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Review Article

Peritoneal Dialysis in the Modern Era: A Comprehensive Review of Clinical Practice, Evolving Challenges, and Technological Advancements

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ABSTRACT

Peritoneal dialysis (PD) is a recognized renal replacement therapy (RRT) for individuals with end-stage kidney disease (ESKD), leveraging the peritoneal membrane's ability to clear toxins and excess fluid efficiently. Since its clinical adoption in 1959, the percentage has increased from approximately 12% in the United States to 73.6% in Hong Kong. PD has undergone substantial developments, including refined catheter placement techniques and effective fluid ultrafiltration, thereby increasing its accessibility and enhancing patient quality of life. PD is particularly suitable for individuals with challenging vascular access or those who want home-based treatment options. However, its benefits must be weighed against contraindications, which include current infections and insufficient patient support, which must be carefully evaluated. Frequent complications include infections such as peritonitis, catheter-associated problems, fluid overload, and metabolic disturbances. This review presents a comprehensive examination of peritoneal anatomy and physiology, indications and contraindications for PD, associated difficulties, and new advancements in biocompatible PD solutions, wearable artificial kidneys, and infection prevention methodologies. Despite advancements in treatment choices, obstacles remain in patient selection, technique survival, and psychosocial support, contributing to PD's global underutilization (e.g., approximately 12% in the United States to 73.6% in Hong Kong). Future efforts must prioritize adopting biocompatible solutions, integrating AI and wearable technologies, and implementing personalized strategies to enhance technique survival and global accessibility.

Key words: Peritoneal dialysis, ESKD, biocompatible dialysis fluids, PD complications, wearable artificial kidney, infection prevention in PD, peritoneal membrane fibrosis

INTRODUCTION

Peritoneal dialysis (PD) is a treatment option for patients with end-stage kidney disease (ESKD) that uses the peritoneal membrane as a filter to remove waste products and excess fluids from the blood. It was first used in 1959 to manage ESKD. [1] The utilization of

PD differs globally, possibly due to the distinct characteristics of healthcare systems. [2, 3] Hong Kong's "PD-first" policy results in high utilization (approximately 73.6% as of 2021, per the Hong Kong Renal Registry 2021 Annual Report), with sustained high PD proportions attributable to policy support. [4] Recent global surveys, such as the ISN-Global Kidney Health Atlas 2023, indicate significant variability, with elevated rates in specific Asian and Latin American contexts influenced by policy and financial considerations, while access remains limited in numerous low-resource regions; post-COVID transitions towards home-based therapies and assisted PD models have additionally facilitated gradual increases in access in certain areas. [5]

Limited alternatives often lead to high utilization in settings like Mexico (61%). In nations with strong educational initiatives (Australia, New Zealand, and Canada), 20% to 30% of patients utilize PD. [2] These figures are drawn from the ISN Global Kidney Health Atlas 2023 [5] and national registry reports; where confidence intervals are not available from registry sources, ranges across reporting periods are noted to convey variability, for example, in the United Kingdom, PD use is consistently reported between 20% to 30% across multiple UKRR reporting cycles. Conversely, in the United States, the prevalence of PD among maintenance dialysis patients declined to 6.9% in 2009, subsequently rising to 10.1% in 2017 and reaching approximately 12.1% in prevalent patients by 2022, with incident starts on PD reaching an all-time high of 14.1% in 2023 and overall home dialysis (including PD) at 14.5% in prevalent ESKD patients by 2023, as reported in the United States Renal Data System (USRDS) 2025 Annual Data Report. [6] In the United Kingdom, between 20% and 30% of the ESKD population used PD, [7] but in Africa, the utilization of PD is lower.

The percentage of new patients starting on PD in the United States increased from 6.2% to 10.4% between 2009 and 2017, a trend largely attributed to the bundled payment system implemented in 2011. [6] Nonetheless, its overall utilization in the United States remains below the levels many nephrologists consider appropriate. [8] **Table 1** summarizes regional PD utilization rates alongside the key policy enablers and barriers that drive this global variability.

Despite these varying global adoption rates, the fundamental principles of the PD technique are consistent. The procedure involves instilling a sterile dialysis solution into the peritoneal cavity via an indwelling catheter. The peritoneal membrane acts as a semi-permeable filter, allowing for the diffusion of waste products and osmosis of excess fluid from the blood into the dialysate, which is subsequently drained and discarded. Over time, advances in medical techniques led to the development of percutaneous techniques [9] and laparoscopic methods for catheter placement. [10] Percutaneous placement involves inserting the catheter through a small incision in the anterior abdominal wall. This procedure makes catheter insertion less invasive and reduces the risk of infection. The advancements in PD catheter manufacturing, the method of its insertion, and new methods of infection prevention made PD a more accessible and effective option for people with ESKD. PD is especially suitable for patients with challenging vascular access or those preferring home-based therapy with greater flexibility and independence in daily activities. [11]

PD has several advantages, including superior patient mobility and independence, allowing individuals to maintain more daily activities. PD is generally simpler to perform, especially with continuous ambulatory peritoneal dialysis (CAPD), which does not require a machine. Moreover, PD helps maintain residual renal function (RRF). The mortality rate during the

Table 1: Regional PD utilization rates, policy enablers, and barriers (approximate, based on the latest available registry data).

