecting commonly used conditioning practices in adolescent athletes (Seiler, 2010; Buchheit and Laursen, 2013). Although the total session duration was longer than that of the HIIT group, this difference reflects the time-efficient nature of HIIT protocols (Tomlin and Wenger, 2001; Gibala et al., 2012). Sessions lasted (40-50 minutes) This discrepancy in training volume should be considered when interpreting the results.

Warm-Up (10 minutes): Drills for dynamic mobility.

Main Set: Endurance: Continuous running at 65-75% HRmax for 20-25 minutes.

Speed: 6-8×60-meter sprints with full 2-3 min passive recovery.

Cool-Down (5 minutes): Light jogging and static stretching.

2.4 Testing procedures

2.4.1 Endurance (VO_2 max)

Endurance capacity was assessed using a graded treadmill test to exhaustion with indirect calorimetry (breath-by-breath gas analysis). The protocol involved:

Initial workload: 6 km/h, increasing by 1 km/h every 2 minutes.

Termination: Volitional exhaustion or failure to maintain running speed.

VO_2 max recorded as the highest oxygen consumption averaged over 30 seconds.

2.4.2 Speed (30m Sprint Test)

Sprint performance was measured using a 30-meter sprint test on an indoor track.

Athletes performed 3 maximal sprints with 3-minute recoveries.

Times were recorded with electronic timing gates at the 0m and 30m marks.

Best time of the three attempts was used for analysis.

2.5 Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics, Version 29 (IBM Corp., Armonk, NY, USA). The Shapiro-Wilk test was used to determine whether the data distributions were normal. Paired-samples t tests were used to assess within-group differences between pre- and post-intervention values. A two-way repeated-measures analysis of variance (ANOVA) was used to examine the differences between groups over time (HIIT vs. control, pre vs. post), with group serving as the between-subjects factor and time as the within-subjects factor. Post hoc analyses were used to investigate pairwise differences further when significant effects were noted. Cohen's d was used to calculate effect sizes; small, medium, and large effects were denoted by values of 0.2, 0.5, and 0.8, respectively. For every test, the threshold for statistical significance was established at $p<.05$.

3 Result

The effects of the eight-week HIIT program were analyzed for VO_2 max and sprint performance. Results are presented with descriptive statistics, inferential tests, and effect sizes (Figure 1).

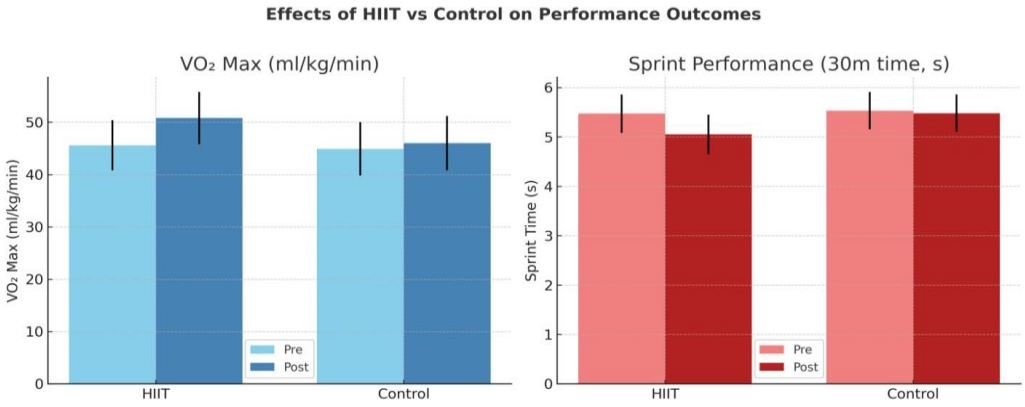

Figure 1 Comparison of VO_2 Max and 30 m Sprint Performance Between HIIT and Control Groups (Pre-and Post-Intervention)

Baseline and post-intervention descriptive statistics for VO_2 max and 30m sprint performance are presented in Table 2. At baseline, the HIIT and Control groups were comparable in VO_2 max ((45.6±4.8) vs. (44.9±5.1) $mL \cdot kg^{-1} \cdot min^{-1}$) and sprint times ((5.47±0.39) vs. (5.53±0.38) s). After the 8-week intervention, the HIIT group showed marked improvements in both VO_2 max ((50.8±5.0) $mL \cdot kg^{-1} \cdot min^{-1}$) and sprint performance ((5.05±0.40) s). The Control group exhibited only minimal changes ((46.0±5.2) $mL \cdot kg^{-1} \cdot min^{-1}$ in VO_2 max; (5.48±0.38) s in sprint times). These findings are consistent with prior reports that HIIT can produce rapid gains in aerobic capacity and speed compared to traditional training (Buchheit and Laursen, 2013; Costigan et al., 2015).

Table 2 Descriptive Statistics

Group	VO_2 Pre (ml/kg/min)	VO_2 Post (ml/kg/min)	Sprint Pre (s)	Sprint Post (s)
HIIT	45.6 ± 4.8 (36-55)	50.8 ± 5.0 (42-60)	5.47±0.39 (4.9-6.3)	5.05±0.40 (4.4-5.8)
Control	44.9 ± 5.1 (35-55)	46.0 ± 5.2 (36-56)	5.53±0.38 (4.9-6.2)	5.48±0.38 (4.9-6.2)

The normality of change scores was evaluated using Shapiro-Wilk tests (Table 3). Changes in sprint time and VO_2 max were roughly normally distributed in both groups, as seen by the non-significant nature of all distributions (p>0.05). This met the parametric testing assumptions.

Table 3 Shapiro-Wilk Normality Tests

Variable	W	p-value
HIIT VO_2 Change	0.96	0.58
Control VO_2 Change	0.95	0.42
HIIT Sprint Change	0.97	0.71
Control Sprint Change	0.96	0.55

Table caption: All p>0.05→data approximately normal

The HIIT group showed significant pre-post improvements in both sprint performance (t(19)=-10.5, p<0.001) and VO_2 max (t(19)=13.1, p<0.001), according to paired t-tests (Table 4). There was no discernible change in sprint performance (t(19)=-1.3, p=0.20), however the control group's VO_2 max improved little but statistically significantly (t(19)=2.1, p=0.047). These findings are consistent with the theory that HIIT offers a more effective training stimulus for developing adolescent athletes' aerobic capacity and speed (Baquet et al., 2010; Rønnestad et al., 2015).

Table 4 Paired t-tests (Pre vs Post within groups)

Group	Variable	t	p-value
HIIT	VO_2	13.1	<0.001
HIIT	Sprint	-10.5	<0.001
Control	VO_2	2.1	0.047
Control	Sprint	-1.3	0.20

According to independent-samples t-tests on change scores (Table 5), the HIIT group outperformed the Control group in both 30m sprint performance (t(38)=-7.2, p<0.001) and VO_2 max (t(38)=8.5, p<0.001). HIIT training was significantly more successful than normal training at eliciting physiological changes, as indicated by these significant between-group differences. The results align with earlier research showing that HIIT improves both aerobic and anaerobic performance more than moderate-intensity continuous training in young people (Buchheit and Laursen, 2013; Racil et al., 2016).

Table 5 Independent t-tests (Change Scores, HIIT vs Control)

Variable	t	p-value
VO_2 Change	8.5	<0.001
Sprint Change	-7.2	<0.001

A two-way repeated measure ANOVA was conducted to further investigate the intervention's effect, using Time (Pre vs. Post) as the within-subject factor and Group (HIIT vs. Control) as the between-subject factor (Table 6).

There was a significant Group×Time interaction (F(1,76=4.30, p=0.042) and a significant main effect of Group (F(1,76)=4.23, p=0.043) and Time (F(1,76)=6.60, p=0.012) for VO_2 max. According to this, the HIIT group improved significantly more than the Control group, even though both groups saw changes throughout time.

Additionally, there was a significant Group×Time interaction (F(1,76)=6.02, p=0.016) and a significant main effect of Group (F(1,76)=5.11, p=0.027) and Time (F(1,76)=7.45, p=0.008) for 30m sprint performance. These outcomes demonstrate that, in comparison to the Control condition, the HIIT intervention led to greater gains in sprint performance.

Table 6 Two-way Repeated Measures ANOVA for VO_2 Max and 30m Sprint

Source	df	F (VO_2 Max)	p (VO_2 Max)	F (Sprint)	p (Sprint)
Group	1	4.23	0.043*	5.11	0.027*
Time	1	6.60	0.012*	7.45	0.008**
Group×Time	1	4.30	0.042*	6.02	0.016*
Error	76	—	—	—	—

Table caption: Group=HIIT vs Control; Time=Pre-test vs Post-test; Group×Time=Interaction effect, testing whether improvement over time differs between groups; $p<0.05$, $p<0.01$

The results of the ANOVA show that, in comparison to traditional training, HIIT produced larger pre-post improvements in both aerobic and anaerobic performance metrics. This supports the effectiveness of high-intensity interval training in adolescent athletes (Baquet et al., 2010; Costigan et al., 2015).

4 Discussion

The current study assessed at how an 8-week high-intensity interval training (HIIT) intervention affected teenage athletes' anaerobic performance (30-meter sprint) and aerobic capacity (VO_2 max). According to the results, the HIIT group significantly improved their sprint performance (-0.42 s) and VO_2 max (+5.2 $mL•kg^{-1}•min^{-1}$), whereas the control group only showed slight or non-significant changes. The HIIT group's improvement was significantly larger than the control group's, according to independent t-tests. Furthermore, the better effectiveness of HIIT was confirmed by the two-way repeated measures ANOVA, which showed significant Group×Time interactions for both sprint and VO_2 max.

These results support earlier research showing that HIIT is an effective and time-efficient training method for improving young athletes' aerobic and anaerobic fitness (Baquet et al., 2010; Buchheit and Laursen, 2013).

The observed gains in VO_2 max are consistent with previous research showing that HIIT programs in adolescents resulted in increases in aerobic capacity of 6-15% (Baquet et al., 2010; Engel et al., 2019). These parameters are supported by the current study's~11% increase in VO_2 max in the HIIT group, which highlights how effective repeated short, high-intensity workouts are at promoting metabolic and cardiovascular adaptations (Buchheit and Laursen, 2013).

The HIIT group had an improvement in sprint performance of about 8%, which is consistent with findings from Racil et al. (2016), who found that adolescent athletes who followed comparable interval regimens saw significant decreases in sprint times. Further evidence that conventional continuous or low-intensity training may not adequately target the neuromuscular adaptations necessary for speed development comes from the control group's absence of significant sprint increases (Edge et al., 2006).

The observed benefits could be explained by a number of physiological processes. According to Gibala et al. (2012), HIIT is known to improve oxygen utilisation efficiency, stroke volume, and mitochondrial biogenesis. Due to their high levels of flexibility throughout growth and maturation, teenagers may experience these changes more quickly (Baquet et al., 2010). Additionally, because HIIT involves repeated sprints, it is likely that neuromuscular changes such as greater anaerobic glycolytic capacity and increased motor unit recruitment led to faster sprint timings (Racil et al., 2016).

These results imply that adding HIIT to youth training regimens can assist coaches and practitioners in two ways: it can increase sprint performance and endurance capacity in a comparatively short amount of time. This is especially helpful for teenage athletes playing sports like soccer, basketball, and hockey that call for both anaerobic and aerobic abilities. Furthermore, according to earlier research demonstrating its applicability in both sports and health-related situations, HIIT might provide a time-efficient substitute for athletes with constrained training schedules (Costigan et al., 2015).

5 Conclusion

In conclusion, the current study offers solid proof that, in comparison to conventional training methods, HIIT dramatically improves both aerobic and anaerobic performance in adolescent athletes. These results add to the

increasing amount of research that shows HIIT is a time-efficient, successful training method for young people and emphasise its applicability to coaches and sport scientists who want to maximise performance results.

6 Limitations and Future Directions

It is important to recognise a number of limitations despite the positive outcomes. First, there may be limitations on generalisability due to the small sample size (n=40) and its restriction to a specific sporting demographic. Second, self-reported external physical activities and training adherence may have introduced bias. Third, injury incidence, recovery indices, and perceived exertion were not tracked, despite the measurement of physiological outcomes. Long-term HIIT programs, larger and more varied cohorts, recovery techniques, and psychological reactions to high-intensity exercise should all be examined in future studies.

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Abhishek Balo and Pranjit Baruah conceived and designed the study. Abhishek Balo and Tonkey Pegu were responsible for data collection and experimental implementation. O. Jiten Singh performed the statistical analysis and interpreted the data. Sidhartha Rajbongshi drafted the manuscript. Pabitra Pran Gogoi and Arindom Baruah revised the manuscript critically for important intellectual content. Mantu Baro supervised the study. All authors read and approved the final version of the manuscript.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Application Strategies and Efficacy Evaluation of Immunotherapy in the Comprehensive Treatment of Advanced Ovarian Cancer

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Abstract This study explores the application strategies, efficacy evaluation, and future prospects of immunotherapy in advanced ovarian cancer. Advanced ovarian cancer is characterized by insidious onset, high recurrence rates, and frequent drug resistance, and the traditional treatment paradigm of cytoreductive surgery combined with platinum-based chemotherapy has limited long-term survival benefits. As an emerging therapeutic approach, immunotherapy-including immune checkpoint inhibitors, cancer vaccines, and adoptive cell therapies, has demonstrated potential efficacy in a subset of patients. Current evidence indicates that immune checkpoint inhibitor monotherapy has limited efficacy, whereas combination strategies with chemotherapy, anti-angiogenic agents, and PARP inhibitors may improve outcomes to some extent, albeit with increased toxicity. Efficacy evaluation still primarily relies on conventional endpoints such as ORR, PFS, and OS; the integration of biomarkers such as PD-L1, TMB, and BRCA/HRD may assist in patient selection, although their predictive value remains limited. Future efforts should focus on optimizing combination strategies, identifying novel immune targets, and advancing precision medicine and high-quality clinical research to further improve the role of immunotherapy in advanced ovarian cancer.

Keywords Advanced ovarian cancer; Immunotherapy; Immune checkpoint inhibitors; Combination therapy; Biomarkers

1 Introduction

Ovarian cancer is the most lethal gynecologic malignancy worldwide, with over 300 000 new cases and more than 200 000 deaths annually, and most patients are diagnosed at an advanced stage. Its onset is typically insidious: early symptoms are vague, such as abdominal discomfort, bloating, dyspepsia, altered bowel habits, and urinary frequency, and are easily misattributed to benign gastrointestinal or gynecologic conditions (Ghose et al., 2024). Population-wide screening strategies based on ultrasound and serum biomarkers such as CA-125 and HE4 have not yet demonstrated sufficient sensitivity and specificity to enable effective early detection, leading to approximately 70%-75% of women presenting with FIGO stage III–IV disease (Papageorgiou et al., 2025). This late-stage diagnosis translates into a sharp decline in prognosis, with 5-year survival falling from over 90% in early-stage disease to around 20%-30% in advanced stages, and overall survival remaining poor despite therapeutic progress (Hong and Ding, 2025). The biological heterogeneity of epithelial ovarian cancer, combined with frequent acquisition of chemoresistance and high recurrence rates, further compounds these adverse outcomes (Tavares et al., 2024).

For several decades, the cornerstone of advanced ovarian cancer management has been maximal cytoreductive surgery combined with platinum-based chemotherapy, often with taxanes, delivered either as primary debulking followed by adjuvant therapy or as neoadjuvant chemotherapy followed by interval debulking (Wang et al., 2025). Although these strategies achieve high initial response and complete remission rates, particularly when no visible residual disease is obtained, the majority of patients experience relapse, and recurrent disease is usually incurable. Real-world data indicate that only about 45%-50% of patients with stage III–IV disease remain alive at 5 years, and many will cycle through multiple lines of chemotherapy with progressively shorter response durations and accumulating toxicity. Targeted agents such as bevacizumab and poly (ADP-ribose) polymerase (PARP) inhibitors have improved progression-free survival in selected subgroups, notably those with BRCA mutations or homologous recombination deficiency, but their impact on long-term cure rates is limited and resistance

frequently develops (Papageorgiou et al., 2025). Consequently, advanced ovarian cancer often evolves into a chronic, relapsing disease state characterized by alternating periods of remission and recurrence, with significant impacts on quality of life and healthcare burden (Tavares et al., 2024).

These limitations of conventional cytotoxic and targeted therapies underscore an urgent need for novel treatment paradigms capable of inducing more durable disease control and potentially long-lasting remission. Immunotherapy, which harnesses or augments the host immune system to recognize and eradicate malignant cells, has revolutionized the management of several solid tumors and is increasingly being investigated in ovarian cancer. Epithelial ovarian cancer is an immunogenic tumor: tumor-reactive T cells and antibodies can be detected in blood, tumor tissue, and ascites, and higher densities of CD8+tumor-infiltrating lymphocytes correlate with improved survival, suggesting that effective antitumor immunity can modify disease course. Multiple immunotherapeutic modalities are under active exploration, including immune checkpoint inhibitors targeting CTLA-4 and PD-1/PD-L1, cancer vaccines, adoptive cell therapies such as CAR-T and TCR-engineered T cells, oncolytic viruses, and cytokine-based strategies (Papageorgiou et al., 2025). However, single-agent checkpoint inhibitors have generally yielded modest response rates in unselected ovarian cancer populations, highlighting the role of an immunosuppressive tumor microenvironment and the need for rational combination approaches and biomarker-guided patient selection.

This study aims to explore the current treatment status and limitations of advanced ovarian cancer. For several decades, its cornerstone has been maximal cytoreductive surgery combined with platinum-based chemotherapy, typically with taxanes, delivered either as primary debulking followed by adjuvant therapy or as neoadjuvant chemotherapy followed by interval debulking. Although these approaches achieve high initial response and complete remission rates, particularly when no visible residual disease is achieved, the majority of patients ultimately relapse, and recurrent disease is generally incurable. Real-world data indicate that only about 45%-50% of patients with stage III–IV disease remain alive at 5 years, and many undergo multiple lines of chemotherapy with progressively shorter response durations and accumulating toxicity. Targeted agents such as bevacizumab and poly (ADP-ribose) polymerase (PARP) inhibitors have improved progression-free survival in selected subgroups, particularly those with BRCA mutations or homologous recombination deficiency, but their impact on long-term cure rates is limited and resistance frequently develops. Consequently, advanced ovarian cancer often evolves into a chronic, relapsing disease characterized by alternating periods of remission and recurrence, imposing a significant burden on both patient quality of life and healthcare systems.

2 Current Treatment Status of Advanced Ovarian Cancer

2.1 Standard therapeutic modalities: surgery and chemotherapy

For most patients with advanced epithelial ovarian cancer, the current standard of care remains a combination of cytoreductive surgery and platinum-based chemotherapy, usually with carboplatin and paclitaxel. Primary debulking surgery aims to achieve complete macroscopic tumor resection, as the extent of residual disease is one of the strongest prognostic factors for overall survival. For patients with high perioperative risk or low likelihood of optimal primary cytoreduction, neoadjuvant chemotherapy followed by interval debulking surgery offers a validated alternative with comparable survival and lower postoperative morbidity (Shawky et al., 2025). International guidelines now emphasize multidisciplinary evaluation by gynecologic oncologists, imaging-based assessment of resectability, and integration of germline and somatic testing at diagnosis to guide both surgical strategy and systemic therapy selection (Gaillard et al., 2025; Papageorgiou et al., 2025).

Despite refinements in surgical techniques, perioperative care, and chemotherapy scheduling, outcomes remain suboptimal, with the majority of women ultimately relapsing after an initial response to first-line therapy. Randomized trials and meta-analyses comparing primary surgery to neoadjuvant chemotherapy consistently show similar overall and progression-free survival, underscoring that cytotoxic chemotherapy plus surgery, regardless of sequence, has reached a therapeutic plateau in many patients. Dose-dense regimens, intraperitoneal chemotherapy, and hyperthermic intraperitoneal chemotherapy (HIPEC) have been explored to enhance first-line efficacy, but toxicity, logistical complexity, and inconsistent phase III data have limited their widespread adoption (Gaillard et

al., 2025). Consequently, traditional surgery-plus-chemotherapy paradigms, while indispensable, are insufficient to secure durable disease control for most patients with stage III-IV disease.

2.2 Targeted therapy and unresolved problems of recurrence and resistance

Over the past decade, targeted therapies have been incorporated into frontline and recurrent treatment, partially reshaping the therapeutic landscape of advanced ovarian cancer. Anti-angiogenic agents, particularly bevacizumab, are now used in selected high-risk patients both concurrently with chemotherapy and as maintenance, improving progression-free survival, especially in those with suboptimal debulking or extensive disease. In parallel, PARP inhibitors such as olaparib, niraparib, and rucaparib have fundamentally changed maintenance strategies by exploiting homologous recombination deficiency, with landmark trials (SOLO1, PRIMA, VELIA, PAOLA-1, ATHENA) demonstrating substantial delays in recurrence, particularly among BRCA-mutated and HRD-positive tumors. These agents are increasingly deployed in both first-line and recurrent settings, and combinations of PARP inhibitors with anti-angiogenic drugs have shown synergistic activity and secured regulatory approvals in defined biomarker-selected populations (Papageorgiou et al., 2025).

Nevertheless, even with modern targeted agents, long-term disease eradication remains rare, and recurrence, often within two to three years, continues to drive mortality in advanced ovarian cancer. Platinum-based chemotherapy achieves initial response rates of up to 80%, but most advanced-stage patients eventually relapse due to acquired or intrinsic drug resistance, transforming the disease into a pattern of repeated remissions and recurrences. Molecular studies highlight that resistance mechanisms are multifactorial, involving enhanced DNA damage repair, altered drug transport, evasion of apoptosis, cancer stem cell populations, and remodeling of the tumor microenvironment (Nunes et al., 2024). These complex resistance networks limit the durability of benefit from both cytotoxic agents and targeted therapies, including PARP inhibitors and bevacizumab, and underscore the need for novel modalities capable of overcoming or bypassing established resistance pathways.