Region/country	Estimated PD utilization (% of dialysis patients)	Data source/year	Key policy enablers	Key barriers
Hong Kong	~73.6%	HK Renal Registry 2021	PD-first policy; government funding	Aging population; high membrane transport rates
Mexico	~61%	ISN-GKHA 2023	Limited HD infrastructure; cost-driven adoption	Supply chain reliability; training capacity
Australia/ New Zealand	~20%–30%	ANZDATA 2022	Home dialysis incentives; strong training programs	Geographic remoteness; access inequity
Canada	~20%–25%	CORR 2022	Provincial home dialysis programs; assisted PD models	Regional variation; caregiver burden
United Kingdom	~20%–30%	UKRR 2022	NHS home dialysis targets; assisted PD programs	Workforce constraints; geographic equity
United States	~12.1% prevalent; 14.1% incident	USRDS 2025	ESKD treatment choices model; bundled payments	Physician bias; training gaps; insurance barriers
Sub-Saharan Africa	<5% in most countries	ISN-GKHA 2023	Cost-effectiveness relative to HD in select settings	Dialysate supply; trained personnel; infrastructure; cost
South/Southeast Asia (excl. HK)	Variable (5%–30%)	ISN-GKHA 2023	Growing home dialysis programs (India, Thailand)	Reimbursement gaps; training heterogeneity

PD, peritoneal dialysis; HD, hemodialysis; HK, Hong Kong; ISN-GKHA, ISN Global Kidney Health Atlas; ANZDATA, Australia and New Zealand Dialysis and Transplant Registry; CORR, Canadian Organ Replacement Register; UKRR, UK Renal Registry; USRDS, United States Renal Data System; ESKD, end-stage kidney disease.

first few years in PD patients is lower, [4] likely due to its gentler impact on the body and fewer complications in the early stages. Registry data and meta-analyses consistently demonstrate lower or equivalent mortality for PD compared to HD during the first 1 to 2 years of dialysis initiation, particularly among younger patients and those with preserved RRF; this early survival advantage attenuates or equalizes over time, with long-term outcomes dependent on comorbidity burden, modality-specific complications, and center experience. [4, 12] This early benefit is attributed to PD's gentler, continuous fluid removal and favorable effects on hemodynamic stability and RRF preservation. These features make PD more favorable than HD for many nephrologists and patients when indications and requirements are well met. [11, 12]

Despite these advantages, PD patients can be prone to fluid overload, which may complicate blood pressure control, though the continuous nature of PD can offer advantages for hemodynamic stability. Furthermore, PD offers a gentler and more continuous removal of excess fluid, which may reduce stress on the heart, especially for patients with heart disease or those needing more stable fluid management. In contrast, hemodialysis (HD) provides more rapid, intermittent fluid removal. PD's continuous nature offers superior hemodynamic stability for some, while HD's intermittent nature is better for others. Therefore, PD may be more suitable for certain patients who have uncontrolled fluid status or significant heart disease; however, the choice of treatment is highly individualized based on each patient's overall health, lifestyle, and preferences. The main advantages and disadvantages of PD and HD are presented in **Table 2**.

PD improves the quality of life for people with ESKD, but major issues still affect outcomes for this population. This comprehensive review will investigate the physiology of the peritoneal membrane, the physiology of PD, indications, contraindications, complications, advantages, and disadvantages of PD, optimal patient selection criteria, and thorough psychosocial assistance to improve adherence and quality of life. Additionally, this review will also examine new technologies like artificial intelligence-driven tailored dialysis management and wearable artificial kidneys (WAKs), which could revolutionize PD care. EMBASE, PubMed, Scopus, and Google Scholar were searched for newly published original and review articles by using different keywords and phrases, such as peritoneal membrane physiology, peritonitis, PD, PD fluids, PD complications, and innovation in PD.

This comprehensive review provides contemporary knowledge on PD, addressing its physiological foundation, clinical indications and contraindications, complications and management strategies, global usage trends, and recent advancements in biocompatible solutions, infection prevention, wearable technologies, and AI integration. The aim is to elucidate evolving practices, ongoing challenges, and future directions to enhance technique survival and accessibility for patients with ESKD.

METHODS

This review was performed as a narrative analysis of the existing literature on PD. A comprehensive literature search was conducted across four principal databases: PubMed, EMBASE, Scopus, and Google Scholar. Search terms encompassed: "peritoneal dialysis," "PD complications," "peritonitis," "biocompatible PD fluids," "peritoneal membrane fibrosis," "wearable artificial kidney," "infection prevention in PD," "AI in peritoneal dialysis," "PD utilization," and "ESKD renal replacement therapy." Key publication reference lists were meticulously examined to identify pivotal and emerging works. The inquiry was predominantly confined to English-language publications from 2010 to 2025 to guarantee clinical contemporaneity; however, seminal mechanistic studies predating 2010—especially those concerning peritoneal membrane biology, mesothelial cell physiology, epithelial-mesenchymal transition (EMT), and glucose degradation

Table 2: Comparative advantages and disadvantages of PD versus HD.