2.3 Toward individualized and precision treatment strategies

The persistent challenge of relapse and resistance has accelerated a shift from “one-size-fits-all” protocols toward more individualized treatment strategies grounded in molecular profiling and risk stratification. Contemporary guidelines increasingly recommend universal germline BRCA testing and expanded somatic profiling to identify homologous recombination deficiency, actionable mutations, and other genomic features that can guide selection of PARP inhibitors, anti-angiogenic agents, or enrollment in biomarker-driven clinical trials (Wang et al., 2025). Treatment decisions in the recurrent setting now explicitly incorporate platinum-free interval, residual toxicity, prior exposure to targeted agents, and patient preferences, allowing differentiation between platinum-sensitive and platinum-resistant pathways, with tailored combinations of chemotherapy, targeted therapy, and, in select cases, surgery or radiotherapy (Papageorgiou et al., 2025).

Beyond genomics, emerging approaches aim to integrate multi-omics data, tumor microenvironment characteristics, and artificial-intelligence-based analyses to refine subtype classification and predict drug response at the individual level (Nunes et al., 2024). Single-cell and spatial profiling have begun to delineate resistant cellular phenotypes that persist after first-line therapy and seed lethal recurrences, opening avenues for rational combination strategies targeting both tumor cells and stromal or immune components (Zhang et al., 2024; Whipman et al., 2025). This precision-medicine trend also extends to the development of novel targeted agents, such as antibody-drug conjugates, PI3K/AKT/mTOR inhibitors, and dual-targeted nanomedicines, that seek to improve selectivity, mitigate systemic toxicity, and overcome resistance (Wang et al., 2025). Within this evolving, increasingly personalized framework, immunotherapy is being actively explored as an integral component of comprehensive treatment, with the goal of achieving more durable control and potentially transforming advanced ovarian cancer into a truly manageable chronic or even curable condition.

3 Basis and Mechanisms of Immunotherapy

3.1 Tumor immune microenvironment in advanced ovarian cancer

The tumor immune microenvironment (TIME) of ovarian cancer is highly complex and profoundly shapes responses to immunotherapy. It comprises malignant cells, stromal components such as cancer-associated fibroblasts, endothelial cells, and a dense infiltrate of innate and adaptive immune cells embedded within an

extracellular matrix rich in cytokines, chemokines, growth factors, and metabolites (Chen et al., 2024a). Tumor-infiltrating lymphocytes (TILs), particularly $CD8^+$ cytotoxic T cells and $CD4^+$ helper T cells, are key mediators of antitumor immunity, and their presence in primary tumors or ascites correlates with improved survival, underscoring the inherent immunogenicity of epithelial ovarian cancer. Innate effectors, including natural killer (NK) cells and dendritic cells, can directly lyse tumor cells or orchestrate T-cell priming, while B cells contribute through antibody production and antigen presentation. However, chronic antigen exposure, persistent inflammation, and hypoxia progressively remodel this initially protective milieu into a protumor niche that supports immune evasion, metastatic spread, and therapy resistance (Garlisi et al., 2024).

A defining feature of advanced ovarian cancer TIME is the dominance of immunosuppressive networks that blunt effector cell function. Regulatory T cells (Tregs), myeloid-derived suppressor cells (MDSCs), and M2-polarized tumor-associated macrophages accumulate in tumors and ascites, where they secrete IL-10, TGF-β and other mediators, downregulate antigen presentation, and inhibit cytotoxic T and NK cell activity. High densities of these suppressive cells associate with poor prognosis and reduced responsiveness to checkpoint blockade. In parallel, abnormal angiogenesis, increased interstitial fluid pressure, and extensive fibrosis impede immune-cell trafficking and reduce drug penetration, further limiting the efficacy of systemic therapies (Garlisi et al., 2024). These intertwined cellular and structural barriers help explain why single-agent immune checkpoint inhibitors have shown modest response rates in unselected ovarian cancer populations, and they provide a strong rationale for combinatorial strategies that simultaneously recondition the TIME and enhance antitumor immunity.

3.2 Immune checkpoint pathways: PD-1/PD-L1 and CTLA-4

The programmed death-1 (PD-1)/programmed death-ligand 1 (PD-L1) axis is a central inhibitory pathway exploited by ovarian tumors to escape immune surveillance. PD-1 is an inhibitory receptor expressed on activated $CD4^+$ and $CD8^+$ T cells, B cells, and some innate lymphoid cells; its ligands PD-L1 and PD-L2 are upregulated on tumor cells, tumor-associated macrophages, dendritic cells, and other stromal elements within the TIME. Engagement of PD-1 by PD-L1 recruits phosphatases that dephosphorylate proximal T-cell receptor (TCR) signaling molecules, attenuating PI3K/AKT and RAS/ERK pathways, thereby inducing T-cell exhaustion, reducing cytokine secretion, and promoting apoptosis of effector cells (Lin et al., 2024). In ovarian cancer, PD-L1 expression is frequently observed on immune cells and, to a lesser extent, tumor cells, and can be induced by inflammatory cytokines such as IFN-γ, linking adaptive immune resistance to local immune activation (Garlisi et al., 2024). Antibodies targeting PD-1 or PD-L1 restore effector function and have revolutionized the treatment of several solid tumors, but in ovarian cancer their activity has generally been limited by the strongly suppressive microenvironment and low baseline T-cell infiltration (Chen et al., 2024a).

CTLA-4 (cytotoxic T-lymphocyte-associated protein 4) represents a complementary checkpoint that regulates earlier stages of T-cell activation, primarily within lymphoid organs. CTLA-4 is expressed on activated conventional T cells and constitutively on Tregs, where it competes with the costimulatory receptor CD28 for binding to CD80/CD86 on antigen-presenting cells (APCs) with much higher affinity, thereby dampening the second signal required for full T-cell activation. CTLA-4 engagement transduces inhibitory signals and promotes trans-endocytosis of CD80/CD86 from APCs, globally reducing their ability to costimulate naïve and memory T cells and enhancing Treg-mediated suppression. In ovarian cancer, CTLA-4 contributes to defective priming and expansion of tumor-reactive T cells and to the maintenance of an expanded intratumoral Treg compartment. Dual blockade of PD-1/PD-L1 and CTLA-4 can synergistically reinvigorate exhausted effector cells and deplete or functionally inhibit Tregs, but at the cost of increased immune-related toxicities, and clinical trials in ovarian cancer have so far produced modest and heterogeneous benefits, underscoring the need for rational combinations and biomarkers to identify likely responders (Figure 1) (Chen et al., 2024a; Garlisi et al., 2024).

3.3 Cancer vaccines and cell-based immunotherapies

Beyond checkpoint blockade, several active and adoptive immunotherapy strategies are being developed to exploit the immunogenicity of ovarian cancer. Cancer vaccines aim to prime or boost tumor-specific T-cell responses by presenting tumor-associated antigens (TAAs) or neoantigens in an immunostimulatory context, often

using autologous dendritic cells (DCs) pulsed with tumor lysate, peptides, or nucleic acids. Personalized DC vaccines loaded with oxidized whole-tumor lysate have demonstrated the ability to induce broad T-cell responses against both shared and private neoantigens in recurrent ovarian cancer, with vaccine-induced immunity correlating with prolonged progression-free and overall survival in early-phase trials. Integrating such vaccines with agents that modulate the TIME, such as bevacizumab, low-dose cyclophosphamide, or interleukin-2, can further enhance T-cell infiltration, reduce Treg frequencies, and promote polyfunctional effector responses. Neoantigen-based peptide or RNA vaccines and oncolytic viruses designed to release tumor antigens in situ are also under investigation, aiming to convert immunologically "cold" tumors into "hot" lesions amenable to checkpoint blockade (Garlisi et al., 2024).

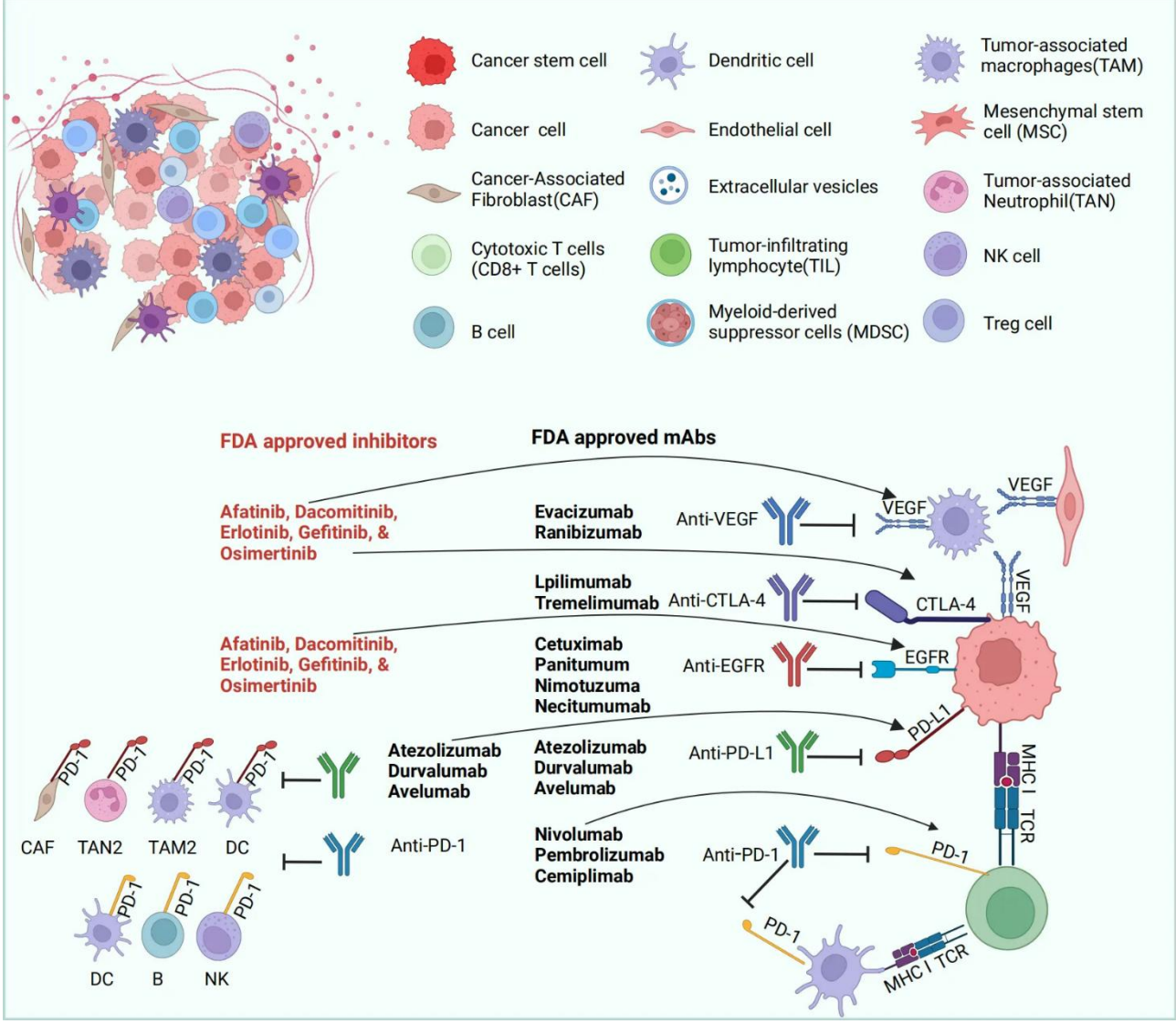

Figure 1 PD-1/PD-L1 interaction-mediated T-cell inhibition (Adopted from Chen et al., 2024a)

Image caption: Many mechanisms, such as genomic aberrations, oncogenic transcription factors and pathways, and post-translational regulation and transport, are involved in the regulation of PD-L1 expression. In addition, anti-PD-1/PD-L1 antibodies can block the activation of PD-1/PD-L1. APCs can absorb tumor antigens and regulate T-cell responses through interactions between the main MHC and TCR. APC can also regulate T-cell activity by regulating the interaction between PD-L1/PD-L2 and PD-1, as well as the interaction between B7 and CD28 (Adopted from Chen et al., 2024a)

Adoptive cell therapies (ACT) represent another major pillar of immunotherapy in advanced ovarian cancer, seeking to provide large numbers of tumor-reactive lymphocytes with enhanced functionality. Strategies include expansion of naturally occurring tumor-infiltrating lymphocytes (TILs), T cells engineered to express high-affinity T-cell receptors (TCRs), and chimeric antigen receptor (CAR)-T cells targeting ovarian cancer antigens such as

mesothelin, MUC16 (CA-125), and folate receptor-α. Preclinical models and early clinical experience indicate that CAR-T cells can mediate potent cytotoxicity and durable tumor control, but their efficacy in solid tumors is constrained by antigen heterogeneity, limited trafficking and persistence, and inhibitory signals from the TIME (Garlisi et al., 2024). To address these barriers, next-generation CAR-T constructs are being engineered to resist PD-1/PD-L1–mediated suppression, secrete checkpoint-blocking antibodies or cytokines, or co-target multiple antigens, and are increasingly combined with checkpoint inhibitors, anti-angiogenic agents, or chemotherapy (Gitto et al., 2024). Together, cancer vaccines and ACT exemplify how immunotherapy can be tailored to the specific antigenic and immune context of ovarian cancer, providing a mechanistic foundation for their integration into comprehensive, multimodal treatment strategies.

4 Application Strategies of Immunotherapy

4.1 Current use of immune checkpoint inhibitors as monotherapy

Immune checkpoint inhibitors (ICIs) targeting PD-1, PD-L1, and CTLA-4 have been extensively investigated as single agents in advanced and recurrent ovarian cancer, largely in phase I–III trials involving heavily pretreated populations. Overall response rates with monotherapy nivolumab, pembrolizumab, avelumab, atezolizumab, durvalumab, or ipilimumab have generally been modest, typically in the 8%-15% range, with few complete responses and no clear overall survival advantage over historical controls. Several phase III trials testing PD-1/PD-L1 inhibitors as frontline or maintenance monotherapy failed to demonstrate significant benefit, and to date, no ICI monotherapy has been approved as standard of care in ovarian cancer (Bogani et al., 2025). These disappointing outcomes contrast sharply with the transformative impact of ICIs in melanoma, lung cancer, and other solid tumors, underscoring disease-specific barriers such as a highly immunosuppressive tumor microenvironment and relatively low tumor mutational burden.

Despite limited efficacy at the population level, monotherapy studies have provided important mechanistic and translational insights that shape current application strategies. Clinical data confirm that a subset of patients, often characterized by higher PD-L1 expression, inflamed immune phenotypes, or mismatch repair deficiency, can achieve durable benefit, suggesting that more refined biomarker-driven selection may rescue the therapeutic potential of single-agent ICIs in defined niches (Ghisoni et al., 2024; Na et al., 2024). Additionally, early trials have clarified toxicity profiles, revealing largely manageable immune-related adverse events but also occasional severe colitis, pneumonitis, endocrinopathies, and rare hyper-progressive disease, which must be carefully monitored when ICIs are deployed alone or in combination. These experiences have shifted the field away from broad, unselected monotherapy use toward rationally designed regimens that embed ICIs within multimodal strategies and individualized treatment algorithms.

4.2 Combination immunotherapy with chemotherapy, targeted therapy, and radiotherapy

Given the modest activity of ICI monotherapy, a major focus has been on combinations that can recondition the tumor microenvironment and enhance antitumor immunity. Chemotherapy can increase tumor antigen release, upregulate MHC expression, and transiently deplete regulatory T cells, providing a biologic rationale for pairing platinum-taxane regimens with PD-1/PD-L1 blockade in both frontline and recurrent settings. Early signal-seeking trials suggested improved response rates with chemo-immunotherapy compared with historical chemotherapy controls, but large randomized studies have yielded heterogeneous and often disappointing results, with no consistent overall survival benefit and increased hematologic and immune-related toxicities (Bogani et al., 2025). These findings indicate that simple additive regimens may be insufficient and that timing, sequencing, and patient selection are critical to unlock synergy.

Combination strategies with targeted agents, particularly anti-angiogenic drugs and PARP inhibitors, have shown more promising activity and are now central to the evolving therapeutic landscape. Anti-VEGF therapy can normalize aberrant vasculature, improve immune-cell trafficking, and reduce myeloid-derived suppressor cell recruitment, potentially sensitizing tumors to ICIs; accordingly, regimens such as bevacizumab plus PD-1/PD-L1 inhibitors have achieved higher response rates and prolonged progression-free survival in subsets of patients, albeit with more hypertension, proteinuria, and immune toxicity. Similarly, PARP inhibitors induce DNA damage

and increase neoantigen load and type I interferon signaling, providing a rationale for PARP-ICI combinations that have demonstrated encouraging activity, especially in BRCA-mutated or homologous-recombination-deficient disease (Chen et al., 2025). Radiotherapy is also being explored as an immunogenic adjuvant capable of inducing in situ vaccination and abscopal effects, with nanoparticle-based radiosensitizers and toll-like receptor agonists under investigation to further amplify systemic immune responses when combined with ICIs.

4.3 Multimodal and individualized immunotherapy strategies

The convergence of clinical and translational data has driven a shift toward multimodal and personalized immunotherapy strategies that integrate ICIs with other immune-based and conventional modalities. Multi-immunotherapy concepts combine checkpoint blockade with adoptive cell therapies, cancer vaccines, or oncolytic viruses to simultaneously expand tumor-specific T-cell clones, enhance their effector function, and dismantle immunosuppressive networks within the tumor microenvironment. Early-phase studies of PD-1/CTLA-4 dual blockade have shown higher response rates and more durable remissions than monotherapy in some recurrent and platinum-resistant cohorts, at the expense of increased immune-related toxicity, prompting careful exploration of optimal dosing and patient selection (Li et al., 2025). Parallel efforts are evaluating ICIs alongside CAR-T or TCR-engineered T cells, dendritic-cell vaccines, and antibody-drug conjugates in order to provide complementary mechanisms of tumor recognition and killing while exploiting immunologic memory for long-term control (Chen et al., 2025).

A central theme in contemporary strategy design is individualized treatment based on immunophenotype and molecular biomarkers. Stratification by $CD8^+$ T-cell infiltration, PD-L1 expression, homologous-recombination status, tumor mutational burden, and gene-expression signatures allows classification of ovarian cancers into “inflamed”, “immune-excluded” and “immune-desert” phenotypes, each requiring distinct combination approaches (Ghisoni et al., 2024). For example, inflamed tumors may be suitable for ICI-based doublets or multi-immunotherapy, whereas immune-desert lesions might first need priming with vaccines, epigenetic modulators, or radiotherapy to recruit effector cells before checkpoint blockade is effective (Figure 2) (Connor et al., 2024). Emerging technologies such as single-cell sequencing, spatial transcriptomics, organoids, and nanomedicine-enabled drug delivery further support the design of tailored regimens, optimize dosing and sequencing, and help predict benefit versus toxicity on an individual basis. Within this framework, ICIs are no longer viewed as standalone agents but as flexible components of comprehensive, patient-specific treatment architectures that combine surgery, chemotherapy, targeted therapy, and diverse immunotherapies to maximize durable benefit in advanced ovarian cancer.

5 Efficacy Evaluation of Immunotherapy

5.1 Traditional endpoints

Objective response rate (ORR), progression-free survival (PFS), and overall survival (OS) remain the core endpoints for evaluating the efficacy of immunotherapy in advanced ovarian cancer, largely inherited from chemotherapy and targeted-therapy trial design. In recurrent ovarian cancer, ORR has historically shown a strong correlation with PFS and a moderate association with OS, supporting its use as a surrogate endpoint in later-line settings. However, large cross-tumor meta-analyses of contemporary immunotherapy trials indicate that, for checkpoint inhibitors and their combinations, trial-level correlations between ORR, PFS, and OS are generally weak, suggesting that conventional radiologic shrinkage does not fully capture long-term benefit from immune-based treatments (Shahnam et al., 2023). This discrepancy is particularly relevant in immuno-oncology, where durable disease stabilization and delayed responses may translate into survival gains despite modest ORR.

The limitations of ORR and PFS are further highlighted by pooled analyses of randomized immunotherapy trials submitted to the FDA. Across multiple agents and tumor types, associations between treatment effects on ORR or PFS and OS were low (R^2 values around 0.13), and attempts to modify PFS definitions by altering progression thresholds did not materially improve surrogacy for OS. Broader meta-analyses of phase III studies confirm that ORR and PFS are poor trial-level surrogates for OS across diverse malignancies and treatment classes, although correlations can be somewhat stronger in specific disease-treatment subsets. These findings support continued use

of ORR, PFS, and OS in ovarian cancer immunotherapy trials but emphasize the need to interpret early endpoints cautiously and in conjunction with immune-specific response metrics and biomarker data (Shahnam et al., 2023).

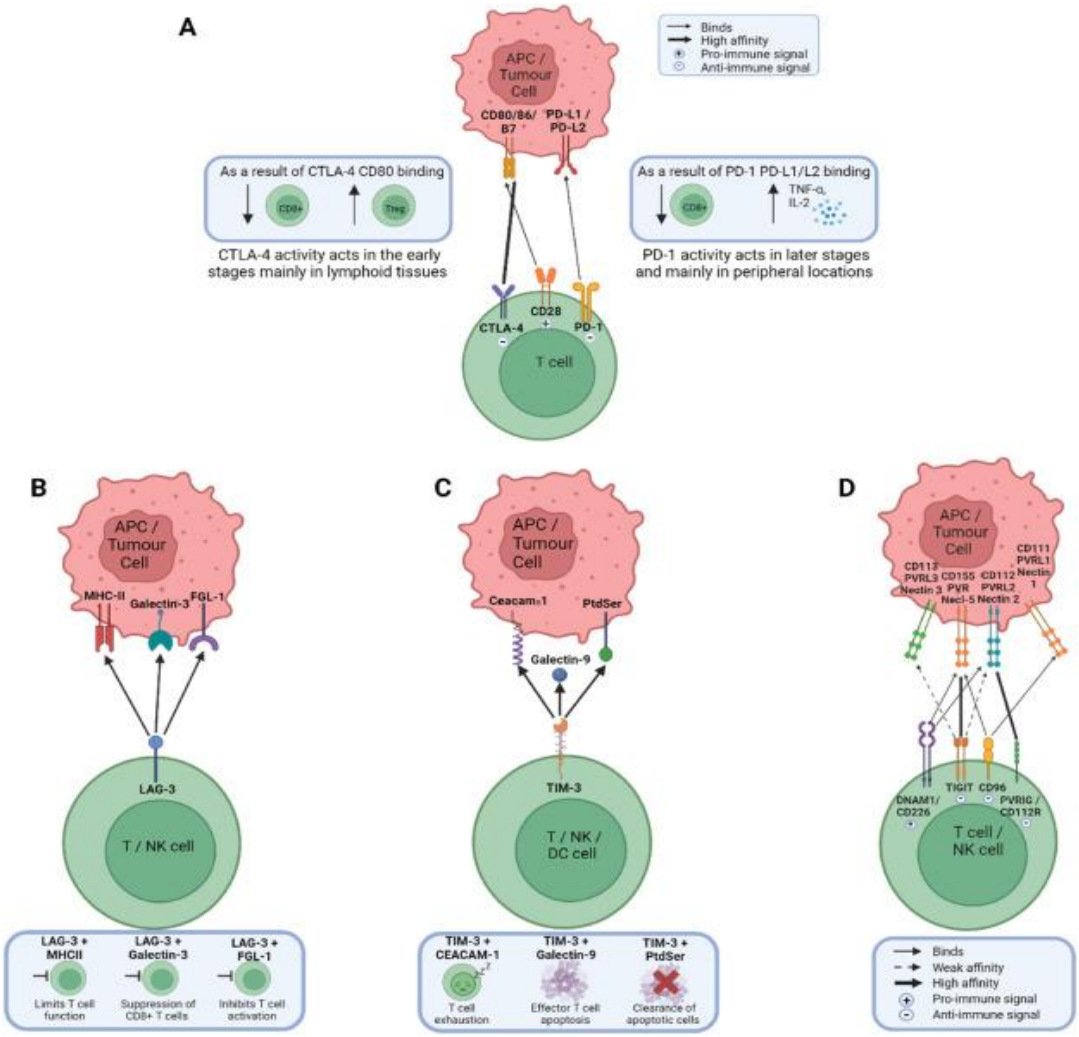

Figure 2 Immune checkpoint receptors and binding ligands, and their immunologic effect (Adopted from Connor et al., 2024)
Image caption: A) The B7-CD28 family: The binding interactions of three of the receptors in this family; CTLA-4, CD28 and PD-1 to the ligands CD80, CD86, PD-L1 and PD-L2. B) LAG3 receptor binding ligands and their immunologic effect. C) TIM-3 receptor binding ligands and their immunological effect. D) TIGIT family receptors: The binding interactions and affinity between receptors and their corresponding ligands (Adopted from Connor et al., 2024)

5.2 Immune-related response criteria and pseudoprogression

Because immune checkpoint blockade can induce unconventional patterns of response, conventional RECIST 1.1 criteria may misclassify some patients who ultimately benefit from treatment. Immune-related criteria such as irRC, irRECIST, and iRECIST were developed to address phenomena like transient tumor enlargement, new lesions followed by regression, and delayed responses. In a large pooled analysis of patients treated with the PD-L1 inhibitor avelumab, approximately 8% of patients categorized as having progressive disease (PD) by RECIST 1.1 actually achieved immune-related disease control by irRECIST, and this discordant subgroup displayed a distinct, more favorable survival curve. Nonetheless, immune-related PFS did not outperform conventional PFS as a surrogate for OS at the population level, indicating that immune-adapted criteria add clinical nuance but do not fundamentally replace standard endpoints (Manitz et al., 2022).

Pseudoprogression, initial radiologic progression followed by tumor regression without treatment change, is an established but relatively infrequent phenomenon in patients receiving ICIs, with pooled estimates around 6% across solid tumors and reported rates rarely exceeding 10%. Systematic reviews and meta-analyses show that

pseudoprogression rates vary modestly by tumor type, definition, and response criteria, and are somewhat more common with PD-1/PD-L1 monotherapy than with other ICI regimens (Park et al., 2020). Conversely, hyperprogression and dissociated responses have also been described, complicating decisions about treatment beyond progression. In practice, most guidelines still recommend RECIST-based assessment, reserving treatment continuation after apparent progression for carefully selected, clinically stable patients, ideally supported by confirmatory imaging consistent with immune-related criteria.

5.3 Biomarkers for efficacy evaluation: PD-L1, TMB, BRCA and HRD

Biomarker-driven patient selection is central to improving the risk-benefit profile of immunotherapy in advanced ovarian cancer, with PD-L1 expression, tumor mutational burden (TMB), and homologous recombination-related markers (including BRCA1/2) among the most widely studied. Across cancer types, large genomic datasets indicate that PD-L1 expression and TMB are largely independent biomarkers with limited correlation at the tumor level, and each exerts non-overlapping effects on ICI response rates. In ovarian cancer, PD-L1 positivity on tumor or immune cells is relatively common and has been associated with an inflamed microenvironment, but clinical trials such as KEYNOTE-100 and others have shown only modest enrichment of pembrolizumab responses at higher PD-L1 combined positive scores, with overall ORR remaining low (Matulonis et al., 2019). Global analyses of ICI trials therefore support PD-L1 as an imperfect, context-dependent biomarker whose predictive value in ovarian cancer is weaker than in highly ICI-sensitive tumors like non-small cell lung cancer.

TMB and BRCA/HRD status provide additional, but also imperfect, layers of prognostic and predictive information. Mechanistically, BRCA1/2-mutated high-grade serous ovarian cancers exhibit higher neoantigen loads, increased $CD8^+$ T-cell infiltration, and elevated PD-1/PD-L1 expression in tumor-associated immune cells, and these features correlate with improved survival and a more immunogenic phenotype. However, biomarker analyses from the phase III IMagyn050 trial demonstrated that most newly diagnosed ovarian cancers have low TMB regardless of BRCA or HRD status, that TMB ≥10 mut/Mb is rare, and that neither BRCA1/2 mutations nor HRD predicted enhanced benefit from adding atezolizumab to bevacizumab-chemotherapy. Collectively, current evidence suggests that PD-L1, TMB, and BRCA/HRD primarily function as prognostic or weakly predictive markers in ovarian cancer; meaningful efficacy evaluation and individualized immunotherapy strategies will likely require composite algorithms integrating multiple biomarkers with tumor-infiltrating lymphocytes, gene-expression signatures, and clinical features (Figure 3) (Morand et al., 2021; Pizarro et al., 2023).

6 Clinical Progress and Efficacy Analysis

6.1 Major recent clinical trial outcomes

Over the past decade, multiple phase I–III trials have evaluated PD-1/PD-L1 and CTLA-4 inhibitors in advanced ovarian cancer, either as monotherapy or in combination with chemotherapy, anti-angiogenic agents, or PARP inhibitors. A comprehensive review of 20 clinical studies (16 phase I/II and 4 phase III) confirmed that single-agent ICIs achieved low response rates and did not improve survival, with several trials halted early due to toxicity or lack of efficacy. In contrast, combination regimens, particularly those integrating ICIs with platinum-based chemotherapy, bevacizumab, or PARP inhibitors, generally produced higher objective response rates and longer progression-free survival (PFS), albeit at the cost of increased treatment-related adverse events.

Large randomized phase III programs have further clarified the magnitude of benefit from immune-based strategies. A recent meta-analysis of eight phase II–III randomized trials including 6205 patients found that adding PD-1/PD-L1 inhibitors to chemotherapy or placebo did not significantly improve PFS in either first-line or recurrent settings (overall HR 1.02), and subgroup analyses by PD-L1 status also failed to show a clinically meaningful advantage (Vida et al., 2025). Consistently, a systematic review of seven phase III trials in newly diagnosed and recurrent epithelial ovarian cancer concluded that PD-L1 inhibitor monotherapy lacked efficacy in the frontline setting, while CPI-based combinations delivered, at best, modest PFS gains without clear overall survival (OS) benefit to date (Bogani et al., 2025). These results underscore that, although immunotherapy is firmly established in many solid tumors, its clinical impact in ovarian cancer remains constrained and highly regimen-dependent.

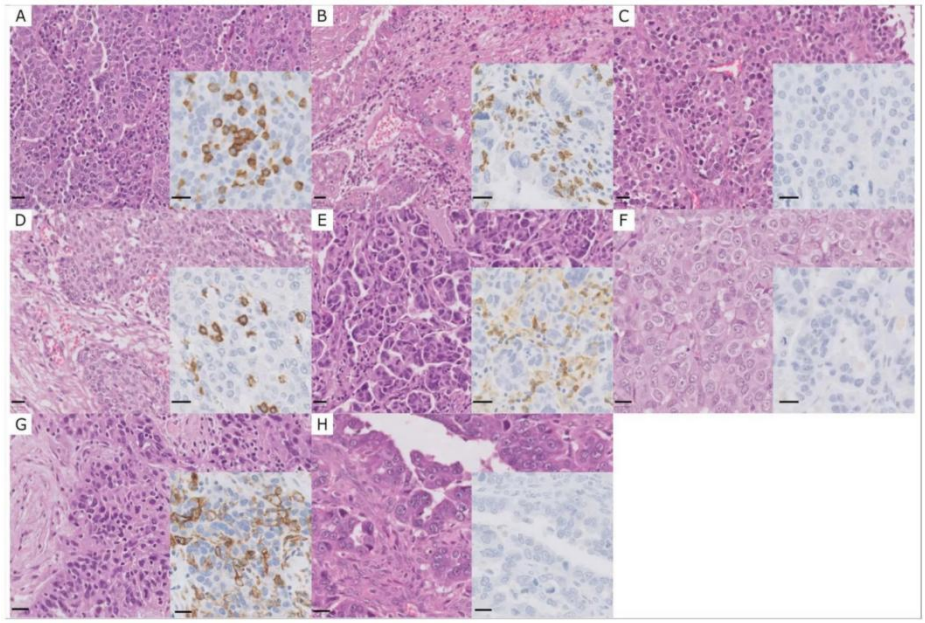

Figure 3 Histopathological and immunohistochemical analysis of the immune microenvironment and immune marker expression in advanced ovarian cancer tissue (Adopted from Pizarro et al., 2023)

Image caption: (A) Case with high iTILs CD8+, Inset: CD8 immunohistochemistry; (B) Case with high sTILs CD8+; Inset: CD8 immunohistochemistry; (C) Case with no CD8+lymphocytes; Inset: CD8 immunohistochemistry; (D) Case with high iTILs CD4+; Inset: CD4 immunohistochemistry; (E) Case with high sTILs CD4+; Inset: CD4 immunohistochemistry; (F) Case with no CD4+lymphocytes; Inset: CD4 immunohistochemistry; (G) PD-L1-positive case; Inset: PD-L1 immunohistochemistry; (H) PD-L1-negative case; Inset: PD-L1 immunohistochemistry; Scale bar 20 μm (Adopted from Pizarro et al., 2023)

6.2 Comparative efficacy of different treatment strategies

Comparative analyses across monotherapy, dual checkpoint blockade, and multi-drug combinations reveal important differences in clinical efficacy. Pooled clinical experience indicates that single-agent PD-1/PD-L1 or CTLA-4 blockade in unselected advanced ovarian cancer yields modest objective response rates and no survival improvement over historical chemotherapy benchmarks, positioning monotherapy primarily as an investigational option for highly selected biomarker-defined subgroups (Ghisoni et al., 2024). In contrast, dual PD-1/CTLA-4 blockade (such as nivolumab plus ipilimumab or durvalumab plus tremelimumab) has shown higher response rates and more durable responses, particularly in recurrent and platinum-resistant disease, although at the expense of greater immune-related toxicity and with notable heterogeneity across histologic subtypes (Li et al., 2025).

Combination regimens that layer ICIs onto established standards, chemotherapy, bevacizumab, and PARP inhibitors, have emerged as the most clinically mature strategies and allow direct comparison with non-immunotherapy controls. The FIRST/ENGOT-OV44 phase III trial demonstrated that adding dostarlimab to first-line platinum-based chemotherapy followed by dostarlimab-niraparib maintenance resulted in a statistically significant but clinically modest PFS extension (20.6 vs. 19.2 months; HR 0.85) without OS improvement, and with toxicity profiles consistent with the component agents (Hardy-Bessard et al., 2025). Similarly, a systematic review of CPI incorporation into epithelial ovarian cancer showed that triplet maintenance with bevacizumab, olaparib, and durvalumab prolonged PFS compared with bevacizumab alone in BRCA-wild-type patients, whereas CPI addition to standard therapy in platinum-sensitive and platinum-resistant settings generally failed to improve outcomes (Bogani et al., 2025). Collectively, these data suggest a gradient of efficacy from least with monotherapy, intermediate with dual checkpoint blockade, and modest but most clinically relevant benefit with carefully selected multi-agent combinations.

6.3 Survival benefits and current evidence

From a survival standpoint, the aggregate evidence indicates that immunotherapy has not yet replicated in ovarian cancer the transformative OS gains seen in melanoma or lung cancer. The meta-analysis of randomized

PD-1/PD-L1 trials showed no significant PFS benefit and, by extension, no convincing OS advantage in the overall or PD-L1-positive populations, highlighting a disconnect between mechanistic rationale and realized clinical benefit (Vida et al., 2025). Broad reviews of ICI experience in ovarian cancer similarly conclude that, while some regimens achieve encouraging disease control and prolonged remission in small subsets of patients, robust and consistent OS improvements across trial populations remain elusive (Ghisoni et al., 2024). This pattern reflects both the immunologically "cold" nature of many ovarian tumors and the dominance of competing resistance mechanisms that blunt durable immune control.

Nevertheless, specific combination strategies and immunophenotypically enriched cohorts show signals of meaningful survival benefit that inform ongoing development. Maintenance triplets integrating anti-angiogenic therapy, PARP inhibition, and PD-L1 blockade have prolonged PFS compared with bevacizumab-based standards in selected biomarker-defined groups, suggesting a path toward incremental survival improvement when immune therapy is used as part of rationally designed, biology-driven regimens (Bogani et al., 2025). Moreover, innovative multi-immunotherapy approaches, such as the phase II regimen of pembrolizumab plus bevacizumab and metronomic cyclophosphamide, have reported a median PFS of 10.2 months and a 47.5% objective response rate in heavily pretreated recurrent ovarian cancer, with a subset achieving disease control beyond one year, hinting at the possibility of durable clinical benefit in carefully selected patients (Rosario et al., 2024). Overall, current evidence supports a nuanced view: survival gains from immunotherapy in advanced ovarian cancer are modest and context-dependent at present, but rational combinations and precision immunophenotyping are beginning to delineate scenarios in which clinically meaningful benefit can be achieved.

7 Safety and Adverse Reactions

7.1 Types and manifestations of immune-related adverse events

Immune checkpoint inhibitors (ICIs) trigger a characteristic spectrum of immune-related adverse events (irAEs) that differ fundamentally from cytotoxic chemotherapy toxicities. The most frequently involved organs are skin (rash, pruritus), gastrointestinal tract (diarrhea, colitis), endocrine glands (thyroiditis, hypophysitis, adrenal insufficiency), lung (pneumonitis), liver (hepatitis), and musculoskeletal system (arthritis, myositis), whereas neurologic, cardiac, renal, hematologic, and ophthalmologic irAEs are less common but potentially life-threatening. Incidence and pattern vary by drug class: CTLA-4 blockade is more strongly associated with high-grade gastrointestinal and dermatologic toxicity, while PD-1/PD-L1 inhibitors more often produce thyroid dysfunction, pneumonitis, and rheumatologic manifestations (Casagrande et al., 2024). Overall, most irAEs are grade 1-2, but grade 3-4 events occur in a relevant minority, and treatment-related mortality is reported in up to ~2% of patients, depending on agent and regimen.

Gynecologic oncology cohorts illustrate these patterns in the ovarian cancer population. In a retrospective series of 61 patients with gynecologic malignancies (including ovarian cancer) treated with ICIs, 32.8% developed at least one irAE; hypothyroidism was the most common event, followed by hepatitis and colitis, and nearly half of irAEs were grade 3-4, though they were generally manageable with standard interventions. Median time to irAE onset was about 24 weeks, underscoring the delayed and sometimes prolonged course of toxicity compared with chemotherapy (Shehaj et al., 2024). Across tumor types, cutaneous, gastrointestinal, and endocrine toxicities frequently appear early, whereas some neurologic, cardiac, and rheumatologic irAEs may present late and with nonspecific symptoms, complicating diagnosis (Casagrande et al., 2024). These observations highlight the need for sustained vigilance throughout the entire course of immunotherapy, including maintenance and combination phases commonly used in advanced ovarian cancer.

7.2 Safety risks in combination immunotherapy strategies

As combination strategies gain prominence in advanced ovarian cancer, safety profiles become more complex. Dual checkpoint blockade (e.g., PD-1 plus CTLA-4 inhibition) typically increases both the incidence and severity of irAEs compared with monotherapy, with higher rates of high-grade colitis, hepatitis, dermatitis, and endocrinopathies reported across solid tumors (Casagrande et al., 2024). In addition, combining ICIs with agents such as PARP inhibitors, anti-angiogenic drugs, or chemotherapy, common in ovarian cancer regimens, may

exacerbate overlapping toxicities (myelosuppression, diarrhea, fatigue, hepatic injury) and make it challenging to distinguish immune-mediated events from drug-specific adverse effects. These overlapping patterns can delay correct diagnosis and appropriate immunosuppressive treatment if clinicians attribute symptoms solely to cytotoxic or targeted agents.

Meta-analytic data across multiple tumor indications show that adding ICIs to chemotherapy increases the risk of all-grade adverse events (relative risk~1.11) and serious (grade ≥3) events (relative risk~1.16), particularly high-grade diarrhea, dyspnea, fatigue, rash, and elevated liver enzymes, although treatment-related mortality is not substantially increased compared with chemotherapy alone (Rached et al., 2024). In gynecologic malignancies, a single-center analysis found that the duration of ICI exposure, rather than use of combination regimens per se, was the main predictor of irAE occurrence, suggesting a cumulative immune-stimulatory burden (Shehaj et al., 2024). For ovarian cancer specifically, systematic reviews note that ICI-based combinations can improve efficacy but at the cost of a "worse safety profile," reinforcing the need to balance modest survival gains against heightened toxicity when designing and selecting combination strategies.

7.3 Monitoring and management strategies

Effective management of irAEs in advanced ovarian cancer relies on early recognition, standardized grading, and prompt initiation of immunosuppression when appropriate. Major oncology societies, including ASCO and SITC, recommend organ-specific algorithms built on common principles: continue ICI with close observation for most grade 1 toxicities (except select neurologic, hematologic, and cardiac events), hold treatment for grade 2 events with consideration of low- to moderate-dose corticosteroids, and suspend ICIs with initiation of high-dose systemic steroids (prednisone or methylprednisolone 1-2 mg/kg/day) for grade 3 toxicities. Grade 4 events usually mandate permanent discontinuation, except for endocrine irAEs that can be controlled with hormone replacement. Steroid tapers should extend over at least 4-6 weeks to minimize relapse; steroid-refractory cases should prompt the use of additional immunosuppressants such as infliximab, mycophenolate mofetil, or other agents, depending on the affected organ.

Given the broad organ spectrum and often subtle onset of irAEs, structured monitoring programs are critical for patients receiving immunotherapy as part of comprehensive treatment for ovarian cancer. Consensus guidelines emphasize baseline assessment (history of autoimmunity, organ function tests, endocrine panels), regular interval monitoring of blood counts, liver enzymes, renal function, thyroid tests, and glucose, as well as low thresholds for imaging and subspecialty referral when new symptoms arise. Multidisciplinary toxicity teams involving oncologists, endocrinologists, gastroenterologists, pulmonologists, cardiologists, and rheumatologists are recommended to optimize diagnosis and management, particularly for rare or overlapping syndromes such as myositis-myocarditis-myasthenia gravis complexes. Patient education about early warning symptoms (diarrhea, dyspnea, palpitations, visual changes, severe fatigue) and clear pathways for rapid evaluation can reduce the risk of severe or fatal outcomes while allowing continuation of efficacious immunotherapy whenever safely possible.

8 Problems and Challenges

8.1 Limited overall response to immunotherapy

Despite a compelling biological rationale, the clinical response rate to immune checkpoint inhibitors in ovarian cancer remains low, especially with PD-1/PD-L1 monotherapy. Across early- and late-phase trials, objective response rates typically range around 8%-15% in unselected advanced or platinum-resistant populations, with no consistent survival advantage compared with standard therapies. A recent synthesis of 20 ICI trials in advanced ovarian cancer reported no improvement in overall survival and only modest gains in response when ICIs were added to chemotherapy, anti-angiogenic agents, or PARP inhibitors, emphasizing that immunotherapy has not yet altered the standard of care in this disease. These disappointing results contrast sharply with the transformative impact of ICIs in melanoma and lung cancer, underscoring intrinsic disease-specific barriers.

The "cold tumor" phenotype of many ovarian cancers contributes substantially to these limited responses. Ovarian tumors frequently display low tumor mutational burden, sparse tumor-infiltrating lymphocytes, and an immunosuppressive microenvironment dominated by regulatory T cells, M2 macrophages, and myeloid-derived

suppressor cells. Such features are associated with poor priming and expansion of effective cytotoxic T-cell responses and with rapid restoration of immune tolerance, even when checkpoint pathways are blocked. Moreover, most clinical experience with ICIs has been in heavily pretreated, recurrent disease, where immune exhaustion and treatment-induced clonal evolution further reduce the likelihood of durable benefit. Together, these factors help explain why, to date, immunotherapy has yielded only incremental efficacy in advanced ovarian cancer.

8.2 Lack of reliable patient selection biomarkers

A central barrier to optimizing immunotherapy in advanced ovarian cancer is the absence of robust, clinically validated biomarkers that can reliably identify patients likely to benefit. While markers such as PD-L1 expression, tumor mutational burden, homologous recombination deficiency, and tumor-infiltrating lymphocytes are being actively investigated, their predictive value in ovarian cancer is inconsistent and often modest (Na et al., 2024). For example, although PD-L1 positivity and higher $CD8^+$ T-cell infiltration correlate with improved prognosis, these features have not translated into reproducible enrichment of ICI responders in large trials, and many PD-L1–positive tumors still fail to respond. Similarly, high tumor mutational burden and microsatellite instability, strong predictors of ICI benefit in other cancers, are rare in ovarian cancer, limiting their practical utility.