Aspect	PD details	HD details
Patient autonomy/ mobility	High; home-based, flexible scheduling allows daily activities and travel.	Lower; clinic-based sessions (3–4×/week, 3–5 hours each) restrict mobility.
Treatment location	Home or self-managed, no need for vascular access.	In-center or home (less common), requires a machine and trained staff.
Cost	Generally lower long-term (home-based, fewer staff needs); cost-effective in resource-limited settings.	Higher due to clinic visits, equipment, and staff; bundled payments may influence utilization.
Complications	Peritonitis, catheter issues, fluid overload, metabolic disturbances (e.g., hyperglycemia), and membrane fibrosis.	Vascular access infections/failure, hypotension, rapid fluid shifts, and cramps.
Survival outcomes/ mortality	Lower or equivalent mortality in the first 1 to 2 years, particularly in younger and lower-comorbidity patients (registry and meta-analytic data); survival advantage attenuates over time; preserves RRF.	Comparable long-term; higher early risks in some comorbidities.
Hemodynamic stability	Gentler, continuous removal; better for heart disease or unstable patients.	Rapid, intermittent; may cause stress, but effective for severe fluid overload.
Quality of life	Improved independence and flexibility; potential for better psychosocial outcomes with support.	Structured but can lead to fatigue from travel/ sessions; varies by patient.
RRF preservation	Better maintained, supporting overall outcomes.	Declines faster due to its intermittent nature.

PD, peritoneal dialysis; HD, hemodialysis; RRF, residual renal function.

product (GDP) biochemistry—were judiciously included when they substantiate current clinical comprehension. Sources were categorized as primary research studies, registry/database reports (e.g., USRDS, ISN Global Kidney Health Atlas), systematic reviews and meta-analyses, clinical practice recommendations (e.g., ISPD 2022, ISPD Catheter-Related Infection 2023), and expert consensus or narrative reviews. Articles were selected based on relevance, clinical significance, and methodological quality, according to the author's judgment. Formal systematic screening with PRISMA flow or meta-analysis was not performed; this review represents a clinically oriented synthesis rather than a systematic review. Where quantitative data are reported (e.g., utilization rates, peritonitis incidence), specific source years and registry editions are cited to maximize transparency.

PERITONEUM ANATOMY AND PHYSIOLOGICAL FUNCTION

The peritoneum is a thin, transparent, and serous membrane that lines the abdominal cavity and covers most of the abdominal organs. It has two layers: (A) visceral peritoneum: covers the external surfaces of the abdominal organs. (B) Parietal peritoneum (a thin membrane) that lines the internal surface of the abdominal and pelvic organ walls. Between these two layers is the peritoneal cavity, a potential space filled with a small amount of lubricating serous fluid, typically 50 to 100 mL in healthy adults. The mesentery is a fold of peritoneum that anchors the intestines to the abdominal wall and contains blood vessels, lymphatics, and nerves. The omenta are layers of the peritoneum that drape over the stomach and intestines (e.g., greater and lesser omenta). At the same time, the peritoneal ligaments connect organs to the abdominal wall or to each other (e.g., the falciform ligament).

Histologically, the peritoneum is a serous membrane consisting of two main layers with distinct histological features. (A) Mesothelium, which is the outermost layer. It comprises a single layer of simple squamous epithelial cells called mesothelial cells. The mesothelium layer functions as a serous fluid producer, which reduces friction between organs. This layer acts as a selective barrier for fluids and solutes and plays a significant role in immune responses and tissue repair by producing cytokines and growth factors. (B) Submesothelial connective tissue layer. It is located beneath the mesothelium, and this layer contains loose connective tissue, which contains collagen and elastic fibers for structural support. The submesothelium layer also contains arteries, veins, lymphatics, and nerve endings. In the submesothelial layer, immune cells, such as macrophages and mast cells, contribute to the defense mechanism functions of the peritoneum. The peritoneal macrophages in the peritoneum play a crucial role in clearing debris and preventing infection within the peritoneal cavity. This layer contains lymphatic stomata, small openings in the mesothelium, allowing fluid drainage into the lymphatic system. Unfortunately, during inflammation or injury, mesothelial cells can undergo EMT and subsequent fibrosis. The detailed molecular cascade—from GDPs to EMT to peritoneal fibrosis and encapsulating peritoneal sclerosis (EPS)—is described in the "PD Fluid Types, Advantages, and Disadvantages" section. The schematic peritoneal membrane structure and dialysis process are illustrated in **Figure 1**.