Recent efforts employing multi-omics approaches underscore both the promise and current limitations of biomarker-guided immunotherapy. Comprehensive reviews highlight homologous repair deficiency, PD-L1, chemokine signatures, and TIL density as key candidate biomarkers for advanced ovarian cancer, but emphasize that assay heterogeneity, dynamic biomarker changes, and intratumoral spatial variation impede standardization and validation (Na et al., 2024). Novel composite signatures, such as protein-based immune risk scores derived from integrated proteomic and transcriptomic profiling, have shown superior prognostic performance and may better stratify patients into immunotherapy-responsive versus resistant subgroups (Chen et al., 2024b). However, these models remain exploratory, often lack external validation, and are not yet ready for routine clinical use. As a result, most immunotherapy trials still enroll largely unselected populations, diluting observable benefit and slowing progress toward precision strategies.

8.3 Complex resistance mechanisms and limited evidence base

The mechanisms of primary and acquired resistance to immunotherapy in ovarian cancer are multifactorial and only partially understood. Reviews of immune resistance highlight tumor heterogeneity, low immunogenicity, defective antigen presentation, and a profoundly immunosuppressive tumor microenvironment as major contributors. Ovarian tumors often exhibit low neoantigen load, downregulation of MHC class I, and upregulation of alternative inhibitory checkpoints and metabolic suppressive pathways, all of which blunt T-cell activation despite PD-1/PD-L1 or CTLA-4 blockade. Within the microenvironment, regulatory T cells, M2 macrophages, and myeloid-derived suppressor cells secrete cytokines such as IL-10, TGF-β, and VEGF that further dampen effector function and sustain tolerance. Recent spatial-genomic data also implicate tumor-derived factors such as IL-4 in reprogramming macrophages toward tumor-supportive phenotypes and driving resistance to checkpoint inhibition (Rausch et al., 2025).

At the same time, the clinical evidence base for overcoming resistance remains limited, with most data derived from small, heterogeneous early-phase studies and retrospective analyses. Combination approaches integrating ICIs with chemotherapy, anti-angiogenic agents, PARP inhibitors, radiotherapy, vaccines, or adoptive cell therapies are being actively explored, but results to date are mixed and often show only incremental improvements in progression-free survival, accompanied by added toxicity (Kefas and Flynn, 2024). Many trials lack embedded, hypothesis-driven translational programs capable of systematically dissecting resistance pathways and validating candidate biomarkers, leading to fragmented and sometimes conflicting findings (Ghisoni et al., 2024). Consequently, while a broad conceptual framework of immune resistance in ovarian cancer has emerged, high-quality prospective data linking specific molecular or microenvironmental features to defined resistance mechanisms and tailored therapeutic strategies are still scarce. Addressing this gap will require large, integrated, and biomarker-rich clinical trials that can couple mechanistic insight with clinically meaningful endpoints.

9 Conclusion

The future development of immunotherapy in advanced ovarian cancer will rely on the expansion of novel immune targets and the optimization of mechanism-driven combination strategies. Beyond the classical PD-1/PD-L1 and CTLA-4 pathways, emerging checkpoints such as LAG-3, TIM-3, and TIGIT, as well as immunosuppressive components of the tumor microenvironment, are becoming important therapeutic targets. Rational combinations integrating immune checkpoint inhibitors with anti-angiogenic agents, PARP inhibitors, metabolic modulators, or cell-based therapies may help convert "cold" tumors into "hot" ones, thereby enhancing treatment responsiveness. Current evidence suggests that combination therapies are more promising than monotherapy; however, their benefits remain limited and are often accompanied by increased toxicity. This highlights the need for further optimization of treatment regimens, dosing, and sequencing based on underlying biological mechanisms to achieve a balance between efficacy and safety.

At the same time, precision medicine is expected to play a central role in advancing immunotherapy. With the development of multi-omics technologies, single-cell sequencing, and spatial transcriptomics, the molecular heterogeneity and immune landscape of ovarian cancer are being increasingly elucidated, enabling biomarker-guided individualized treatment strategies. Biomarkers such as PD-L1 expression, tumor mutational burden (TMB), homologous recombination deficiency (HRD), tumor-infiltrating lymphocytes (TILs), and immune-related gene signatures are being integrated into composite predictive models to better identify patients who are most likely to benefit. In addition, innovative clinical trial designs, such as basket trials, umbrella trials, and adaptive platform trials, along with artificial intelligence-assisted analyses, are expected to further refine treatment selection and improve the precision of immunotherapy.

Overall, although immunotherapy has demonstrated durable clinical benefits in a subset of patients, its overall efficacy in advanced ovarian cancer remains limited and has not yet translated into significant improvements in overall survival. Therefore, it should currently be regarded as a promising but still evolving component of multimodal treatment rather than a standalone approach. Future progress will depend on high-quality, biomarker-integrated randomized clinical trials, as well as strengthened multidisciplinary collaboration and translational research efforts. Only through the integration of mechanistic insights, robust clinical evidence, and advanced technologies can immunotherapy move from a promising strategy to a broadly effective treatment, ultimately improving long-term survival and quality of life for patients with advanced ovarian cancer.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Artificial Intelligence-Assisted Minimally Invasive Gynecologic Surgery: Rationale and Clinical Context

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Abstract This study explores the current applications and clinical progress of artificial intelligence (AI)-assisted techniques in minimally invasive gynecologic surgery (MIGS). With the advancement of gynecologic surgery toward minimally invasive and precision-based approaches, conventional techniques still face limitations in complex anatomical recognition, operative precision, and standardization. AI technologies, by integrating preoperative imaging, intraoperative video, and multimodal clinical data, demonstrate significant potential in preoperative evaluation, individualized surgical planning, intraoperative navigation, robotic-assisted surgery, and surgical training. This study reviews the core technical foundations of AI and its primary application models in MIGS, with a particular focus on its potential to enhance surgical safety, accuracy, and efficiency. It also summarizes current challenges, including limited data scale, insufficient model generalizability, lack of high-quality clinical evidence, and ethical and regulatory concerns. Looking forward, with the advancement of multimodal data integration, digital surgery ecosystems, and multidisciplinary collaboration, AI is expected to further promote the evolution of gynecologic minimally invasive surgery toward precision, intelligence, and personalization. However, its widespread clinical implementation still depends on the establishment of standardized frameworks and validation through evidence-based medicine.

Keywords Artificial intelligence; Minimally invasive gynecologic surgery; Robotic surgery; Computer vision; Precision surgery

1 Introduction

In recent years, gynecologic surgery has gradually shifted from traditional open procedures toward minimally invasive approaches, forming a modern system of minimally invasive gynecologic surgery (MIGS) centered on laparoscopy, hysteroscopy, and robotic-assisted techniques. Various approaches, including conventional multiport laparoscopy, laparoendoscopic single-site surgery (LESS), vaginal natural orifice transluminal endoscopic surgery (vNOTES), and robotic-assisted surgery, have been widely applied in the diagnosis and treatment of uterine fibroids, endometriosis, ovarian tumors, and gynecologic malignancies such as endometrial cancer, and have progressively replaced laparotomy for many indications. Compared with open surgery, minimally invasive approaches offer significant advantages, including reduced intraoperative blood loss, lower perioperative complication rates, shorter hospital stays, less postoperative pain, and faster recovery. They also demonstrate important clinical value in preserving organ function, reducing postoperative adhesions, and improving quality of life (Ioana et al., 2024). In gynecologic oncology, studies have shown that, with appropriate patient selection, minimally invasive surgery can achieve oncologic outcomes comparable to open surgery, further establishing its central role in modern gynecologic practice. However, as procedural complexity increases and indications expand, minimally invasive surgery places higher demands on surgeons in terms of technical precision, spatial perception, and complex anatomical recognition. It is also associated with a steep learning curve and remains limited in areas such as deep infiltrating lesion identification, management of complex pelvic adhesions, and accurate tumor margin assessment (D'Augè et al., 2025).

At the same time, the rapid development of artificial intelligence (AI) has created new opportunities for transformation in surgical medicine. AI encompasses core technologies such as machine learning, deep learning, computer vision, and natural language processing, enabling complex pattern recognition and predictive analytics in medical data. These technologies are increasingly applied in imaging interpretation, risk assessment, clinical decision support, and surgical navigation (Luțenco et al., 2024; Varghese et al., 2024). In surgical settings, AI can

integrate preoperative imaging, intraoperative video, and multimodal clinical data to achieve key anatomical structure recognition, surgical workflow analysis, and risk prediction, thereby improving the objectivity and consistency of decision-making (Chevalier et al., 2025). In particular, robotic-assisted surgery generates large volumes of high-quality video and kinematic data, allowing AI to support surgical skill assessment, optimization of operative trajectories, phase recognition, and even partial automation of specific tasks (Knudsen et al., 2024). Preliminary studies suggest that AI-assisted systems can enhance surgical precision, reduce errors, and improve efficiency; however, their clinical application remains at an early stage and is still challenged by limited generalizability, lack of interpretability, and incomplete ethical and regulatory frameworks.

In the field of gynecology, the integration of AI with minimally invasive surgery holds particularly promising potential. Advances in high-definition three-dimensional imaging, augmented reality navigation, and sophisticated robotic platforms have significantly expanded the technical boundaries of minimally invasive surgery, while the incorporation of AI further enhances its precision and reproducibility (Osman et al., 2025; Pavone et al., 2025). Computer vision-based algorithms can identify critical anatomical structures such as the ureter, uterine artery, and pelvic nerves in real time during surgery, thereby reducing the risk of complications. Machine learning models can be used for preoperative risk stratification and individualized surgical planning, as well as for providing dynamic intraoperative decision support (Varghese et al., 2024; Chevalier et al., 2025). In addition, AI enables objective assessment of surgical skills and optimization of training through the analysis of robotic surgical data, promoting quality control and standardization (Knudsen et al., 2024; Pipes et al., 2025). Nevertheless, current research also highlights several limitations in gynecologic AI applications, including small dataset sizes, heterogeneity in algorithms and evaluation systems, and a lack of high-quality clinical evidence, which to some extent restrict their widespread implementation.

This study aims to explore the technical pathways and clinical application progress of artificial intelligence (AI)–assisted minimally invasive gynecologic surgery. By systematically reviewing the current applications of AI in preoperative evaluation, intraoperative navigation, postoperative analysis, and surgical training, it analyzes its potential advantages in improving surgical precision and efficiency, while also summarizing the existing technical and clinical challenges. On this basis, key future directions are further discussed, including multimodal data integration, algorithm optimization, evidence-based evaluation, and standardized implementation. Within the framework of minimally invasive gynecologic surgery (MIGS), this study provides a comprehensive analysis of the application models, clinical value, and existing limitations of AI, and offers perspectives on its future development, with the aim of providing theoretical support and practical reference for advancing gynecologic surgery toward greater precision, intelligence, and personalization.

2 Technical Foundations of Artificial Intelligence and Surgical Application Models

2.1 Core technologies: machine learning, deep learning, and computer vision

The application of artificial intelligence (AI) in surgery is primarily built upon core technologies such as machine learning (ML), deep learning (DL), and computer vision (CV). Machine learning fundamentally involves learning underlying patterns from data without explicit rule-based programming, enabling tasks such as classification, regression, clustering, and prediction. It has therefore been widely applied in perioperative risk assessment, prognosis prediction, resource utilization analysis, and clinical decision support (Varghese et al., 2024). Traditional ML methods, including support vector machines, decision trees, Bayesian networks, random forests, and ensemble learning, are particularly effective in handling structured clinical data. By integrating demographic characteristics, comorbidities, laboratory indicators, and perioperative parameters, these methods can predict surgical duration, postoperative complications, and hospitalization outcomes. However, such approaches typically rely on manual feature engineering and often exhibit limited performance and generalizability when applied to high-dimensional, unstructured data such as surgical images and videos (King et al., 2025).

With advancements in computational power and the accumulation of large-scale datasets, deep learning has emerged as the dominant paradigm in surgical AI. DL utilizes multilayer neural networks to automatically learn hierarchical representations, significantly reducing reliance on handcrafted features and making it particularly

suitable for complex data types such as images and videos (Varghese et al., 2024). Convolutional neural networks (CNNs) are adept at capturing spatial features and are widely used in analyzing preoperative MRI, CT, ultrasound, and intraoperative endoscopic images. Meanwhile, recurrent neural networks (RNNs), long short-term memory (LSTM) networks, and more recent Transformer architectures are effective in modeling temporal dependencies in surgical videos, such as workflow progression, instrument trajectories, and step transitions (King et al., 2025). In minimally invasive gynecologic surgery, DL has been applied to lesion detection, organ segmentation, intraoperative phase recognition, and quantitative assessment of surgical skills. Some models have achieved accuracies exceeding 80%-90% in surgical phase and structure recognition tasks, demonstrating performance comparable to, or even surpassing, expert interpretation (Paracchini et al., 2025).

Computer vision serves as the critical bridge that embeds ML and DL into surgical practice, enabling computers to "understand" surgical images and videos. From object detection, semantic and instance segmentation to pose estimation, instrument tracking, and three-dimensional reconstruction, CV transforms raw surgical video into structured, analyzable data. In minimally invasive gynecologic surgery, these techniques enable real-time localization and annotation of the uterus, ureter, pelvic vessels, and surgical instruments, as well as pixel-level identification of tissue boundaries through semantic segmentation, thereby supporting intraoperative navigation and risk alerts (Paracchini et al., 2025). Furthermore, the integration of deep learning and computer vision forms the foundation of "surgical intelligence," allowing AI to learn expert procedural patterns, automatically segment surgical phases, detect abnormal maneuvers, and provide objective support for intraoperative decision-making and postoperative quality control (Knudsen et al., 2024; Varghese et al., 2024).

2.2 Medical data sources: imaging, surgical video, and clinical data

The performance of AI systems heavily depends on the quality, diversity, and integration of medical data. In minimally invasive gynecologic surgery, the primary data sources include medical imaging, intraoperative video, and structured and unstructured clinical data. Imaging data, such as ultrasound, CT, MRI, PET-CT, and intraoperative fluorescence imaging, provide rich anatomical information and serve as a fundamental basis for AI model training and application (Varghese et al., 2024). In oncologic surgery, radiomics and deep learning approaches can extract high-dimensional quantitative features from imaging data to predict tumor characteristics, lymph node metastasis, extent of invasion, and treatment response, thereby supporting individualized surgical planning and preoperative risk stratification. In gynecologic MIS, preoperative three-dimensional reconstruction and augmented reality navigation increasingly rely on high-quality imaging data to achieve precise alignment between preoperative planning and intraoperative anatomy.

Intraoperative video has become one of the fastest-growing yet most challenging data sources in surgical AI. Laparoscopic and robotic systems continuously record high-resolution videos that capture instrument motion, tissue interaction, anatomical exposure, and procedural workflow, providing an ideal dataset for surgical phase recognition, instrument tracking, anatomical detection, and skill assessment. Studies have shown that some AI models achieve accuracies exceeding 85%-90% in phase recognition and instrument detection tasks in gynecologic and other minimally invasive surgeries (Paracchini et al., 2025). However, intraoperative video data present several challenges, including high annotation costs, variability in data acquisition standards across centers, differences in equipment and viewing angles, and complexities related to patient and team privacy. Therefore, establishing standardized frameworks for surgical video data management and governance is essential for clinical translation of surgical AI.

In addition to imaging and video, clinical data are critical for building high-value AI models. These data include patient demographics, body mass index, comorbidities, surgical history, laboratory results, pathology findings, perioperative events, hospitalization outcomes, and long-term follow-up information. When integrated with imaging and video data, these sources enable the development of multimodal models for risk prediction, complication monitoring, length-of-stay estimation, and treatment evaluation, thereby facilitating comprehensive patient profiling. Moreover, unstructured data in electronic health records contain valuable information that can be mined using natural language processing (NLP) techniques to identify patterns in preoperative assessments,

intraoperative documentation, and postoperative care. Nevertheless, challenges such as data silos, poor interoperability, privacy concerns, and limited representativeness continue to hinder the development of multimodal surgical AI, highlighting the need for improved data-sharing mechanisms, federated learning, and multicenter collaborative frameworks.

2.3 Application modes of AI in surgery: decision support, recognition, and control

AI applications in surgery can be broadly categorized into three levels: decision support, recognition, and control, reflecting a progression from analysis to intervention. At the decision-support level, AI systems integrate multimodal perioperative data to provide predictions and recommendations for preoperative, intraoperative, and postoperative management without directly performing surgical actions. These systems have been used to predict postoperative complications, operative duration, intraoperative hypotension, resource utilization, and patient outcomes, thereby assisting clinical teams in optimizing surgical planning, assessing individual risks, and improving postoperative care (Varghese et al., 2024). In minimally invasive gynecologic surgery, such applications can support the evaluation of anatomical complexity, selection of optimal surgical approaches, and development of individualized treatment pathways, making them among the most readily translatable AI applications in clinical practice.

Recognition-based applications represent the most active and mature domain of surgical AI. These technologies, primarily based on deep learning and computer vision, enable real-time understanding of intraoperative conditions, including surgical phase segmentation, instrument identification, hand and instrument tracking, anatomical labeling, and risk zone detection (Knudsen et al., 2024; Yangi et al., 2025). Studies have demonstrated that some models achieve high sensitivity and specificity, often exceeding 0.95, in tasks such as phase recognition, instrument detection, and motion tracking (Paracchini et al., 2025). In gynecologic surgery, AI has shown the potential to identify key steps of hysterectomy, critical pelvic structures, and lesion regions, thereby providing real-time assistance in complex minimally invasive procedures and promoting standardization in quality control and training assessment.

Control-oriented applications represent the frontier of surgical AI, where systems move beyond recognition and recommendation toward active participation in surgical execution. Although current robotic systems remain surgeon-controlled, AI has begun to contribute to subtasks such as camera control, suturing trajectory planning, instrument positioning, tremor suppression, and partial automation of specific actions (Knudsen et al., 2024). In the future, semi-autonomous or partially autonomous control may be feasible in highly standardized tasks, such as specific incisions, localized hemostasis, or repetitive procedural steps (Guni et al., 2024; Leivaditis et al., 2025). However, control applications also carry the highest safety, ethical, and legal risks. Their implementation requires rigorous validation, clearly defined responsibility boundaries, and continuous surgeon oversight. Therefore, in minimally invasive gynecologic surgery, a pragmatic approach is to prioritize the development of decision-support and recognition applications, while cautiously advancing control technologies as evidence accumulates.

3 Current Status and Challenges of Minimally Invasive Gynecologic Surgery

3.1 Common surgical types and technical characteristics

Currently, minimally invasive gynecologic surgery (MIGS) encompasses a wide range of diagnostic and therapeutic applications for both benign and malignant gynecologic diseases. It primarily includes laparoscopic surgery, hysteroscopic surgery, and robotic-assisted surgery, and has further expanded to novel approaches such as single-port surgery, ultra-minimally invasive techniques, and natural orifice transluminal endoscopic surgery (Wu et al., 2025). Among these, laparoscopy remains the most mature and widely used platform, applicable to procedures such as myomectomy, ovarian cystectomy, tubal surgery, hysterectomy, and selected gynecologic oncologic staging procedures. Its core advantage lies in performing complex operations through small incisions, thereby reducing intraoperative blood loss, alleviating postoperative pain, and shortening hospital stay (Vazquez et al., 2025). Hysteroscopic surgery, on the other hand, is mainly used for intrauterine pathologies such as endometrial polyps, submucosal fibroids, and intrauterine adhesions, utilizing natural orifices and offering lower invasiveness with faster recovery. In gynecologic oncology, minimally invasive approaches have become the

standard of care for early-stage endometrial cancer and are increasingly applied in selected ovarian cancer staging and cytoreductive procedures, although their use in cervical cancer remains controversial, requiring stricter patient selection (Baba, 2024; Balafoutas and Vlahos, 2024; D'Augè et al., 2025).

In recent years, robotic-assisted surgery has emerged as an important direction in the development of MIGS. Compared with conventional laparoscopy, robotic platforms provide three-dimensional high-definition visualization, articulated instruments, multiple degrees of freedom, motion scaling, and tremor filtration, significantly enhancing flexibility and stability in deep pelvic, confined spaces, and complex anatomical regions. These advantages make robotic systems particularly suitable for technically demanding procedures such as deep infiltrating endometriosis resection, radical hysterectomy, and pelvic or para-aortic lymphadenectomy (Kang et al., 2024). Meanwhile, minimally invasive techniques continue to evolve toward "ultra-minimally invasive" approaches, including mini-laparoscopy and percutaneous "needlescopic" techniques using trocars of 3 mm or smaller, which reduce abdominal wall trauma while maintaining feasibility for complex procedures. Single-port surgery and vaginal natural orifice transluminal endoscopic surgery (vNOTES) further offer advantages in cosmetic outcomes and rapid recovery.

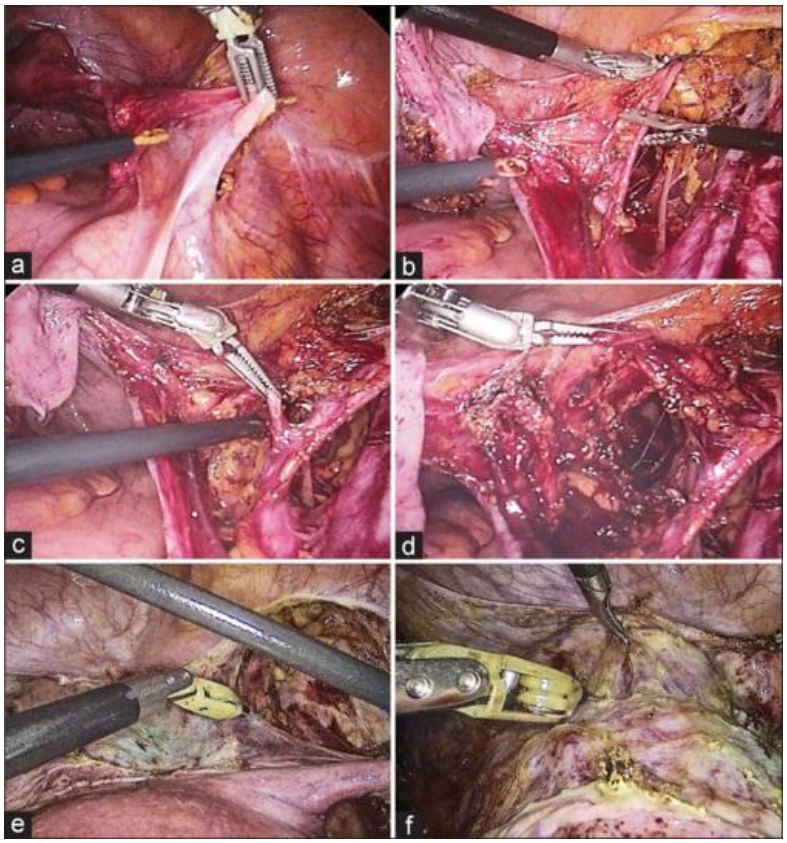

Figure 1 Intraoperative images showing technical advantages of articulation during gynecologic cancer surgery (Adopted from Pavone et al., 2025)

Image caption: (a-d) Fenestrated forceps, (e and f) Monopolar spatula (Adopted from Pavone et al., 2025)

3.2 Key challenges and limitations in surgical practice

Despite the advantages of MIGS, such as reduced trauma, faster recovery, and improved perioperative outcomes, it still faces several key challenges in clinical practice. From a technical perspective, conventional laparoscopy is limited by restricted instrument degrees of freedom, the fulcrum effect of long instruments, and difficulties in spatial perception under two-dimensional visualization. These limitations make complex suturing, deep pelvic dissection, and management of unexpected bleeding particularly challenging, especially for surgeons in the early stages of the learning curve. Although robotic systems improve visualization and instrument flexibility, issues such as lack of tactile feedback, instrument collisions, and spatial constraints in the narrow pelvis persist,

potentially increasing the difficulty of procedures such as lymphadenectomy, parametrial dissection, and complex tumor cytoreduction (Kang et al., 2024). In single-port and ultra-minimally invasive techniques, challenges such as instrument crowding, limited maneuverability, reduced traction, and insufficient torque may prolong operative time and increase complication risk.

In addition to technical factors, patient characteristics and disease complexity significantly influence the safety and feasibility of MIGS. Conditions such as extensive pelvic adhesions, deep infiltrating endometriosis, prior multiple surgeries, severe obesity, cardiopulmonary comorbidities, or pregnancy-related factors may limit pneumoperitoneum tolerance, positioning adaptability, and surgical exposure, thereby increasing intraoperative risk and the likelihood of conversion to open surgery (Appelbaum, 2024). These limitations are particularly evident in gynecologic oncology. While MIGS is well established for early-stage endometrial cancer, findings from the LACC trial and subsequent studies have led to stricter indications for minimally invasive radical hysterectomy in cervical cancer. In ovarian cancer, concerns regarding tumor rupture, inadequate staging, and incomplete cytoreduction restrict the use of minimally invasive approaches to carefully selected patients in high-volume centers (Baba, 2024; Balafoutas and Vlahos, 2024).

System-level challenges are also significant. The high acquisition and maintenance costs of robotic systems, potential prolongation of operative time in certain cases, and variability in insurance coverage and resource allocation limit accessibility in resource-constrained settings and raise concerns regarding cost-effectiveness. Furthermore, the steep learning curve of minimally invasive techniques, lack of standardized training, and variability in surgeon experience contribute to heterogeneity in conversion rates, complication rates, and oncologic outcomes across institutions. These issues highlight that, although MIGS has been widely adopted, there is still considerable room for improvement in safety, consistency, reproducibility, and equitable access.

3.3 Clinical demand for precision and standardization

As MIGS evolves from simply being feasible to achieving high-quality outcomes, precision and standardization have become central clinical demands. Precision surgery emphasizes accurate lesion localization, boundary delineation, and optimal resection based on a comprehensive understanding of individual anatomical variations, disease extent, and functional preservation goals. For example, in deep infiltrating endometriosis, fertility-preserving myomectomy, and complex oncologic cytoreduction, surgeons must not only achieve maximal lesion removal but also precisely preserve critical structures such as the ureters, nerves, vessels, and reproductive tissues to minimize complications and optimize long-term functional and reproductive outcomes (D'Augè et al., 2025). In challenging patient populations, such as obese individuals, adolescents, patients with multiple prior surgeries, or those with complex comorbidities, the need for precision is even greater due to limited visualization, restricted operative space, and reduced tolerance to pneumoperitoneum (Appelbaum, 2024).

At the same time, standardization is essential for improving overall healthcare quality and reducing inter-institutional variability. Establishing uniform criteria for indications, standardized operative steps, and quality control metrics can reduce variability in surgical approaches, resection extent, and perioperative management, thereby enhancing consistency and reproducibility of outcomes (Vazquez et al., 2025; Wu et al., 2025). However, significant heterogeneity persists in current clinical practice, with substantial differences in technique selection, procedural pathways, and oncologic indications across regions and institutions. This is particularly evident in controversial areas such as cervical and ovarian cancer, where variations in patient selection and operative techniques can significantly influence outcomes (Balafoutas and Vlahos, 2024). Therefore, standardization should not equate to rigid protocols but rather represent individualized adjustments within an evidence-based framework.

In this context, the integration of intelligent assistive technologies is considered a key pathway to achieving both precision and standardization. By combining preoperative imaging, intraoperative video, perioperative parameters, and postoperative outcomes, data-driven surgical decision-support systems can be developed. Additionally, technologies based on real-time recognition, navigation, and quality assessment can provide continuous, objective, and quantifiable intraoperative guidance, reducing reliance on individual experience and improving consistency in

complex procedures. Particularly under the framework of enhanced recovery after surgery (ERAS), the demand for low trauma, high efficiency, and stable outcomes further elevates precision and standardization from technical goals to comprehensive quality management objectives (Vazquez et al., 2025).

4 Key Applications of AI in Minimally Invasive Gynecologic Surgery

4.1 Preoperative evaluation and individualized surgical planning

In minimally invasive gynecologic surgery, preoperative evaluation plays a critical role in determining the surgical approach, procedural selection, and risk management strategies. Traditional assessment relies primarily on ultrasound, CT, MRI, and surgeon experience; however, in cases such as deep infiltrating endometriosis, complex pelvic adhesions, and gynecologic malignancies, it is often difficult to precisely quantify lesion extent and its spatial relationship with critical structures such as the ureters, vessels, and bowel. In recent years, AI-driven imaging analysis tools have enabled the integration of clinical data, imaging information, and prior surgical records to achieve perioperative risk stratification and predict operative time, blood loss, length of hospital stay, and complication risk. These capabilities assist in selecting laparoscopic, robotic, or open approaches, thereby improving preoperative counseling and individualized decision-making (Chevalier et al., 2025; Osman et al., 2025; Pipes et al., 2025). For example, a decision tree–based model has been used to predict the feasibility and risk of single-port versus conventional laparoscopy, achieving an AUC of 0.77, highlighting the practical value of AI in personalized surgical approach selection.

Furthermore, AI-based image segmentation, radiomics, and three-dimensional reconstruction are advancing minimally invasive gynecologic surgery toward a “visualized planning” paradigm. AI-enhanced MRI, CT, and ultrasound analyses can differentiate benign from malignant adnexal masses, predict deep myometrial or cervical stromal invasion, and assess lymph node metastasis risk, thereby informing decisions regarding the extent of hysterectomy, lymphadenectomy, and fertility-sparing procedures (Paiboonborirak et al., 2025). In deep infiltrating endometriosis, AI-assisted 3D reconstruction models provide a clearer representation of lesion relationships with adjacent organs compared to traditional 2D imaging, facilitating surgical approach selection, dissection planning, and nerve preservation (Polat and Arslan, 2024). In the future, integrated models combining imaging, pathology, clinical variables, and prior outcomes may generate individualized “surgical roadmaps,” potentially evolving into platforms for preoperative virtual simulation and “digital twin”-based planning.

4.2 Intraoperative navigation and intelligent anatomical recognition

The intraoperative phase represents the most direct application scenario for AI, with its core function being the transformation of real-time surgical video into actionable navigation information. Deep learning-based computer vision models can analyze gynecologic laparoscopic videos in real time to perform organ classification and segmentation, identify critical anatomical structures, track instruments, and recognize surgical actions. Systematic reviews have demonstrated that such models achieve high accuracy in anatomical recognition, instrument tracking, and action identification, supporting their feasibility in procedures such as hysterectomy, myomectomy, and endometriosis surgery (Gkrozou et al., 2025). For high-risk structures such as the ureters, uterine arteries, and pelvic nerves, real-time AI-based labeling and alerts can reduce the likelihood of injury under conditions of complex adhesions or limited visualization, thereby improving intraoperative safety (Polat and Arslan, 2024).

Building on this, the integration of AI with augmented reality (AR) navigation further enhances intraoperative perception. By registering preoperative imaging and 3D models with the real-time surgical field, surgeons can access an “augmented view” that overlays anatomical information, tumor boundaries, and potential risk zones, enabling more precise resection and functional preservation in complex pelvic surgeries (Pavone et al., 2025). Additionally, AI can perform surgical phase recognition and workflow analysis. In a multicenter study of laparoscopic hysterectomy, AI models achieved 93% accuracy in identifying key procedural steps, providing a foundation for context-aware guidance, deviation alerts from standard workflows, and postoperative quality assessment (Leaf et al., 2024; Levin et al., 2024). Thus, AI-assisted intraoperative navigation extends beyond simple structure recognition, contributing to the development of an intelligent monitoring system aimed at improving safety, efficiency, and standardization.

4.3 Integration of AI in robotic surgical systems

Robotic surgical platforms provide an ideal digital environment for AI integration, as they can simultaneously capture high-definition video, instrument kinematics, and system operation data, forming high-density multimodal datasets. Based on these data, AI has been applied to automatically analyze surgeon motion trajectories, smoothness, path efficiency, and motion redundancy, enabling objective assessment of surgical skills and correlation with expert evaluations and clinical outcomes (Knudsen et al., 2024). These tools can be embedded within robotic platforms to provide immediate postoperative feedback, long-term performance tracking, and personalized training design, thereby shortening the learning curve for complex procedures such as robotic radical hysterectomy or lymphadenectomy (Leaf et al., 2024).

Beyond assessment, AI is progressively transitioning toward assistive control within robotic systems. Currently, AI applications in robotic surgery mainly include intelligent camera control, tremor filtration, instrument path optimization, and semi-autonomous execution of specific subtasks such as suturing, knot tying, and local trajectory correction (Osman et al., 2025). Experimental studies have demonstrated that systems such as the Smart Tissue Autonomous Robot (STAR) can perform soft tissue recognition and automated suturing based on deep learning, suggesting the potential for task-level automation under strict supervision. Moreover, robotic platforms can integrate 3D reconstruction, augmented reality, intraoperative ultrasound, and fluorescence imaging, and AI-driven analysis of these multimodal data can enhance tumor localization, vascular identification, and margin assessment, thereby improving the safety of complex pelvic surgeries (Figure 2) (Pavone et al., 2025).

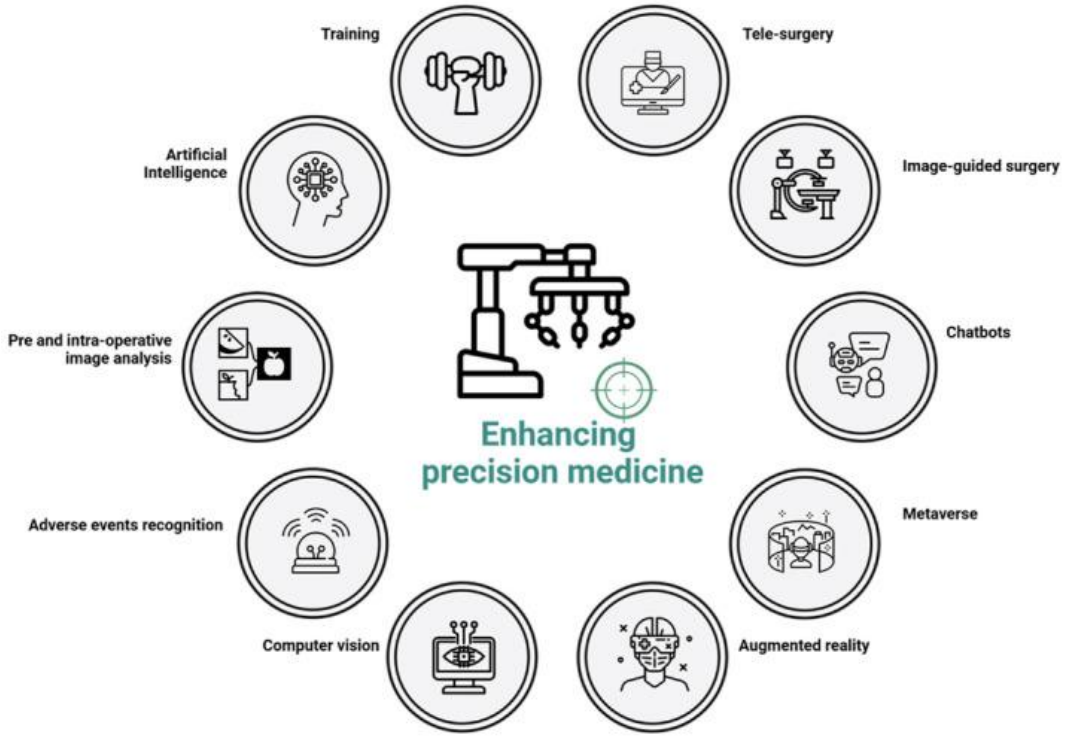

Figure 2 Potential benefits of robotic surgery: integration with new technologys (Adopted from Pavone et al., 2025)

5 Applications of AI in Surgical Training and Skill Assessment

5.1 Intelligent assessment systems based on surgical video

With the rapid digitalization of minimally invasive surgery, large volumes of high-quality laparoscopic and robotic surgical videos have provided a critical data foundation for AI-driven skill assessment. Using computer vision, deep learning, and other machine learning techniques, surgical videos can be automatically segmented, actions recognized, and semantic information extracted, enabling the quantification of spatiotemporal features such as operative time, instrument trajectory smoothness, motion redundancy, tissue handling precision, and workflow continuity (Power et al., 2025). Compared with traditional expert-based subjective scoring, these

approaches offer greater objectivity, reproducibility, and scalability. Studies have shown that a three-stage machine learning system, integrating instrument detection, motion feature extraction, and skill prediction, can achieve up to 87% accuracy in distinguishing high- and low-quality performance, suggesting that motion trajectories and operational efficiency serve as reliable indicators of surgical skill.

In robotic surgery, AI-based video analysis further expands the scope of skill assessment. Research indicates that models relying solely on two-dimensional video and residual neural networks can classify key skills such as suturing, needle passing, and knot tying with average accuracies exceeding 80%, demonstrating that robust automated assessment can be achieved even without high-fidelity kinematic sensors. Additionally, hybrid models combining convolutional neural networks and long short-term memory networks (CNN-LSTM) can simultaneously recognize surgical actions and assess surgeon expertise from a single video stream, achieving 81% accuracy in experimental settings. These findings indicate that AI video analysis can not only identify "what was performed" but also evaluate "how well it was performed" (Figure 3) (Hashemi et al., 2025).

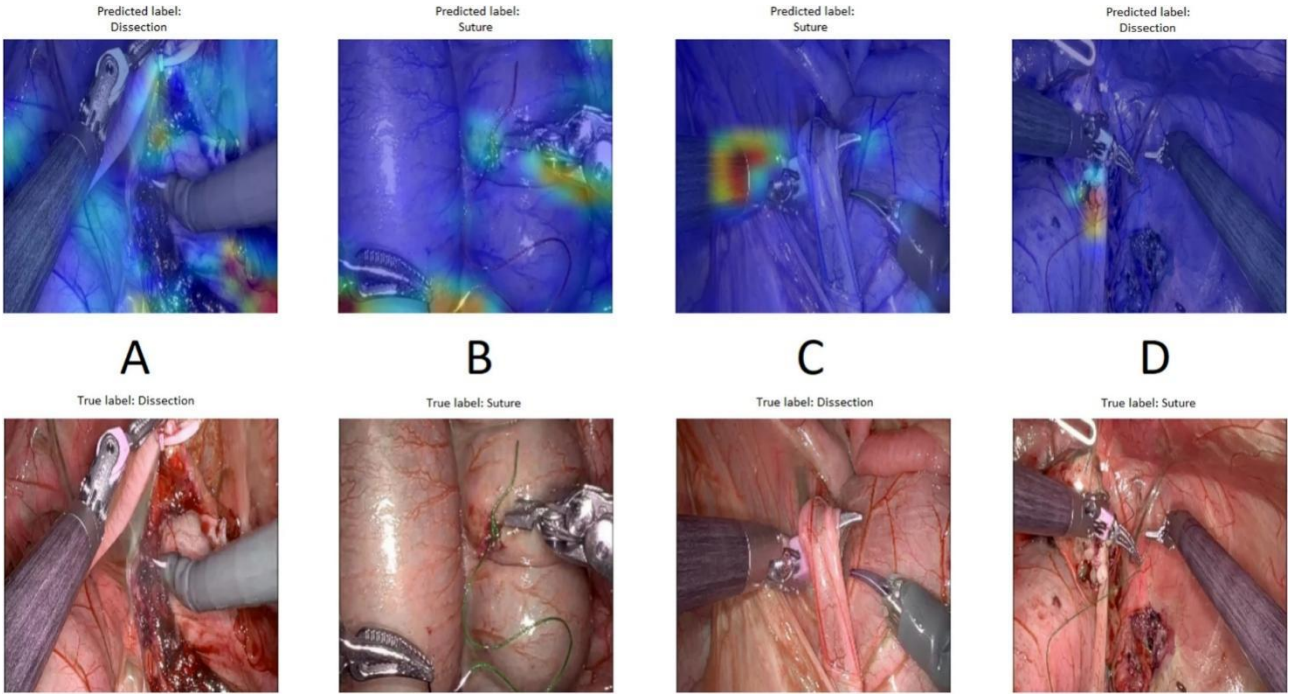

Figure 3 The regions of interest for the algorithm during surgical procedures (Adopted from Hashemi et al., 2025)
Image caption: A and B The areas in focus when classifying dissection and suturing, C shows a misclassification of a dissection sequence, and D shows a misclassification of suturing (Adopted from Hashemi et al., 2025)

Importantly, AI-based video assessment systems are evolving to integrate both summative evaluation and formative feedback. Some deep learning frameworks can generate high-stakes ratings comparable to expert judgments and provide interpretable feedback through heatmaps or key-frame visualization, highlighting areas of suboptimal performance. This enables trainees to identify deficiencies in instrument control, tissue handling, and procedural execution. Systematic reviews suggest that most AI models based on video or motion data achieve accuracies above 80% in simulated environments; however, limitations remain in external validation, standardization of evaluation metrics, and linkage to patient outcomes. In gynecologic laparoscopy and robotic surgery, the customization of such systems for procedures like hysterectomy, salpingectomy, and hysteroscopy could facilitate a shift from case volume-based training to competency-based progression (Tesfai et al., 2024).

5.2 Virtual reality and simulation-based training technologies

The introduction of virtual reality (VR) and augmented reality (AR) technologies has created highly controllable, repeatable, and low-risk training environments for minimally invasive gynecologic surgery. Systematic reviews and meta-analyses demonstrate that both high- and low-fidelity laparoscopic simulators significantly improve operative skills and reduce operative time compared with traditional observation-based or case accumulation

training methods (Orejuela et al., 2022). In gynecologic settings, AI-supported virtual platforms can realistically reconstruct complex pelvic anatomy and various pathological conditions, such as adhesions, bleeding, and tumor infiltration, allowing trainees to repeatedly practice critical procedures without patient risk. This reduces learning costs and avoids ethical concerns associated with "learning on patients".

In terms of training outcomes, VR simulators have been shown to effectively enhance both basic and procedure-specific surgical skills. For instance, VR platforms for laparoscopic salpingectomy can significantly shorten procedural time, reduce simulated blood loss, and improve expert ratings and trainee confidence after repeated training sessions. In hysteroscopy training, VR/haptic simulators incorporating force feedback improve navigation efficiency, reduce applied force, and effectively differentiate between novice and expert users. AI plays a central role in these systems by analyzing motion trajectories, error patterns, and completion times in real time, enabling automated scoring and personalized feedback without the need for constant instructor supervision (Escobar-Castillejos et al., 2024; Power et al., 2025).

Furthermore, the integration of VR/AR systems with real-time evaluation modules is creating a closed-loop model of "training–assessment–feedback." AI can dynamically detect incorrect actions and provide immediate feedback during training, allowing trainees to correct errors before they become ingrained. This real-time feedback mechanism is more effective for skill acquisition than traditional delayed evaluations (Seeger et al., 2025). In gynecology, emerging VR training programs, such as those for cervical loop excision and hysteroscopic navigation, have demonstrated scalable and open-access educational potential. With the addition of AI-based longitudinal tracking and performance analytics, these systems may support large-scale implementation in residency and specialist training programs (Trapp et al., 2025).

5.3 Personalized training pathways and skill enhancement mechanisms

AI-driven personalized training systems are transforming minimally invasive surgical education from a standardized approach to a competency-based paradigm. By integrating longitudinal performance data from simulators, box trainers, surgical videos, and robotic platforms, machine learning models can construct individual skill profiles, identify strengths and weaknesses, predict learning curves, and recommend targeted training tasks (Escobar-Castillejos et al., 2024; Raghavan et al., 2025). For example, trainees with poor instrument control or excessive motion redundancy can be directed toward fine motor skill and suturing exercises, while those with insufficient anatomical recognition may benefit from enhanced imaging interpretation and spatial navigation training. Compared with fixed curriculum-based training, this individualized approach better accommodates differences in baseline experience, cognitive capacity, and learning pace.