The main functions of the peritoneum include supporting and protecting the abdominal and pelvic organs, immunity, storage, lubrication, and transportation of nutrients and waste products. Its primary functions are: (A) Support and protection function: the peritoneum anchors organs and prevents their displacement while protecting them. (B) Lubrication: the serous fluid reduces friction, allowing smooth organ movement during digestion and respiration. (C) Immunity: the greater omentum contains immune cells and can "wall off" infections, isolating pathogens to prevent spread. (D) Storage: fat in the omentum provides energy reserves and insulation. (E) Transport: the peritoneum facilitates the passage of blood vessels, lymphatics, and nerves to the abdominal organs. The complex structure that comprises the peritoneum achieves these functions. Interestingly, because of the peritoneum's histological structure and physiological function, PD is used for nonrenal conditions with reasonable response, such as refractory heart failure, hyperthermia, hepatic failure, hyponatremia, fever, drug toxicity, some inherited enzyme deficiency diseases, pancreatitis, and dialysis-induced ascites. [13] The peritoneal space was utilized for giving chemotherapy, nutrition, and insulin.

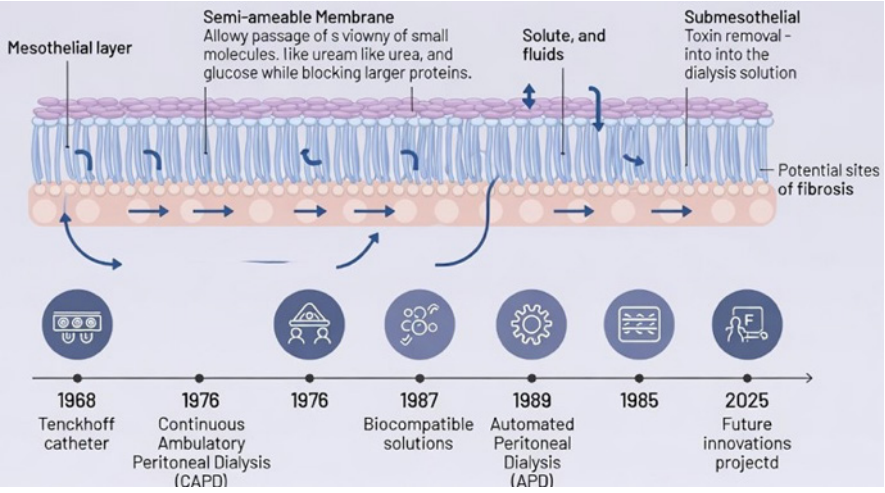

Figure 1: Schematic diagram of peritoneal membrane structure and dialysis process.

HISTORY OF PD

PD has had substantial advancements from its first experimental stages. The notion of using the peritoneum for dialysis originated from animal research in the 1920s, although its clinical implementation started in earnest after World War II. In 1959, PD was first effectively used in a human patient with ESKD for 6 months, signifying a crucial transition from intermittent therapies to an effective RRT. Nonetheless, earlier implementations encountered significant obstacles, including elevated infection rates (often surpassing 50% in preliminary studies) attributed to suboptimal catheter designs, insufficient infection control measures, and the absence of medicines specifically formulated for peritoneal application. These complications often led to peritonitis, procedural failure, and patient hesitance before the 1970s.

In 1962, 3 years later, the first automated cycling PD system was recorded, facilitating more uniform fluid transfers. By 1964, two patients treated with this apparatus had long-term survival of up to 2 years, illustrating PD's potential for chronic care. [14] In 1968, Henry Tenckhoff developed the silicone peritoneal catheter, which was implanted using open surgery. This invention reduced the need for recurrent punctures and enhanced dwell durations. In 1970, Tenckhoff documented the treatment of about 16 patients via self-administered PD for periods extending up to 4 years, therefore establishing PD as a viable home-based alternative. [15]

The 1970s saw significant progress in infection prevention, as enhanced sterilization techniques and antibiotic prophylaxis contributed to a reduction in peritonitis rates. PD achieved significant acclaim with the 1978 development of CAPD by Popovich and Moncrief, enabling patients to do manual exchanges throughout the day without apparatus, hence improving mobility and quality of life. [16, 17] This period has also seen improvements in catheter materials and connectors to reduce infections further.

The next decades concentrated on less invasive insertion methods. The introduction of percutaneous catheter implantation in the 1980s made the surgery less invasive, hence decreasing recovery duration and infection risks. [9] In the 1990s, laparoscopic techniques were introduced, providing accurate installation and reduced complication rates. [12, 14] The percutaneous placement, generally conducted under fluoroscopic or ultrasound guidance via the Seldinger technique, is linked to diminished procedure durations, lower anesthesia demands, and swift commencement of dialysis; success rates surpass 90% in proficient facilities, with malposition rates around 5% to 15% and early leak rates between 2% to 10%. [9, 12] Laparoscopic placement provides direct vision of catheter positioning, facilitates simultaneous adhesiolysis and omentectomy, and results in reduced catheter malfunction rates (malposition rates < 5% with competent practitioners), albeit requiring general anesthesia and extended operational duration. [10, 12] Surgical open placement is predominantly designated for individuals with a history of significant abdominal surgery or unsuccessful minimally invasive procedures. Patient selection among procedures must take into account body habitus, previous surgical history, urgency of dialysis commencement, local proficiency, and anesthetic danger. These advancements, together with biocompatible fluids and antibacterial coatings, resolved several initial problems and enhanced the worldwide accessibility of PD. The chronology of significant milestones in PD is summarized in **Table 3** and **Figure 2**. **Table 4** presents a comparative overview of PD catheter placement techniques.