Building on this, adaptive learning and reinforcement learning frameworks further enhance training system flexibility. These systems dynamically adjust task difficulty, feedback frequency, and training content based on real-time performance, maintaining an optimal level of challenge and preventing stagnation or frustration (Raghavan et al., 2025). Systematic reviews indicate that models based on kinematic or video data can reliably stratify skill levels, supporting the development of progression criteria based on competency thresholds rather than case numbers. This is particularly important in gynecologic laparoscopy and robotic surgery, where case volume and exposure to complex procedures vary significantly across training centers. AI-driven personalized training can help ensure that trainees achieve consistent technical proficiency before advancing to high-risk procedures (Tesfai et al., 2024).

Moreover, AI-supported training frameworks are expanding beyond technical skills to include cognitive and visuospatial training. Addressing challenges such as depth perception, instrument navigation, and visuospatial workload in laparoscopy, multimodal training systems integrating real-time auditory guidance, visuospatial exercises, and motion analysis can improve cognitive control and coordination in complex environments. In this model, the future of surgical education is not one in which AI replaces instructors, but rather one of human–AI collaboration: AI provides continuous assessment, real-time feedback, and personalized learning pathways, while expert mentors focus on clinical decision-making, complex judgment, non-technical skills, and professional development (Raghavan et al., 2025). For subspecialties such as gynecologic oncology, where operative exposure

may be limited, AI-driven personalized training pathways are especially valuable, ensuring high-quality skill acquisition even in low-case-volume settings.

6 Clinical Outcomes and Existing Challenges

6.1 Impact on surgical safety, precision, and efficiency

The primary goal of AI-assisted minimally invasive gynecologic surgery is to improve surgical safety by enhancing preoperative prediction, intraoperative visualization, and the standardization of complex procedures. Existing studies suggest that AI-based preoperative planning, intraoperative navigation, and robotic assistance can reduce the risk of injury to critical structures such as the ureters, blood vessels, and nerves through more accurate lesion localization, clearer identification of key anatomical structures, and more stable instrument control, thereby decreasing intraoperative complication rates (Polat and Arslan, 2024; Pipes et al., 2025; Wah, 2025). In scenarios involving complex pelvic anatomy, dense adhesions, or limited operative space, AI-driven risk alerts and anatomical labeling are particularly valuable, not only by improving visualization but also by helping surgeons maintain stable operative boundaries during high-risk steps (Arakaki et al., 2024; Osman et al., 2025).

In terms of precision, AI integrates preoperative imaging, intraoperative video, and system parameters to achieve more accurate delineation of lesion boundaries, anatomical planes, and resection margins. For tumor resection, lymphadenectomy, and management of deep infiltrating disease, such multimodal assistance facilitates a better balance between maximal resection and preservation of critical functions, thereby improving surgical quality and long-term functional outcomes (Polat and Arslan, 2024; Pipes et al., 2025). Some cross-disciplinary and robotic surgery studies further indicate that AI-assisted systems can enhance targeting accuracy, margin assessment, and procedural consistency, optimizing precision in complex surgical interventions (Suriya et al., 2025; Wah, 2025). However, it should be noted that most of these positive findings are derived from early-stage studies or cross-specialty experiences, and high-level validation specific to gynecology remains limited.

From an efficiency perspective, AI also demonstrates potential advantages. Through automated recognition of surgical steps, optimization of instrument pathways, context-aware assistance, and efficient use of intraoperative data, AI may shorten operative time, reduce redundant maneuvers, and improve workflow continuity (Osman et al., 2025). In robotic systems, AI-driven optimization of camera control, instrument trajectories, and localized task execution can further reduce surgeon workload and enhance procedural stability. Some studies even suggest that machine learning–enhanced telesurgery and task-level automation may surpass traditional mechanical control in precision. However, in real-world clinical settings, AI systems often require an initial adaptation and calibration period, and their efficiency benefits may not be immediately evident; such advantages typically emerge gradually as surgeons become familiar with the technology.

6.2 Current clinical evidence and application status

At present, the clinical application of AI in minimally invasive gynecologic surgery is transitioning from proof-of-concept to early clinical translation. Existing studies mainly focus on preoperative planning, intraoperative structure recognition, surgical workflow analysis, robotic motion analysis, and training assessment. However, most are single-center, small-sample, retrospective studies or early prospective explorations, resulting in an overall limited and fragmented evidence base (Brandão et al., 2024; Pipes et al., 2025). In gynecologic oncology, AI has been more extensively applied in imaging-based diagnosis, prognostic evaluation, and treatment planning, while intraoperative applications remain relatively limited, primarily focusing on ovarian surgery, hysterectomy, and selected robotic procedures (Paiboonborirak et al., 2025; Restaino et al., 2025).

From a practical perspective, some AI functions have begun to enter preliminary clinical use. Deep learning–based surgical video analysis systems are being used for postoperative quality assessment, skill feedback, and automated workflow segmentation; augmented reality and image-guided technologies are showing value in complex tumor resections and pelvic procedures; and AI within robotic platforms is mainly applied to motion analysis, task recognition, and outcome prediction. However, these technologies largely remain as assistive tools and have not yet evolved into standardized, scalable, and reproducible clinical pathways. A systematic review

including 3 436 patients reported that although AI shows promising potential in robotic surgery data analysis and prediction, there is still no conclusive evidence demonstrating a significant improvement in patient safety.

From an evidence-based medicine perspective, several limitations persist. Most AI models are trained on datasets of fewer than 1 000 cases, with limited external validation, restricting their robustness and generalizability. There is also substantial heterogeneity in study endpoints, evaluation metrics, algorithm architectures, and implementation methods, making cross-study comparisons difficult. Furthermore, studies focusing on long-term outcomes, such as recurrence rates, functional recovery, and quality of life, remain scarce. Therefore, although AI-assisted minimally invasive gynecologic surgery has demonstrated feasibility and multiple potential applications, it remains in a translational phase. Future progress will depend on multicenter, standardized studies with long-term follow-up to clarify its true clinical value and applicability boundaries (Brandão et al., 2024; Pipes et al., 2025).

6.3 Major challenges in data, algorithms, and ethics

Despite its significant potential, the clinical implementation of AI in minimally invasive gynecologic surgery is constrained by challenges related to data, algorithms, and ethical/legal considerations. From a data perspective, the availability of high-quality annotated datasets remains a major bottleneck. Most studies rely on small, single-center datasets with limited diversity in patient populations and equipment, resulting in insufficient generalizability across different clinical environments (Pipes et al., 2025). Additionally, gynecologic surgical video and imaging data are inherently complex and sensitive in terms of privacy, while standards for data collection, annotation, and storage are not yet unified, further complicating cross-study comparisons and external validation (Arakaki et al., 2024; Jeganathan et al., 2025).

At the algorithmic level, many current AI systems function as “black boxes” with decision-making processes that are difficult for clinicians to interpret and validate. This lack of transparency not only affects trust but also complicates physician–patient communication (Pipes et al., 2025). Moreover, issues such as imbalanced training data, labeling bias, and environmental variability may introduce algorithmic bias, while performance drift in real-world clinical settings can undermine reliability and reproducibility (Hmido et al., 2025). Consequently, explainability, robustness, continuous calibration, and external validation have become essential prerequisites for the safe deployment of AI in high-risk surgical scenarios.

Ethical and legal concerns are equally critical. The use of AI in surgery raises issues related to data privacy protection, informed consent for secondary data use, liability in cases of AI-assisted decision errors, and the potential erosion of surgical skills due to overreliance on technology (Jeganathan et al., 2025; Rad et al., 2025). As AI evolves from assistive analysis to semi-autonomous control, these concerns become even more pronounced. In addition, high costs, infrastructure requirements, and disparities in digital resources may concentrate advanced AI surgical systems in high-income regions and large medical centers, thereby exacerbating healthcare inequities (Osman et al., 2025; Wah, 2025). Therefore, advancing the standardized application of AI in minimally invasive gynecologic surgery requires not only technological innovation but also the establishment of robust data governance frameworks, ethical review systems, clear accountability mechanisms, and equitable implementation strategies.

7 Future Directions and Conclusion

In the future, AI-assisted minimally invasive gynecologic surgery will increasingly rely on multimodal data integration to achieve true precision surgery. Currently, robotic surgical platforms are capable of integrating endoscopic video, kinematic data, and system information, and combining them with preoperative MRI/CT, ultrasound, pathology, and genomic data to construct individualized surgical models. In gynecology, AI-enhanced imaging analysis and navigation technologies have been applied to the precise localization of endometrial cancer, sentinel lymph nodes, and submucosal fibroids, not only improving surgical targeting but also reducing operative time and intraoperative blood loss. Further integration with three-dimensional reconstruction, augmented reality, and robotic ultrasound is expected to optimize anatomical recognition, enhance surgical precision, and better protect critical structures.

In reproductive medicine and gynecologic oncology, multimodal predictive models, integrating clinical data, imaging, and biomarkers, are being used to develop individualized surgical strategies that balance treatment efficacy with functional and fertility preservation. With the advancement of data standardization and digital surgery ecosystems, surgeons will be able to utilize integrated platforms for preoperative planning, intraoperative navigation, and real-time risk prediction, facilitating a shift from experience-based to precision, individualized surgery. At the same time, AI is driving the evolution of surgical environments toward greater intelligence and semi-automation, while being deeply integrated into multidisciplinary care pathways. Robotic platforms are increasingly serving as central hubs that integrate computer vision, image-guided navigation, and large language model–based decision support, enabling real-time access to patient information and evidence-based guidance during surgery. In addition, AI applications in gynecologic cancer screening, diagnosis, and staging are further promoting the development of AI-supported multidisciplinary decision-making models.

However, the widespread implementation of AI-assisted minimally invasive gynecologic surgery still depends on the establishment of standardized frameworks and the advancement of clinical translation. Most current studies remain in early stages, with limitations such as small sample sizes, methodological heterogeneity, and lack of external validation, and there is still limited evidence demonstrating improved patient outcomes in real-world clinical settings. Therefore, consensus is urgently needed regarding data standards, evaluation systems, and research methodologies, along with the development of robust ethical and regulatory frameworks addressing data privacy, algorithmic bias, and accountability. In the future, through multicenter data sharing, high-quality clinical research, and clinically driven technological development, AI-assisted minimally invasive gynecologic surgery is expected to achieve standardized and scalable implementation, ultimately enhancing surgical safety, precision, and personalized patient care.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Feature Review Open Access

Assessment and Rehabilitation Interventions for Diastasis Recti Abdominis

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Abstract This study explores the assessment methods and rehabilitation interventions for postpartum diastasis recti abdominis (DRA). As a common structural and functional disorder following pregnancy and childbirth, DRA has a high prevalence and may persist long-term, adversely affecting core stability, lumbopelvic function, and quality of life in postpartum women. This review systematically summarizes the anatomical basis, pathophysiological mechanisms, and major risk factors of DRA, with a particular focus on assessment methods, including clinical palpation, imaging techniques (primarily ultrasound), and functional evaluations, while highlighting inconsistencies in current measurement standards and procedures. In terms of intervention, this study reviews exercise-based rehabilitation as the core approach, along with adjunctive therapies such as neuromuscular electrical stimulation, biofeedback, manual therapy, and abdominal support. It further compares the effectiveness of single interventions versus comprehensive rehabilitation programs in improving inter-recti distance, muscle strength, and functional recovery. The findings indicate that multimodal rehabilitation approaches demonstrate superior overall effectiveness compared to single exercise interventions; however, existing evidence is limited by methodological heterogeneity, lack of standardized protocols, and insufficient long-term follow-up. Future research should focus on establishing standardized assessment systems, promoting individualized and precision-based rehabilitation, and integrating multidisciplinary collaboration with digital technologies to optimize clinical management and long-term outcomes of DRA.

Keywords Diastasis recti abdominis; Postpartum rehabilitation; Inter-recti distance; Core stability; Rehabilitation intervention

1 Introduction

Postpartum diastasis recti abdominis (DRA) refers to the widening of the linea alba accompanied by separation of the rectus abdominis muscles on both sides, and is one of the most common musculoskeletal adaptations during pregnancy and childbirth. Epidemiological evidence indicates that DRA has a high prevalence during late pregnancy and the postpartum period, reaching approximately 70% in the third trimester, about 60% at 6 weeks postpartum, and persisting in 30%-33% of women at 12 months postpartum. In addition, several cross-sectional and cohort studies suggest that approximately 60%-80% of women exhibit measurable DRA in the early postpartum period, with a substantial proportion remaining affected months later (Selvam et al., 2025). Across different populations and measurement methods, the overall prevalence of postpartum DRA is estimated to be around 30%-60%, indicating that it is a common postpartum health condition with potential long-term consequences rather than merely a cosmetic concern (Chen et al., 2023). With the advancement of perinatal medicine and women's health research, DRA has increasingly become a key topic in multidisciplinary fields including obstetrics, rehabilitation medicine, and exercise science (Skoura et al., 2024).

DRA is not only a structural alteration of the abdominal wall but is also closely associated with reduced core stability and impaired trunk function. Decreased tension of the linea alba may weaken the regulation of intra-abdominal pressure, thereby affecting the overall function of the lumbopelvic stability system (Chen et al., 2023). Previous studies have suggested associations between DRA and low back pain, pelvic girdle pain, and impaired postural control, although the strength of these relationships remains debated. In addition, DRA may be accompanied by reduced abdominal muscle strength, postural abnormalities, and pelvic floor dysfunction (Butt et al., 2023; Fitriani et al., 2025). More broadly, changes in abdominal appearance and functional limitations may negatively impact the psychological well-being and quality of life of postpartum women, including body image

dissatisfaction, reduced self-confidence, and limitations in daily activities (Zhu et al., 2024). Therefore, a comprehensive evaluation of DRA from structural, functional, and psychosocial perspectives is of significant clinical and public health importance.

In terms of assessment, a variety of quantitative methods have been developed in both clinical and research settings, including finger-width palpation, caliper measurement, and imaging techniques such as ultrasound and MRI (Chen et al., 2023). Among these, ultrasound is considered a reliable method for measuring inter-recti distance (IRD) due to its non-invasive nature, real-time capability, and high reproducibility; however, the lack of standardization in measurement sites, body positions, and diagnostic thresholds has prevented the establishment of a unified assessment system. Meanwhile, palpation remains widely used because of its simplicity and feasibility, and has shown a certain degree of agreement with clinical assessment in some contexts. Dynamic assessment, such as measuring IRD during muscle contraction, has also gained increasing attention. In terms of intervention, rehabilitation has become the cornerstone of DRA management, including transversus abdominis training, core stabilization exercises, pelvic floor muscle co-contraction, as well as adjunctive therapies such as electrical stimulation, manual therapy, and abdominal support. Some studies suggest that structured exercise programs can improve IRD, muscle strength, and quality of life; however, the effectiveness of different interventions remains inconsistent, and inappropriate exercise may even exacerbate the condition. Given the high prevalence of DRA, its clear functional impact, and the lack of methodological consistency in current research, a systematic synthesis of assessment methods and rehabilitation strategies is of considerable importance.

This study aims to analyze the available evidence on assessment methods and rehabilitation interventions for postpartum DRA. The focus is on systematically summarizing current clinical and research approaches to measuring IRD and related outcome indicators, evaluating their strengths, limitations, and emerging consensus, and comprehensively assessing the effectiveness and safety of both exercise-based and non-exercise rehabilitation strategies in improving DRA severity, core function, posture, and health-related quality of life. By integrating data across different study designs and settings, this review seeks to clarify the current level of evidence, identify key barriers to guideline development, and provide a systematic basis for optimizing the assessment and conservative management of postpartum DRA in clinical practice and future research.

2 Overview of Diastasis Recti Abdominis

2.1 Anatomical basis, definition, and diagnostic criteria

Diastasis recti abdominis (DRA) is essentially an anatomical alteration involving the midline structure of the anterior abdominal wall, characterized by thinning, widening, and reduced tension of the linea alba under mechanical stretching and tissue remodeling, resulting in an abnormal increase in the inter-recti distance (IRD). The anterior abdominal wall consists of the rectus abdominis, external oblique, internal oblique, transversus abdominis, and their associated fascial systems. The rectus abdominis muscles are symmetrically distributed on both sides of the linea alba and play key roles in maintaining intra-abdominal pressure, assisting respiration, contributing to trunk flexion, and transmitting lumbopelvic loads. The linea alba, formed by the interweaving aponeurotic fibers of the lateral abdominal muscles, serves as a central structure for force transmission and core stability. Unlike abdominal wall hernia, DRA presents as midline widening and abdominal bulging but typically lacks a true fascial defect or hernial orifice, a distinction that is important for diagnosis and treatment planning.

From a definitional perspective, DRA is commonly described as the separation of the rectus abdominis muscle bellies along the linea alba without muscle fiber rupture, with increased IRD as the primary diagnostic indicator. However, there is no consensus on the threshold defining “abnormal” separation. Different studies have proposed various cut-off values depending on measurement sites, populations, and assessment tools, such as ultrasound measurements exceeding 20 mm, clinical palpation ≥2 fingerbreadths, or stricter criteria of ≥30 mm (Lin et al., 2024). Notably, imaging studies have shown that some degree of linea alba widening may also be present in men and nulliparous women, suggesting that IRD varies anatomically among individuals; thus, DRA diagnosis should consider contextual factors such as measurement location, age, sex, and postpartum stage (Cavalli et al., 2021).

This indicates a shift from purely distance-based definitions toward a more comprehensive assessment integrating structural width, tissue tension, and functional performance.

In clinical practice, the identification and quantification of DRA rely primarily on bedside examination and imaging techniques. Traditional finger-width palpation and curl-up-based assessments are simple and cost-effective, making them suitable for initial screening and primary care settings, but they are subjective and influenced by examiner experience, body habitus, and muscle contraction. Calipers and tape measures can improve objectivity to some extent, though reliability remains limited. In contrast, ultrasound imaging allows precise measurement of IRD at multiple sites both at rest and during contraction, while simultaneously visualizing linea alba morphology and muscle coordination, and is therefore widely regarded as the most practical and reliable tool. CT and MRI offer higher resolution but are mainly used for research purposes or complex cases (Figure 1) (Du et al., 2025). Recent advances, including AI-assisted ultrasound segmentation and elastography, further enable assessment of linea alba thickness, tissue stiffness, and quality, although these techniques are not yet widely adopted in routine clinical practice (Huang et al., 2025).

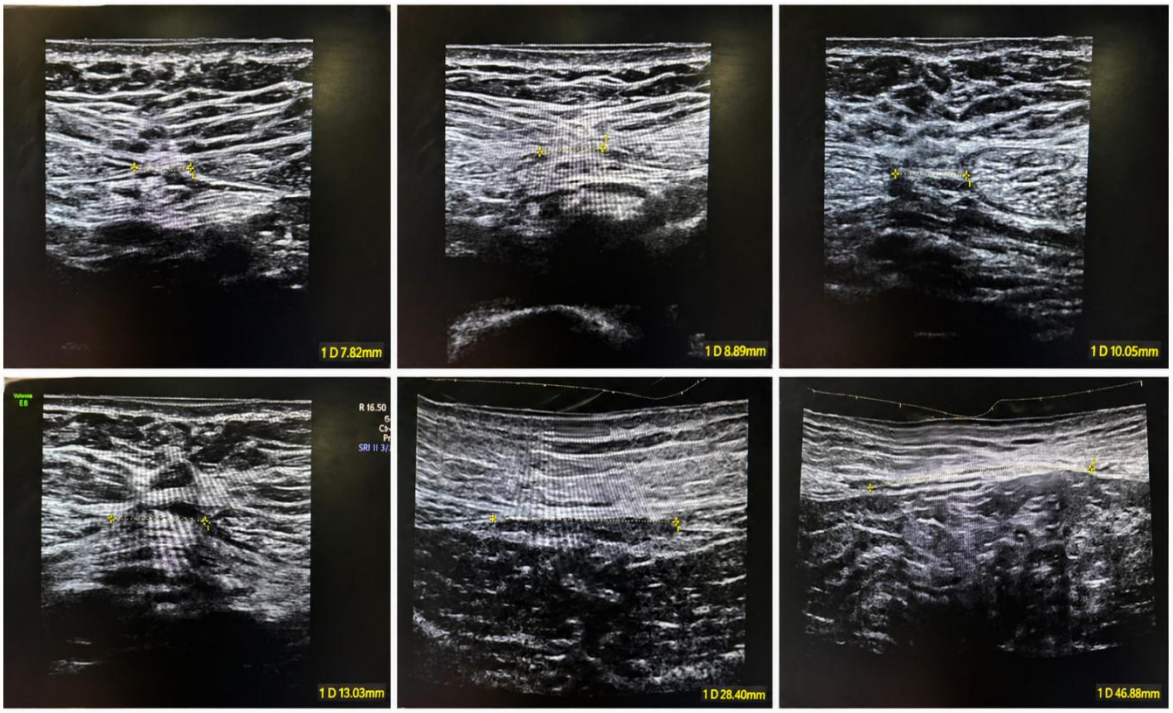

Figure 1 Ultrasound images of different degrees of rectus abdominis diastasis in females

Image caption: The figure shows six ultrasound images representing different degrees of rectus abdominis diastasis; The yellow markers indicate the distance between the medial borders of the rectus abdominis muscles (i.e., inter-rectus distance, IRD). The measurements displayed in the lower right corners are approximately 7.82 mm, 8.89 mm, 10.05 mm, 13.03 mm, 28.40 mm and 46.88 mm, respectively

2.2 Pathophysiological mechanisms

The development of DRA is multifactorial and can be understood as the interaction between increased mechanical loading, altered connective tissue properties, and impaired neuromuscular control. During pregnancy, progressive uterine enlargement, fetal growth, increased amniotic fluid, and maternal weight gain impose sustained and increasing mechanical stress on the anterior abdominal wall, leading to elevated intra-abdominal pressure and elongation and thinning of the linea alba. Chronic and progressive mechanical stretching induces plastic deformation and microstructural remodeling of the linea alba, resulting in gradual widening of IRD. Longitudinal ultrasound studies further demonstrate that IRD increases significantly from early to late pregnancy, accompanied by reduced rectus abdominis thickness and decreased tissue stiffness, with only partial recovery postpartum, suggesting that mechanical factors not only initiate DRA but also contribute to its persistence (Du et al., 2025).

In addition to mechanical loading, pregnancy-related hormonal changes play a critical role. Elevated levels of relaxin, estrogen, and progesterone affect collagen fiber alignment, cross-linking, and extracellular matrix metabolism, thereby reducing connective tissue stiffness and tensile strength and increasing the compliance of the linea alba and myofascial system. The combination of sustained mechanical loading and tissue laxity makes the linea alba more susceptible to irreversible elongation (Du et al., 2025). Furthermore, factors such as obesity, chronic cough, constipation, heavy physical labor, and inappropriate high-intensity exercise can lead to chronically elevated intra-abdominal pressure, further increasing abdominal wall stress and exacerbating DRA.

Importantly, DRA is not merely a geometric widening but also involves impaired force transmission and reorganization of the core functional system. The transversus abdominis, diaphragm, and pelvic floor muscles work synergistically to regulate intra-abdominal pressure and maintain lumbopelvic stability. When pregnancy and childbirth alter their activation patterns and coordination, delayed muscle recruitment, reduced force transmission, and compensatory strategies may occur, creating a cycle of "structural laxity–functional dysfunction." Clinically, this may manifest as midline bulging, reduced trunk stability, postural fatigue, lumbopelvic pain, and pelvic floor symptoms, although the exact causal relationships remain to be fully elucidated.

2.3 Risk factors

The development and persistence of DRA are influenced by multiple maternal, pregnancy-related, and delivery-related factors, among which multiparity is considered one of the most significant. Repeated pregnancies subject the linea alba to cycles of stretching, repair, and reloading, potentially leading to cumulative damage to elastic fibers and collagen structure and reducing the capacity for recovery. Cross-sectional and cohort studies consistently show that higher parity is associated with greater IRD and increased risk of clinically significant DRA, both in the early postpartum period and in long-term follow-up (Sartori et al., 2024). Multiple gestations, fetal macrosomia, and diabetes may further increase mechanical and metabolic stress, thereby elevating the risk of DRA (Lin et al., 2024).

Advanced maternal age and higher pre-pregnancy or postpartum body mass index (BMI) are also important risk factors. With increasing age, the regenerative capacity of connective tissue declines and collagen metabolism becomes less efficient, making the linea alba more prone to irreversible stretching under pregnancy-related stress. Elevated BMI not only increases sustained abdominal wall loading but may also alter intra-abdominal pressure distribution and force transmission. Studies have demonstrated a significant association between higher BMI and more severe DRA, with severe cases also linked to higher rates of abdominal hernia, urinary incontinence, pelvic organ prolapse, and pain (Lin et al., 2024; Sartori et al., 2024). Research in Chinese populations further indicates that high-risk postpartum women often report poorer patient-reported outcomes, suggesting that risk factors influence not only structural changes but also functional status and quality of life (Zhu et al., 2024).

The role of delivery mode and perinatal behaviors in DRA remains complex and inconclusive. Some studies suggest that cesarean section, prior abdominal surgery, and higher birth weight are associated with increased DRA risk, while others report that vaginal delivery may be negatively associated with certain types of DRA in multivariate analyses, indicating that the relationship between delivery mode and DRA is not straightforward (Li et al., 2024; Guo et al., 2025). Additionally, chronic heavy physical labor, inappropriate high-intensity abdominal exercise, chronic constipation, chronic cough, connective tissue disorders, and generalized joint laxity may contribute to the development and persistence of DRA by increasing intra-abdominal pressure or reducing connective tissue stability.

3 Assessment Methods for Diastasis Recti Abdominis

3.1 Clinical assessment methods

Clinical assessment forms the basis for screening, preliminary diagnosis, and follow-up management of diastasis recti abdominis (DRA), particularly in settings with limited access to imaging, such as maternal and child healthcare services, community rehabilitation, and physiotherapy. The most commonly used bedside method is finger-width palpation. This is typically performed with the patient in a supine hook-lying position, where she is

asked to slightly lift her head or perform a standardized curl-up to activate the rectus abdominis and expose the linea alba gap. The examiner palpates the medial borders of the rectus muscles and estimates the inter-recti distance (IRD) at standardized locations, including above, at, and below the umbilicus. In some studies, a threshold of ≥2 fingerbreadths or approximately ≥2 cm is used for screening, with further classification into mild, moderate, and severe degrees (Chen et al., 2023). Due to its simplicity, low cost, and wide clinical applicability, this method remains one of the most commonly used screening tools in routine practice.

The curl-up test is not only used to identify the presence of DRA but also provides preliminary information on abdominal wall function. During this test, visible midline bulging (doming), groove formation, or uneven tension following rectus contraction may indicate reduced mechanical integrity of the linea alba and impaired load transfer. Compared with static palpation, the curl-up test offers a degree of dynamic assessment, allowing observation of abdominal wall behavior during functional movement and evaluation of linea alba quality based on width, depth, and tactile feedback (Soleimanzadeh et al., 2023). In recent years, some clinical protocols have also incorporated standing observation, cough testing, and midline depth assessment to overcome the limitations of width-only measurements.

However, clinical assessment methods have notable limitations. Finger-width palpation is influenced by examiner finger size, experience, and patient muscle activation, resulting in only moderate inter-rater reliability even with standardized procedures, and limited validity compared to ultrasound. To improve objectivity, some studies recommend using digital calipers, rulers, or tape measures across the midline during curl-up testing. These tools provide greater accuracy than finger palpation and show better correlation with ultrasound measurements (Petronilla et al., 2023).

3.2 Imaging assessment methods

Imaging provides more objective and reproducible measurements for DRA and represents a core method in both research and specialized clinical practice. Among available modalities, two-dimensional B-mode ultrasonography is widely regarded as the reference standard for measuring IRD due to its non-invasive nature, absence of radiation, relatively low cost, and real-time visualization of the rectus muscles and linea alba (Opala-Berdzik et al., 2023). Compared with palpation, ultrasound enables precise measurement of IRD at standardized anatomical landmarks above, at, and below the umbilicus, reducing measurement error. Measurement studies have demonstrated excellent intra- and inter-rater reliability across different positions and muscle states, with intraclass correlation coefficients often exceeding 0.80 (Billis et al., 2025; Espinoza-Bravo et al., 2025).

Moreover, ultrasound allows not only static structural assessment but also dynamic evaluation. Observing IRD changes during curl-up, transversus abdominis activation, breathing maneuvers, or other functional tasks provides insight into linea alba tension regulation, core muscle coordination, and rehabilitation response (Billis et al., 2025; Espinoza-Bravo et al., 2025). This integrated “structure–function” assessment enhances its value in monitoring natural progression and treatment outcomes. Recently, shear wave elastography has been used to quantify tissue stiffness of abdominal muscles and the linea alba, revealing differences between DRA patients and healthy individuals. In addition, novel ultrasound-based classification systems incorporating IRD width and length have been proposed to guide decisions between conservative and surgical treatment (Shen et al., 2024).

Despite its advantages, considerable heterogeneity remains in ultrasound measurement protocols. Variations exist in measurement sites, patient positioning, breathing phase, contraction status, and number of repetitions. Measurement locations may range from a single umbilical point to multiple sites 2-12 cm above and 2-4.5 cm below the umbilicus, which limits comparability across studies and the establishment of unified diagnostic criteria (Figure 2) (Opala-Berdzik et al., 2023). In contrast, CT and MRI provide high-resolution imaging of abdominal wall structures and can detect associated hernias, but due to radiation exposure, cost, and limited accessibility, they are mainly used for preoperative planning or research rather than routine postpartum screening (Du et al., 2025). Therefore, standardizing ultrasound measurement protocols remains a key step toward improving comparability and evidence quality in DRA assessment.

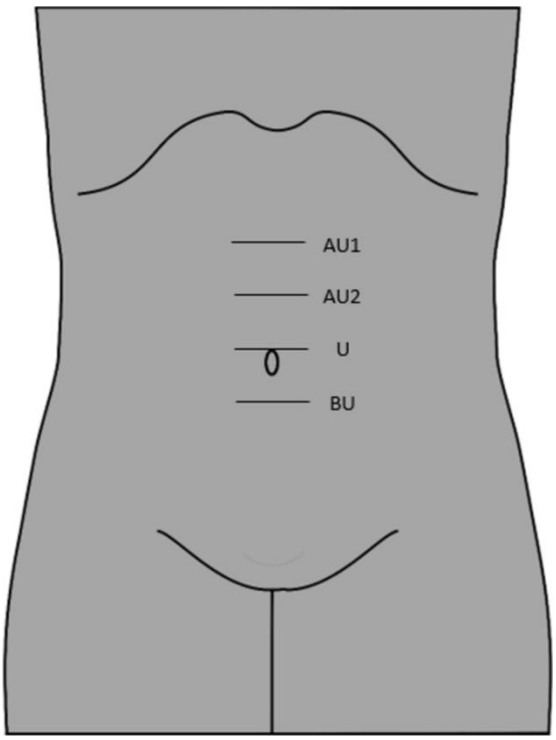

Figure 2 Proposed sites for inter-recti distance measurement using ultrasonographic imaging based on the scoping review results synthesis (Adopted from Opala-Berdzik et al., 2023)

Image caption: AU1: 1/2 of the superior umbilical border-xiphoid distance; AU2: 1/4 of the superior umbilical border-xiphoid distance; U: the superior umbilical border; and BU:1/4 of the superior umbilical border-pubis distance (Adopted from Opala-Berdzik et al., 2023)

3.3 Functional assessment methods

With increasing recognition of DRA as a condition with functional implications, reliance solely on structural indicators such as IRD is insufficient, making functional assessment an essential complement. Core muscle function assessment is central, focusing on activation capacity, recruitment sequence, and coordination of deep stabilizing muscles, including the transversus abdominis, multifidus, diaphragm, and pelvic floor muscles. Common objective methods include pressure biofeedback units (PBU), surface electromyography (sEMG), ultrasound-based muscle thickness observation, and functional tests such as plank, bridging, and curl-up endurance tests (Du et al., 2025). Multidimensional tools such as the Abdominal Trunk Function Protocol (ATFP) combine objective performance and subjective symptoms to comprehensively evaluate core stability, muscle endurance, and functional limitations in daily activities (Du et al., 2025).

Pain and symptom burden are also important components of functional assessment. DRA is often associated with low back pain, lumbopelvic pain, fatigue, and difficulty in specific movements. Clinical evaluation typically uses visual analog scale (VAS) or numeric rating scale (NRS) to quantify pain intensity, along with assessment of onset, duration, and impact on functional activities. Studies have shown that DRA patients may exhibit altered abdominal activation patterns and muscle thickness changes during Valsalva maneuvers, coughing, and functional movements. These abnormalities may not always correlate directly with IRD width but can significantly affect load transfer and core control (Skvortsov et al., 2024). Therefore, relying solely on structural measurements may be insufficient to explain clinical symptoms and functional impairment.

Quality of life and patient-reported outcomes (PROs) provide a broader perspective on the overall impact of DRA. Common instruments include the SF-36, Disability Rating Index (DRI), the self-reported component of ATFP, and pelvic floor and urogenital symptom questionnaires such as UDI-6 and IIQ-7. These tools assess limitations in activities such as lifting, running, heavy work, social participation, and psychological well-being (Du et al., 2025). Importantly, previous studies indicate that IRD is not always an independent predictor of functional impairment or

reduced quality of life, suggesting that the clinical consequences of DRA are multifactorial (Bixo et al., 2021). Therefore, combining structural measurements, objective functional testing, pain assessment, and quality-of-life evaluation is essential for constructing a comprehensive multidimensional assessment framework and guiding individualized rehabilitation strategies.

4 Rehabilitation Interventions for Diastasis Recti Abdominis

4.1 Exercise therapy

Exercise therapy is the cornerstone of conservative management for diastasis recti abdominis (DRA). Its primary goals are to restore abdominal wall tension, reconstruct the core stabilization system, and promote the functional integration of the linea alba. Existing scoping reviews, systematic reviews, and meta-analyses consistently indicate that training centered on activation of the transversus abdominis (TrA) is one of the most commonly used and theoretically grounded interventions. As a key muscle in regulating intra-abdominal pressure and maintaining abdominal wall tension, contraction of the TrA may enhance linea alba tension through a "corset effect," thereby reducing inter-recti distance (IRD) to some extent and improving trunk stability (Deka, 2025). Common training modalities include diaphragmatic breathing, the draw-in maneuver, deep core stabilization exercises, functional training, and Pilates. Previous meta-analyses have shown that isolated TrA training may reduce IRD compared with minimal intervention, with a mean difference of approximately -0.6 cm, although the overall quality of evidence remains low, suggesting that while potential benefits exist, higher-quality studies are still needed to confirm its efficacy (Skoura et al., 2024).

On the basis of TrA training, pelvic floor muscle training (PFMT) is often incorporated into comprehensive rehabilitation programs for DRA. The theoretical rationale lies in the fact that the transversus abdominis, pelvic floor muscles, and diaphragm together form the "core pressure system," and their coordinated contraction helps maintain dynamic balance of intra-abdominal pressure, improve lumbopelvic stability, and optimize load transfer. Clinical studies and reviews suggest that combining abdominal exercises with PFMT, particularly when integrated with breathing control, postural regulation, and functional daily activities, is more beneficial for improving IRD and quality of life (Figure 3) (Khan and Bulbuli, 2024; Skoura et al., 2024). However, high-quality evidence supporting the effectiveness of PFMT alone for DRA remains limited. Current systematic reviews indicate that the quality of evidence is low, suggesting that PFMT is more appropriately incorporated within an overall core stabilization framework rather than applied in isolation.

Building on this, core stability training further integrates the coordinated control of deep and superficial muscle groups. Typical exercises include bridging, quadruped support, modified planks, and progressive curl-up or trunk flexion exercises. Recent network meta-analyses and narrative reviews suggest that isotonic training engaging both deep and superficial abdominal muscles, combined with breathing and postural control, may be more effective in reducing IRD than isolated exercise or purely passive treatments (Weber et al., 2024; Bigdeli et al., 2025; Wu et al., 2025). However, exercise prescription should follow individualized and progressive principles, and high intra-abdominal pressure or high-load exercises in the early postpartum period, such as traditional sit-ups or poorly controlled forceful curl-ups, should be avoided, as they may induce abdominal doming, pain, or pelvic floor discomfort (Chen et al., 2023). Therefore, the currently favored approach is a comprehensive exercise model characterized by "TrA-PFM co-activation+progressive core training+integration of functional movements," rather than reliance on a single exercise or isolated muscle training.

4.2 Physical therapy modalities

Physical therapy serves as an important adjunct to exercise therapy and offers unique advantages in promoting neuromuscular activation, improving local tissue condition, and enhancing adherence to training. In recent years, multiple systematic reviews, meta-analyses, and network meta-analyses comparing different non-surgical interventions have consistently indicated that neuromuscular electrical stimulation (NMES) combined with abdominal exercise is more effective in reducing IRD than exercise alone, passive treatment, or no intervention, and ranks highly among conservative treatment strategies (Bigdeli et al., 2025; De Oliveira et al., 2025). Further subgroup analyses suggest that isotonic abdominal exercise combined with electrical stimulation may achieve

even greater reductions in IRD (Wu et al., 2025). In addition, some clinical trials and case studies have shown that multimodal programs integrating Russian current or NMES with TrA training, aerobic exercise, and abdominal support can produce clinically meaningful short-term improvements, although these findings should be interpreted cautiously because of small sample sizes and short follow-up durations (Kaya and Menek, 2023; Khan and Bulbuli, 2024).

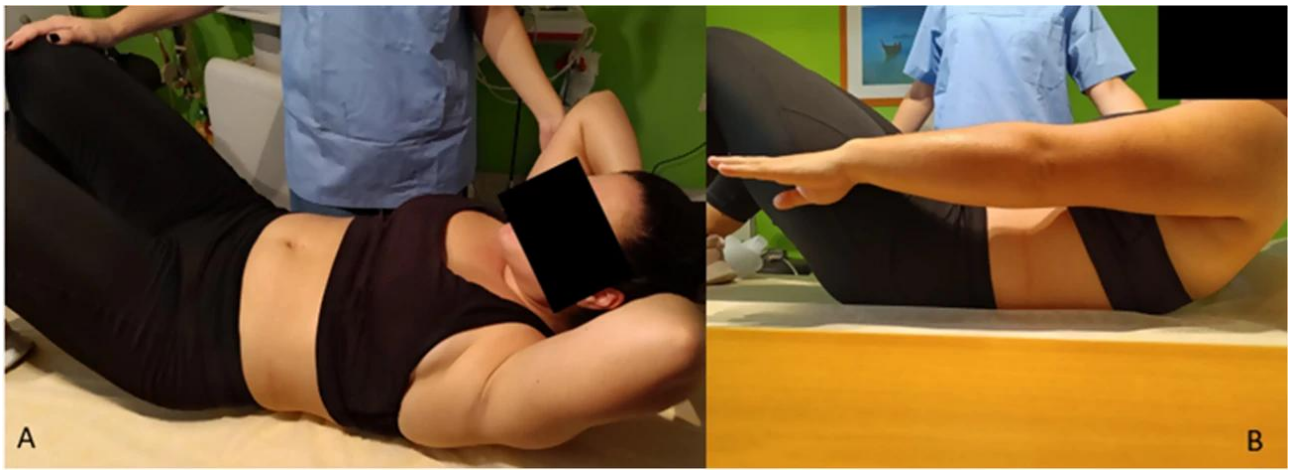

Figure 3 Abdominal muscle exercises (rectus abdominis focused) (Adopted from Skoura et al., 2024)
Image caption: A. Crunch exercise. The patient is positioned in supine with legs bent and arms supporting the head. Then they are asked to dynamically elevate their head and upper torso until their shoulder blades lift off the surface. B. Curl-up exercise. Positioned in supine with bent legs and arms extended beside the hips, parallel to the bed, the patient is instructed to curl their upper back and shoulders in a controlled way, until their shoulder blades are off the bed while maintaining their lower back in contact with the bed. The arms remain parallel to the ground, reaching towards the feet (Adopted from Skoura et al., 2024)

Biofeedback techniques provide real-time information on muscle activity and help patients establish appropriate neuromuscular recruitment patterns, making them especially suitable for postpartum individuals with poor motor control or limited training awareness. Common forms include surface electromyography (EMG) biofeedback, pressure feedback, and ultrasound visual feedback. Randomized controlled trials have shown that EMG biofeedback-assisted pelvic floor muscle training combined with rectus abdominis NMES results in greater reductions in IRD and improved health-related quality of life compared with NMES alone, indicating added value from neuromuscular retraining (Liang et al., 2022). This suggests that the benefits of physical therapy extend beyond passive stimulation, as these modalities can also enhance muscle awareness and motor control, thereby improving the quality and adherence of active exercise.

In addition to electrical stimulation and biofeedback, adjunctive interventions such as manual therapy, Kinesio taping, and electroacupuncture are frequently included in multimodal rehabilitation programs. Myofascial release, soft tissue mobilization, the Noble technique, and related manual approaches are primarily used to improve fascial glide, relieve local tension, and optimize force transmission pathways, and are often combined with postural training and exercise therapy (Chen et al., 2023). Kinesio taping may provide short-term support and proprioceptive input, potentially enhancing the effects of deep core training, although its standalone effectiveness appears limited (Muthulakshmi et al., 2023; Weber et al., 2024). Electroacupuncture and acupuncture combined with exercise have also shown some efficacy in certain network meta-analyses, but most studies are concentrated in specific regions and exhibit considerable methodological heterogeneity (Bigdeli et al., 2025; Zhu et al., 2025).

4.3 Comprehensive management

Rehabilitation management of DRA should emphasize the integration of multiple strategies in order to optimize structural support, functional recovery, and behavioral adaptation. Given that DRA often coexists with trunk instability, pelvic floor dysfunction, pain, aesthetic concerns, and body image issues, an increasing number of scholars advocate a comprehensive management model that includes exercise therapy, physical therapy, external support, health education, lifestyle guidance, and, when necessary, surgical intervention (Skoura et al., 2024;

Janiszewska et al., 2025). Among these, abdominal binders, corsets, and elastic bandages are commonly used in the early postpartum period to provide proprioceptive feedback, enhance subjective stability, and temporarily reduce stress on the abdominal wall during activity. Randomized controlled trials and meta-analyses suggest that abdominal support alone can improve IRD, pain, and functional performance, but its effects are greater when combined with core stabilization exercises (Kaya and Menek, 2023). Network meta-analyses further indicate that abdominal support combined with core training performs particularly well in improving IRD below the umbilicus, whereas binders alone show only moderate effects (Abdullah et al., 2025; Zhu et al., 2025).

Postural guidance and modification of daily behaviors are also important components of comprehensive management. Improper movement patterns during getting in and out of bed, carrying an infant, lifting, and performing household activities may continuously increase intra-abdominal pressure and aggravate stress on the linea alba. Therefore, rehabilitation programs should generally include maintenance of neutral spine alignment, breathing coordination, load management, self-monitoring of abdominal doming, and retraining of functional movement patterns. For example, using a "side-lying to push-up" technique instead of directly sitting up from supine, and avoiding breath-holding during lifting and childcare tasks, may help reduce midline stress and promote long-term behavioral change (Skoura et al., 2024; Fajar et al., 2025). Although this component is often categorized as "education," it is in fact of substantial clinical value for symptom control, improving adherence, and preventing recurrence.

For patients with poor response to conservative treatment or severe separation, surgery may serve as the final option within comprehensive management. Surgical intervention is generally indicated for cases with large separation (e.g., >3-5 cm), marked functional impairment, associated abdominal wall hernia, or persistent symptoms despite adequate conservative treatment. Common procedures include linea alba plication, retromuscular repair, and minimally invasive endoscopic repair. The main goals are to reconstruct abdominal wall continuity, restore mechanical stability, and relieve associated symptoms. Previous reviews suggest that surgery can significantly improve core function, pain, urinary symptoms, and quality of life, particularly when followed by structured postoperative rehabilitation, which appears to enhance long-term outcomes (Skoura et al., 2024; Janiszewska et al., 2025). Nevertheless, surgery still carries risks of complications and recurrence, and should therefore be considered cautiously only after sufficient conservative treatment, clear indications, and informed shared decision-making.