PD MODALITIES: CONTINUOUS AMBULATORY AND AUTOMATED PD

PD is delivered via two principal modalities. CAPD involves the manual instillation of 2 to 2.5 L of dialysate into the peritoneal cavity, with dwell times of approximately 4 to 6 hours during the day and 8 to 10 hours overnight, resulting in 3 to 5 exchanges

Table 3: Timeline of key milestones in PD.

Year	Milestone	Key details and impact
1959	First successful clinical use in an ESKD patient	Treated for 6 months; established PD as a viable therapy, though plagued by high infection rates (>50% in early cases due to poor catheters and hygiene).
1962	First automated cycling PD machine	Enabled consistent exchanges and reduced manual labor, but initial models were bulky.
1964	Long-term survival demonstrated (up to 2 years)	Proved chronic viability; highlighted the need for better infection control.
1968	The Tenckhoff indwelling catheter was invented.	Silicone design for permanent access; reduced repeated punctures and early infections.
1970	Self-PD reported in 16 patients (up to 4 years)	Promoted home dialysis; shifted focus to patient training amid ongoing peritonitis risks.
1978	Introduction of CAPD	Manual, ambulatory exchanges; improved patient independence and addressed pre-1970s mobility/infection limitations.
1980s	Percutaneous catheter placement	Less invasive insertion; lowered surgical risks and recovery time.
1990s	Laparoscopic insertion techniques	Precise placement further reduces complications like malposition and infections.
2000s+	Biocompatible fluids and AI integration	Modern advancements focus on membrane preservation and personalized care to overcome historical challenges.

PD, peritoneal dialysis; ESKD, end-stage kidney disease; CAPD, continuous ambulatory peritoneal dialysis.

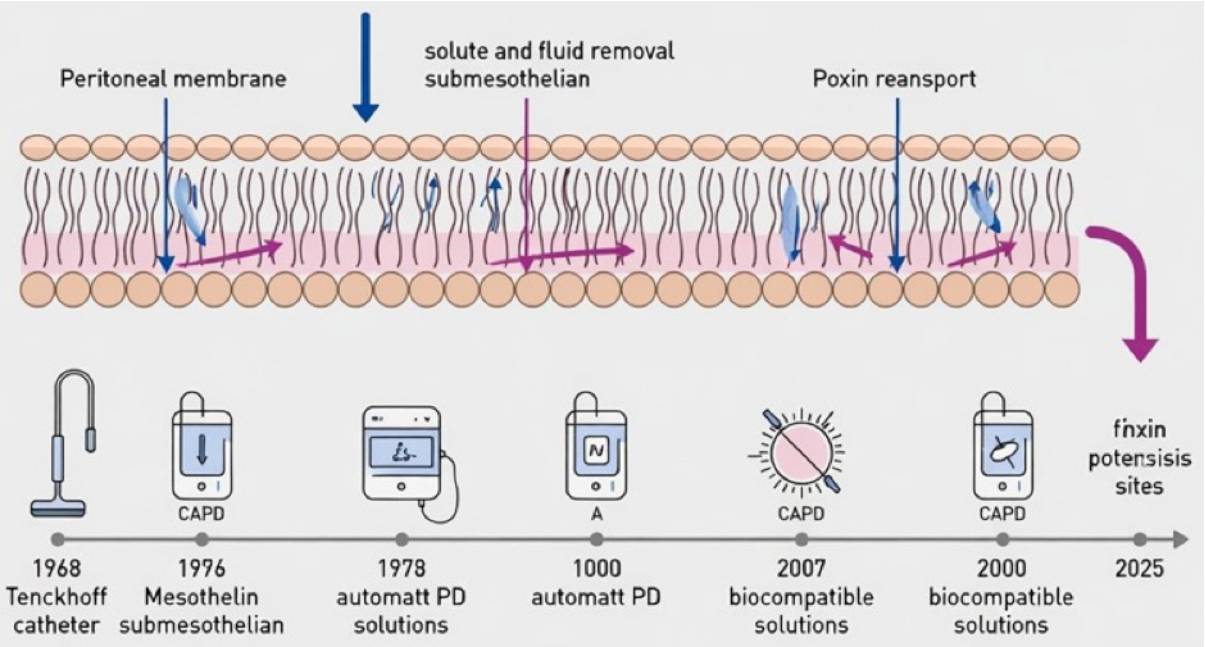

Figure 2: Timeline of key milestones in peritoneal dialysis (PD) history.

Table 4: Comparative overview of peritoneal dialysis catheter placement techniques.

Feature	Percutaneous (Seldinger/fluoroscopic)	Laparoscopic	Open surgical
Anesthesia	Local ± sedation	General	General/regional
Procedure time	Short (30–60 min)	Moderate (60–90 minutes)	Moderate–long
Malposition rate	5%–15%	<5% (with competent operator)	Variable
Early leak rate	2%–10%	<5%	2%–8%
Adhesiolysis possible	No	Yes	Yes
Omentectomy possible	No	Yes	Yes
Best for	Urgent start, low surgical risk	Prior surgery, high malposition risk	Failed prior placements, complex anatomy
Key references	[9]	[10, 12]	[12]

per day performed by the patient without a machine. CAPD is simple, requires no electricity or machinery, and is well-suited to motivated patients in resource-limited settings or those preferring maximum independence. Automated peritoneal dialysis (APD) uses a cycler machine to perform multiple exchanges overnight (typically 3–5 cycles of 2–3 L over 8–10 hours) while the patient sleeps, allowing daytime freedom. APD may incorporate a daytime dwell (continuous cycling PD [CCPD]) or be performed without one (intermittent/nocturnal APD). APD is preferred for patients with high peritoneal transport rates (who benefit from shorter dwell times to maximize ultrafiltration), patients struggling with daytime exchange schedules (e.g., working adults, school-age children), and those with poor manual dexterity who can be assisted by a caregiver with device setup. Choosing CAPD or APD must be guided by peritoneal membrane transport abilities that can be assessed by the peritoneal equilibration test, RRF, patient lifestyle, and local resource availability.

INDICATIONS OF PD

PD is a form of dialysis used to treat individuals with ESKD. The primary indications for initiating PD are fluid overload, uremic symptoms, transplantation failure, patient preference, difficult or absent vascular access, medical conditions, patient's lifestyle, infections, and intolerable HD complications. The decision to initiate PD should consider the patient's clinical condition, preferences, and any contraindications after a thorough evaluation of the risks and benefits of starting PD. **Table 5** summarizes the indications for initiating PD.

CONTRAINDICATIONS OF PD

PD is generally regarded as a safe and effective treatment option for patients with ESKD. However, certain clinical conditions require meticulous exclusion or consideration prior to the selection of this dialysis method. PD is absolutely contraindicated in any circumstances that carry severe patient risk or technical impossibility. The absolute contraindications include the loss of peritoneal membrane function, which can occur as a result of extensive intra-abdominal adhesions caused by previous significant surgeries or severe episodes of peritonitis. In these instances, the peritoneum's capacity to function as a dialysis membrane is significantly impaired. [18] Recent significant abdominal surgery, particularly with open or poorly healed wounds or leaks, is another absolute

Table 5: Indications of PD.

ESKD	GFR of <15 mL/min, and those who are symptomatic or at high risk for complications.
CKD	The progression to stage 5 CKD necessitates RRT.
Overload	Failure of conservative therapy for fluid overload.
Uremia features	nausea, vomiting, fatigue, or pruritus.
Preference	A patient wants more PD than HD due to lifestyle factors, ease of use, etc.
Vascular access	Difficult AV fistula creation or cannulation.
Lifestyle	Individuals with a good support system and who can manage PD at home are suitable candidates.
Clinical status	Consider the clinical status, comorbidities, abilities, and contraindications of other RRT methods.
HD complication	Patients who develop HD complications, such as hypotension, are good candidates for PD.

ESKD, end-stage kidney disease; CKD, chronic kidney disease; GFR, glomerular filtration rate; AV, arteriovenous fistula; PD, peritoneal dialysis; RRT, renal replacement therapy; HD, hemodialysis.

contraindication, as the introduction of dialysate could impede healing and increase the risk of infection. [18] This category also encompasses patients with active, untreated intra-abdominal infections, such as tuberculous peritonitis, as dialysis fluid may either exacerbate the infection or fail to clear it adequately. [19] Furthermore, severe respiratory compromise due to an increase in intra-abdominal pressure from the PD solution could jeopardize ventilation, causing discomfort, hypoxia, and poor compliance. [20] Additionally, dialysate leakage or intra-abdominal compartment syndromes are increased by significant abdominal wall or diaphragmatic defects that are irreparable, such as large, non-correctable hernias. [19]

Conversely, relative contraindications should initiate a thorough benefit-risk evaluation; however, they do not entirely exclude PD as a therapeutic option. Individuals who have abdominal wall stomas, such as colostomies or ileostomies, are at an elevated risk of infection or dialysate leakage. However, PD can frequently be performed with the implementation of specific precautions. [19] Obesity is acknowledged as a relative contraindication, as it can impede the passage of dialysate and the placement of catheters. Nevertheless, numerous obese individuals have successfully undergone PD. [18] The risk of peritonitis or technical complications can be elevated by conditions such as active inflammatory bowel disease or previous recurrent abdominal wall or inguinal hernias. However, hernias can frequently be surgically repaired before the initiation of PD, and inflammatory conditions can be managed before therapeutic intervention is initiated. [19] Also, individuals with severe cognitive or psychiatric disorders may experience difficulty preserving sterile technique; however, PD can occasionally be administered with the assistance of appropriate caregiver training or support. [21] With advances in surgical techniques—such as percutaneous insertion and advanced laparoscopic placement (including adhesiolysis)—some previously relative or borderline contraindications (e.g., prior abdominal surgeries causing adhesions) have become more manageable, expanding PD eligibility in select patients when performed by experienced teams.