5 Comparison of Different Intervention Approaches

5.1 Differences between single exercise interventions and comprehensive rehabilitation

In rehabilitation research on diastasis recti abdominis (DRA), comparing single exercise interventions with comprehensive rehabilitation programs has become a key focus of evidence-based evaluation. Single exercise interventions typically emphasize selective activation and strengthening of specific muscle groups, such as transversus abdominis activation, curl-up training, or basic core stabilization exercises. Existing systematic reviews and meta-analyses suggest that these interventions can produce modest improvements in inter-recti distance (IRD), particularly in mild to moderate DRA, but the overall effect size is small and the quality of evidence is generally low (Beamish et al., 2024; De Oliveira et al., 2025). For example, a meta-analysis by Gluppe et al. (2021) reported that isolated transversus abdominis training reduced IRD by approximately 0.6 cm compared with minimal intervention; however, this conclusion was based on studies with small sample sizes and a high risk of bias. Similarly, a randomized controlled trial found that a 12-week curl-up program increased abdominal muscle thickness and strength without worsening DRA, but did not significantly reduce IRD compared with no intervention (Gluppe et al., 2023).

In contrast, comprehensive rehabilitation emphasizes a multidimensional approach, typically integrating active exercise training, neuromuscular electrical stimulation (NMES), breathing and postural control, pelvic floor muscle coordination, abdominal support, taping, and manual therapy. Network meta-analyses and systematic reviews consistently indicate that multimodal interventions are more effective than single exercise approaches in reducing IRD. Combinations such as "exercise+NMES," "core training+abdominal support," and

"exercise+breathing control+pelvic floor coordination" demonstrate higher effect rankings and more stable clinical outcomes (Bigdeli et al., 2025; Wu et al., 2025; Zhu et al., 2025). De Oliveira et al. (2025) further reported that combining abdominal exercise with adjunctive interventions resulted in an additional IRD reduction of approximately -3.6 mm compared with exercise alone, suggesting an additive effect of comprehensive strategies.

Mechanistically, the superiority of comprehensive rehabilitation lies in its broader focus beyond structural width alone, targeting neuromuscular control, postural behavior, and functional load management. Through approaches such as biofeedback, electrical stimulation, and patient education, individuals develop improved awareness of proper muscle recruitment and intra-abdominal pressure regulation, leading to better adherence and movement quality. Current evidence therefore supports comprehensive rehabilitation models as aligning with an integrated "structure-function-behavior" framework, particularly for individuals with moderate to severe DRA, higher symptom burden, or limited response to isolated exercise (Deka, 2025).

5.2 Effects of different rehabilitation methods on IRD, muscle strength, and functional recovery

Different rehabilitation strategies demonstrate distinct pathways in improving DRA-related outcomes. Regarding IRD, most studies support active exercise as the fundamental intervention, while multi-component programs further enhance structural improvement. Large meta-analyses indicate that abdominal exercise significantly reduces IRD compared with no intervention, particularly below the umbilicus, and that combining exercise with adjunctive modalities, such as NMES, taping, breathing training, or pelvic floor muscle training, can result in an additional reduction of approximately 3-4 mm (De Oliveira et al., 2025; Wu et al., 2025). Network meta-analyses further suggest that suspension training, Pilates, and "abdominal support+core stabilization" rank highly in improving IRD at different anatomical levels (Zhu et al., 2025). In contrast, passive approaches such as abdominal binders or taping alone may provide short-term support but generally have limited or moderate effects on structural IRD reduction (Abdullah et al., 2025; Bigdeli et al., 2025).

In terms of muscle strength recovery, active exercise remains the most critical intervention. Curl-up training, core stabilization, and progressive abdominal strengthening can improve rectus abdominis thickness, trunk flexion strength, and muscular endurance, even when IRD changes are not always significant (Gluppe et al., 2023; Du et al., 2025). Comparative studies show that core stabilization, abdominal support, and their combination all improve strength, endurance, and balance, with combined interventions producing superior outcomes in both structural and functional measures (Kaya and Menek, 2023). Furthermore, combining EMG biofeedback-assisted pelvic floor training with NMES enhances neural activation and motor control, leading to improvements in both IRD and health-related quality of life. This suggests a potential synergistic relationship between muscle strengthening, neuromuscular control, and structural recovery.

From a functional perspective, the overall value of rehabilitation strategies becomes particularly evident. Increasing evidence indicates that IRD alone is a structural marker and does not fully reflect symptom burden or functional status. Combined interventions, such as abdominal support with targeted exercise, can improve body image, trunk strength, and subjective function, even when structural changes are modest (Du et al., 2025). Therefore, comparisons between rehabilitation methods should not be limited to IRD reduction alone but should also include outcomes such as strength, endurance, pain, postural control, and quality of life.

5.3 Short-term and long-term outcomes

Current evidence generally suggests that most conservative rehabilitation interventions yield positive short-term effects, with intervention durations typically ranging from 6 to 16 weeks and primary outcomes including IRD, muscle activation, strength, and selected functional indicators. Short-term findings indicate that interventions such as abdominal exercise, exercise combined with NMES, acupuncture or electroacupuncture combined with exercise, and abdominal support combined with core stabilization result in greater reductions in IRD compared with control groups, along with improvements in muscle strength and quality of life (Bigdeli et al., 2025; Wu et al., 2025; Zhu et al., 2025). For example, some studies report that core stabilization combined with NMES can significantly improve IRD, waist circumference, and quality of life within a few weeks, while "exercise+NMES"

may achieve greater short-term structural improvements than "exercise + abdominal support" (Skoura et al., 2024; Du et al., 2025). In addition, both conventional abdominal training and hypopressive training may produce positive effects on IRD within 6 weeks, although differences exist between resting and contraction conditions, and multiparous women may experience greater benefits (Table 1) (Soto-González et al., 2024).

Table 1 Mean (SD) of Inter-Rectus Distance (mm) measured 2 cm (AB2) and 5 cm (AB5) above the umbilicus

Probe Location	Group	Moment 1 (Week 0)	Moment 2 (Week 6)	Probe Location	Group
		RT Mean (SD)	AC Mean (SD)	RT Mean (SD)	AC Mean (SD)
AB2	Conventional	21.5 (8.99)	23.42 (9.20)	17.03 (7.94)	18,79 (8.31)
	Hypopressive	20.81 (8.46)	21.23 (8.68)	19.31 (7.46)	19.62 (7.83)
AB5	Conventional	20.97 (9.89)	16.44# (8.15)	19.03* (10.95)	17.30 (9.95)
	Hypopressive	22.04 (9.31)	20.21 (7.67)	21.38 (10.32)	17.95**# (9.42)

Table caption: * The mean difference is significant (p <.05) between week 0 and week 6; # The mean difference is significant (p<.05) between RT and AC

However, short-term findings are limited by considerable heterogeneity across studies. Variations in intervention frequency, training dosage, participant characteristics, measurement methods, and follow-up duration, along with small sample sizes and high risk of bias in many studies, require cautious interpretation of the evidence despite generally favorable trends. This suggests that short-term improvements do not necessarily translate into sustained long-term benefits. Long-term evidence remains limited, but available data suggest that structural and functional improvements may be maintained when rehabilitation is combined with continued training, behavioral modification, or comprehensive management strategies. Early randomized trials have shown that abdominal support combined with exercise can improve body image and trunk flexion strength at 6-month follow-up. For patients with severe DRA and poor response to conservative treatment, the "training-operation-rehabilitation (TOR)" model has demonstrated significant improvements in functional impairment and quality of life at 1 year postoperatively, with no obvious recurrence, indicating promising long-term outcomes for integrated approaches in refractory cases (Janiszewska et al., 2025). However, mild to moderate DRA may also exhibit natural recovery within the first postpartum year, which complicates interpretation of long-term effects of low-intensity or poorly controlled interventions (Beamish et al., 2024).

6 Current Limitations in Research

6.1 Lack of standardized diagnostic criteria and assessment methods for DRA

Despite increasing research attention, there is still no consensus on the diagnostic criteria and assessment methods for diastasis recti abdominis (DRA), which has become a major barrier to study comparability, evidence synthesis, and clinical translation. Most studies rely on inter-recti distance (IRD) as the primary diagnostic indicator; however, thresholds for defining "abnormal" separation vary considerably. Different studies use cut-offs such as ≥2.0 cm, ≥2.5 cm, ≥28-30 mm, or criteria based on fingerbreadths, body proportions, or population norms, with measurement sites ranging from above, at, or below the umbilicus, and assessment conditions including rest, light curl-up, or muscle activation (Skoura et al., 2024). This variability in definitions and thresholds contributes to substantial heterogeneity in prevalence estimates, severity classification, and reported treatment effects, making cross-study comparisons difficult.

In addition to diagnostic thresholds, assessment methods themselves show considerable heterogeneity. Measurement tools include finger palpation, calipers, ultrasound, and, less commonly, CT and MRI. Although ultrasound is increasingly regarded as a reliable reference method, its measurement process involves multiple technical factors, such as probe pressure, breathing control, body positioning, selection of measurement sites, and repetition, which are not yet fully standardized and may introduce systematic error. Meanwhile, finger-width palpation, although simple and widely used, has only moderate reliability and is more suitable for identifying the presence of DRA rather than detecting subtle changes in IRD, potentially masking clinically meaningful improvements (Skoura et al., 2024). In response, some countries have proposed standardized pathways, for

example, the Swedish consensus recommends caliper- or ruler-based measurements and the use of imaging for suspected hernias or complex cases, but such guidelines have not yet been widely adopted internationally.

Furthermore, current assessment frameworks rely heavily on structural indicators while insufficiently integrating functional status, symptom burden, and patient-reported outcomes. IRD alone cannot fully reflect abdominal wall tension, core stability, pain, functional limitations, or quality of life, and may either underestimate or overestimate the true clinical impact. Therefore, future research should prioritize the development of internationally standardized and validated diagnostic thresholds, measurement protocols, and reporting frameworks, while promoting a transition from purely structural assessment to a multidimensional "structure-function-symptom" evaluation model.

6.2 High variability in rehabilitation protocols and lack of standardized training pathways

Rehabilitation research on DRA is similarly characterized by substantial heterogeneity, with wide variations in exercise content, dosage, supervision, and adjunctive therapies, and a lack of standardized, reproducible training protocols. Existing interventions include transversus abdominis training, pelvic floor muscle training, combined deep and superficial abdominal strengthening, breathing exercises, Pilates, yoga, suspension training, as well as neuromuscular electrical stimulation, electroacupuncture, Kinesio taping, abdominal support, and biofeedback (Zhu et al., 2025). Intervention duration ranges from 4 to 12 weeks, training frequency typically varies from two to five sessions per week, and timing may differ between antenatal, early postpartum, or later postpartum stages (Gluppe et al., 2023). This high level of heterogeneity makes it difficult to compare results across studies and to identify the most effective core components of rehabilitation.

Even within a single intervention type, substantial variability exists. For example, "core stability training" may involve entirely different exercise selections, intensity progressions, and load management strategies across studies. Similarly, curl-up training, transversus abdominis activation, and rectus-dominant exercises are often implemented with differing dosages, limiting direct comparison (Gluppe et al., 2023). The timing of intervention initiation is also inconsistent: some studies advocate early low-load activation training to promote linea alba recovery, whereas others recommend delaying structured training until tissue healing stabilizes. Currently, there is no clear consensus on how to balance safety, effectiveness, and optimal progression pathways.

This lack of standardization is also evident in clinical practice. Survey data indicate that although many physiotherapists routinely assess and treat DRA, their intervention strategies are largely based on personal experience rather than standardized guidelines, particularly regarding the choice between transversus abdominis-focused versus rectus-dominant training, timing of adjunct therapies, and progression strategies (Deka, 2025). Retrospective studies suggest that structured and standardized rehabilitation programs may achieve better outcomes in IRD reduction and quality of life than non-standardized care; however, these protocols are often derived from single-center experiences and have not been widely implemented. Therefore, future research should focus on developing evidence-based, consensus-driven rehabilitation frameworks with clearly defined exercise types, intensity, frequency, progression criteria, and adjunctive interventions to enhance reproducibility and clinical consistency.

6.3 Insufficient high-quality randomized controlled trials and limited long-term evidence

Although the number of studies on DRA rehabilitation and prevention has increased, the overall level of evidence remains limited, with a predominance of small-sample, single-center studies and a relative lack of high-quality randomized controlled trials (RCTs). Multiple scoping and systematic reviews have noted that many existing trials suffer from methodological limitations, including small sample sizes, inadequate randomization, lack of allocation concealment, insufficient blinding, and incomplete outcome reporting, leading to a high risk of bias (Gluppe et al., 2023). Some studies report that general postpartum exercise has no significant effect on DRA prevalence, possibly due to non-specific intervention content, mild baseline severity, or limited sensitivity of palpation-based measurements. In contrast, more targeted interventions, such as core stabilization, curl-up training, suspension training, or antenatal exercise programs, have shown promising results, but their external validity remains limited (Bigdeli et al., 2025).

In terms of follow-up duration, most studies focus on short-term outcomes, typically assessing changes immediately after intervention or within 3-6 months, while long-term evidence is scarce. Given that DRA involves complex processes of structural remodeling, neuromuscular adaptation, and behavioral change, long-term outcomes include not only sustained IRD reduction but also maintenance of functional improvements, recurrence after cessation of training, and long-term effects on pain, pelvic floor function, and quality of life (Du et al., 2025). However, due to the lack of sufficient longitudinal data, the durability and comparative advantages of different interventions remain unclear. Similarly, surgical studies primarily report short- to mid-term outcomes, with limited evidence on recurrence rates, mesh-related complications, and functional outcomes beyond 2-5 years (Janiszewska et al., 2025).

In addition, inconsistency in outcome measures represents another major limitation. Some studies report only IRD changes, neglecting clinically meaningful outcomes such as muscle strength, pain, functional disability, body image, and quality of life, while others include functional measures but use different tools and reporting standards, limiting comparability. Furthermore, the natural course of untreated or conservatively managed DRA remains poorly understood, adding complexity to the interpretation of long-term intervention effects (Du et al., 2025). Therefore, future research should prioritize multicenter, large-scale, high-quality RCTs with standardized diagnostic criteria and core outcome sets, extended follow-up periods, and inclusion of diverse populations to better define the long-term value of rehabilitation strategies, their integration with surgical approaches, and optimal treatment pathways for different patient subgroups.

7 Future Research Directions

7.1 Establishing standardized assessment criteria and classification systems to improve comparability

A primary priority for future research is to establish unified, scalable, and internationally applicable assessment standards and classification systems for diastasis recti abdominis (DRA). Although inter-recti distance (IRD) is currently the most commonly used structural indicator, substantial variability exists across studies in measurement tools, anatomical reference points, body positioning, and diagnostic thresholds, which significantly limits cross-study comparability and the reliability of meta-analyses (Chen et al., 2023). Some studies define DRA solely based on IRD width, whereas others incorporate symptoms, functional impairment, or treatment needs, further reducing the consistency and integrability of existing evidence (Skoura et al., 2024; Bigdeli et al., 2025). Therefore, future work should prioritize large-scale, multicenter studies to establish standardized anatomical landmarks, unified reporting protocols under both resting and activated conditions, and definitions that account for sex, parity, and body composition differences, thereby developing a more universally applicable framework for DRA (Bracale et al., 2025).

Building on this foundation, DRA assessment should evolve from a purely structural classification toward a multidimensional system integrating “structure-function-symptom-psychosocial” domains. Current grading systems are primarily based on IRD width or myofascial deformation, with some classifications tailored to guide decisions between conservative and surgical treatment (Bracale et al., 2025). Future classification systems with greater clinical utility should incorporate multi-site IRD measurements, linea alba quality and elasticity, trunk and pelvic floor function, pain severity, body image concerns, quality of life, and the presence of hernia, thereby improving prediction of treatment response and prognosis (Du et al., 2025; Huang et al., 2025; Janiszewska et al., 2025). Additionally, these systems should be validated through Delphi consensus processes, prospective studies, and multicenter external validation to ensure reliability, reproducibility, and clinical applicability. The establishment of standardized assessment and classification systems is essential not only for improving research comparability but also for advancing randomized controlled trial design, network meta-analysis, and international guideline development.

7.2 Promoting individualized and precision-based rehabilitation strategies

With the advancement of precision medicine, rehabilitation for DRA should transition from experience-driven, uniform protocols toward data-driven, individualized intervention strategies. Existing research highlights significant heterogeneity among patients in terms of separation severity and pattern, parity, BMI, connective

tissue characteristics, pelvic floor function, baseline physical capacity, and symptom burden, resulting in variable responses to the same rehabilitation program. Moreover, emerging evidence suggests that pregnancy-related hormonal changes, extracellular matrix remodeling, and differences in mechanical loading may influence tissue healing capacity and responsiveness to treatment (Du et al., 2025; Huang et al., 2025). Future studies should therefore stratify patients based on these key factors and develop tailored rehabilitation protocols according to severity, functional impairment, and recovery stage, for example, emphasizing functional training and education in mild cases, while adopting multimodal strategies including electrical stimulation, taping, manual therapy, or surgical referral in moderate to severe or symptomatic cases (Bigdeli et al., 2025).

The advancement of precision rehabilitation also relies on innovative diagnostic and predictive technologies. AI-assisted ultrasound has demonstrated high agreement with expert measurements, enabling automated and efficient assessment of IRD and tissue characteristics. Additionally, intelligent rehabilitation systems integrating surface electromyography (EMG), inertial sensors, and real-time feedback offer the potential to monitor movement quality, identify neuromuscular activation patterns, and dynamically adjust training intensity and progression. Future research should explore adaptive training algorithms based on biomechanics, muscle fatigue, patient-reported outcomes, and adherence, while evaluating their cost-effectiveness, scalability, and long-term benefits in real-world clinical settings (Radhakrishnan et al., 2024; Huang et al., 2025). Longitudinal studies are also needed to determine whether precision-based rehabilitation can reduce surgical demand, improve long-term functional outcomes, and mitigate associated conditions such as low back pain and pelvic floor dysfunction. Developing dynamically adjustable, individualized intervention systems based on precise assessment will be a key direction for enhancing rehabilitation effectiveness.

7.3 Strengthening multidisciplinary collaboration and digital rehabilitation technologies

The etiology, assessment, and management of DRA involve multiple disciplines, including obstetrics, rehabilitation medicine, general and hernia surgery, imaging, biomedical engineering, and mental health. Therefore, multidisciplinary collaboration is a critical pathway for advancing both research and clinical practice. Recent consensus statements and reviews emphasize the importance of integrating expertise from obstetricians, physiotherapists, surgeons, radiologists, and other specialists to develop comprehensive diagnostic and treatment pathways (Du et al., 2025). Delphi consensus processes and national guidelines have begun to incorporate multidisciplinary perspectives, providing structured recommendations for screening, conservative management, surgical indications, and postoperative care (Bracale et al., 2025). Future research should further evaluate integrated care pathways, focusing on coordination between early screening, conservative rehabilitation, surgical referral, and postoperative recovery, while assessing outcomes related to patient benefit, healthcare utilization, and equity of access. Importantly, psychological support and patient education should be embedded within these pathways, as body image concerns and quality of life are central issues for many patients (Janiszewska et al., 2025; Zhu et al., 2025).

At the same time, digital rehabilitation technologies offer significant opportunities to expand access to multidisciplinary care and improve adherence. Emerging evidence from telerehabilitation studies suggests that delivering core stabilization and DRA-specific exercise programs through synchronous or asynchronous platforms is feasible, well-accepted, and effective in the short term, particularly for postpartum women facing barriers related to childcare, time, or geographic limitations (Skoura et al., 2025). Furthermore, wearable EMG and inertial measurement unit (IMU) sensors combined with machine learning or convolutional neural networks can accurately identify correct versus incorrect exercise execution, enabling automated feedback and quality monitoring in home-based training programs (Radhakrishnan et al., 2024). Future studies should explore hybrid care models that integrate in-person multidisciplinary assessment with digital exercise platforms, sensor-based feedback, AI-assisted ultrasound monitoring, and teleconsultation. High-quality randomized controlled trials with long-term follow-up are needed to compare these models with traditional face-to-face care in terms of effectiveness, safety, cost-efficiency, and patient experience. With the continued integration of multidisciplinary collaboration and digital technologies, DRA management is expected to evolve toward a precision-based, continuous, and patient-centered model of digital healthcare.

8 Conclusion

Postpartum diastasis recti abdominis (DRA) is a highly prevalent structural and functional condition that has evolved from being considered a cosmetic concern to a clinically significant functional disorder. Evidence indicates that its prevalence among postpartum women ranges from approximately 30% to 60%, with a proportion of cases persisting for years after childbirth. DRA not only compromises the structural integrity of the abdominal wall but is also associated with reduced core stability, lumbopelvic dysfunction, chronic pain, and pelvic floor disorders. Additionally, it may contribute to body image concerns and diminished quality of life. Therefore, DRA should be incorporated into both perinatal care and long-term women's health management, with appropriate conservative or surgical interventions selected based on severity.

A scientific and standardized assessment framework is fundamental to effective intervention. Currently, significant variability exists in measurement tools, anatomical landmarks, and diagnostic criteria, which limits comparability across studies and hinders clinical translation. Although ultrasound is widely regarded as a reliable method for assessing inter-recti distance (IRD), reliance on a single structural parameter is insufficient to capture overall functional status. Thus, a multidimensional assessment approach is needed, integrating IRD measurements with core function, pelvic floor status, pain, and quality-of-life outcomes, alongside dynamic monitoring throughout rehabilitation to better evaluate treatment efficacy and guide clinical decision-making.

Future research should advance toward standardized and precision-based assessment and intervention strategies within an evidence-based framework. The lack of unified diagnostic criteria and core outcome sets remains a major challenge, highlighting the need for internationally consensus-driven classification systems and structured rehabilitation pathways. While comprehensive rehabilitation programs, centered on exercise and supplemented with modalities such as electrical stimulation and taping, have demonstrated promising results, optimal protocols and long-term effectiveness require further validation. High-quality multicenter studies, combined with the integration of intelligent rehabilitation technologies and telemedicine, will be essential to promote individualized, digital, and multidisciplinary management approaches, ultimately improving functional recovery and quality of life in postpartum women.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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