Pregnancy is a clinically significant situation that requires particular attention. Although PD is not strictly prohibited in pregnant patients with ESKD, it presents certain obstacles that differentiate it from the non-pregnant demographic. As the pregnant uterus enlarges, intra-abdominal volume diminishes, requiring reduced dwell volumes—generally 1.0 to 1.5 L in the third trimester compared to the standard 2.0-L exchanges—to prevent excessive intra-abdominal pressure, respiratory distress, and dialysate leakage. Increased frequency of exchanges or a transition to APD with abbreviated cycles may be necessary to provide sufficient solute clearance at diminished fill volumes. Glucose absorption from dialysate may aggravate gestational glycemic dysregulation, necessitating enhanced monitoring. Moreover, attaining sufficient Kt/V objectives becomes increasingly challenging as pregnancy advances, necessitating the occasional addition of extra HD sessions. Outcomes data are restricted to case series and registry reports; nonetheless, PD has been effectively maintained throughout gestation in chosen individuals under rigorous multidisciplinary oversight, including nephrology and maternal-fetal medicine. Considering the increasing incidence of ESKD in women of reproductive age, doctors need to be acquainted with these adjustments instead of automatically opting for a modality change upon conception. Pregnancy should be seen as a relative contraindication for personalized therapy rather than an absolute contraindication. In brief, the common PD contraindications are listed in **Table 6**.

PD FLUID TYPES, ADVANTAGES, AND DISADVANTAGES

PD fluids are specially formulated solutions used to perform dialysis via the peritoneum in patients with chronic kidney disease. Over the years, several different types of fluids have been developed. Their composition, advantages, disadvantages, and associated complications significantly influence technique longevity and patient outcomes.

The most commonly used PD fluids are conventional glucose-based solutions. These contain electrolytes such as sodium, chloride, magnesium, and calcium. Dextrose, a form of glucose, is the main osmotic agent, drawing excess water and toxins from the blood across the peritoneal membrane. Buffers such as lactate, or less commonly bicarbonate, help maintain acid-base balance. [1, 9] However, traditional glucose fluids are associated with high glucose concentrations and acidic pH, often resulting in the generation of GDPs, including methylglyoxal, formaldehyde, and 3,4-dideoxy-glucosone-3-ene (3-DG), during heat sterilization. The elevated GDPs, in conjunction with persistently high local glucose levels, in vitro and biopsy evidence strongly suggest that GDPs contribute to peritoneal mesothelial cell injury by promoting EMT. While the mechanistic evidence from cell cultures and animal models is compelling, direct clinical evidence linking GDP exposure to hard outcomes (technique

Table 6: Contraindications of peritoneal dialysis.

Absolute contraindication
Loss of peritoneal membrane function due to extensive adhesions (e.g., repeated abdominal surgeries or severe peritonitis)
Recent major abdominal surgery, especially with open wounds or leaks
Active, untreated intra-abdominal infection (e.g., tuberculous peritonitis)
Severe respiratory compromise with risk from increased intra-abdominal pressure
Significant, non-repairable abdominal wall or diaphragmatic defects (e.g., large hernia leading to leakage)
Relative contraindication
Abdominal wall stoma (colostomy, ileostomy) increases the risk for infection or leakage.
Obesity, which may complicate catheter placement and dialysate flow
Active inflammatory bowel disease increases the risk of peritonitis.
Recurrent abdominal wall or inguinal hernia may require surgical repair before PD.
Severe cognitive or psychiatric disorders impair the ability to maintain sterile technique, but it is possible with adequate support.
Pregnancy requires reduced dwell volumes, intensified monitoring, and multidisciplinary co-management; not absolutely contraindicated, but it demands individualized adaptation.

survival, EPS incidence) in randomized trials remains indirect and debated. The proposed structural outcome of this prolonged biochemical damage is progressive submesothelial fibrosis, which elevates its solute transport rate (transitioning patients to high-transporter status), diminishes the osmotic gradient available for ultrafiltration, and ultimately results in ultrafiltration failure. This fibrotic process may culminate in EPS, characterized by a thick fibrous sheath around the colon, leading to blockage, significant malnutrition, and elevated death rates. This mechanistic sequence (GDPs → EMT → fibrosis → ultrafiltration failure → EPS) is hypothesized to underpin the development of low-GDP and bicarbonate-buffered biocompatible fluids, which mitigate mesothelial cell damage and diminish EMT-promoting cytokine production in vitro and in clinical biopsy investigations. [22, 23]

In response to these drawbacks, biocompatible or low-GDP fluids were developed. These solutions have neutral pH, reduced GDPs, and may use bicarbonate or lactate buffers. Clinical trials have demonstrated that biocompatible fluids better preserve residual kidney function and urine volume over time compared to conventional ones, with less inflammation and peritoneal membrane damage. [22, 23] Still, their effects on severe outcomes such as peritonitis, technique survival, and mortality require more robust studies, and higher costs have limited their widespread adoption.

Icodextrin-based fluids offer a starch-derived glucose polymer as the osmotic agent, providing effective and sustained ultrafiltration, particularly useful for long overnight stays in high-transport patients. They are reported to reduce episodes of uncontrolled fluid overload, but rare allergic reactions, metabolic complications, and cost concerns exist. [22, 23]

Amino acid-based PD fluids are used for selected patients with malnutrition. These PD fluids contain essential and non-essential amino acids as an osmotic component in place of glucose. However, the risk of metabolic acidosis and elevated blood urea occurs if they are not carefully monitored. [24] Emerging hybrid fluids integrate components such as icodextrin with low-GDP glucose formulations or glucose-sparing techniques to minimize total glucose exposure and GDPs while preserving osmotic effectiveness. These hybrids show potential in increasing metabolic profiles (e.g., reduced insulin resistance and improved lipid regulation), optimizing long-dwell ultrafiltration, and perhaps retaining peritoneal membrane function more efficiently than monotherapy treatments. Nonetheless, they remain experimental or restricted in accessibility, necessitating more research to validate long-term advantages regarding procedure longevity and patient results.

Custom solutions tailored to particular patient requirements, such as specific electrolyte or buffer adjustments, exist but are infrequently used and lack long-term outcome data. [23]

The constituents of PD fluids largely determine the complications they cause. The risk of infection is primarily related to the presence of an external catheter and connection procedures, rather than the specific composition of the dialysate fluid itself. [9, 12] As described above, the GDP-mediated EMT cascade induces progressive submesothelial fibrosis; however, biocompatible and low-GDP fluids diminish this risk by lowering the biochemical triggers for EMT, but they do not completely eradicate it, especially in patients with recurrent peritonitis or extended PD vintage. [22]

Metabolic complications are common with conventional glucose-based fluids, such as weight gain and hyperglycemia. Icodextrin reduces glucose load but can cause rare hypersensitivity or acidosis. Amino acid solutions may benefit nutritional status, but must be closely monitored for metabolic derangements. [22, 23]

Protein loss through the peritoneum is universal in all forms of PD. Amino acid-based solutions partly compensate for this, though they have disadvantages such as limited suitability and cost.

Other issues, like hernias or mechanical problems, stem from high intra-abdominal pressure, which is related more to dwell volumes and PD technique than the fluid type itself. [9, 25]

A commentary on environmental sustainability is necessary. PD fluids are contained in multi-layer polyvinyl chloride (PVC) or polyolefin bags, often in sizes of 2 to 5 L, and an individual undergoing CAPD produces roughly 300 to 400 kg of plastic trash each year. Manufacturing processes need significant energy and water, and the carbon footprint of PD supply

chains, especially in areas reliant on long-distance dialysate imports, is considerable. Comparative life-cycle evaluations indicate that while PD has a reduced carbon footprint per treatment session compared to in-center HD, mainly owing to the absence of travel and facility energy consumption, the plastic waste generated is much more. Innovative mitigation strategies encompass the creation of recyclable or biodegradable bag materials, localized dialysate production to reduce supply chain lengths, and the reclamation of spent dialysate via sorbent regeneration—a concept also pivotal to the advancement of WAKs, which will be addressed subsequently in this review. Regulatory mechanisms for sustainability reporting in dialysis are emerging but expanding, especially within the context of the European Union. Clinicians and healthcare organizations choosing PD methods should increasingly consider environmental effects in addition to therapeutic and economic factors. Considering the dynamic nature of this knowledge base, **Table 5** presents sustainability issues as a framework for awareness rather than a collection of definitive therapeutic recommendations.

In summary, conventional glucose-based PD fluids are accessible, cost-effective, and reliable but have chronic risks of membrane damage and metabolic side effects. Low-GDP/biocompatible solutions provide better preservation of peritoneal membrane function and reduce inflammation but entail higher cost and uncertain impact on long-term clinical outcomes. Among commercially available low-GDP biocompatible solutions, the most extensively researched are bicarbonate/lactate-buffered preparations (e.g., Balance®, BicaVera®) and neutral-pH single-chamber formulations. These solutions mitigate exposure to the three primary GDPs produced during heat sterilization: methylglyoxal, 3-DG, and formaldehyde. Clinical experiments, such as the EurobAlance and balANZ trials, have shown the maintenance of residual diuresis, a decrease in peritoneal inflammation indicators (e.g., CA125, IL-6), and an enhancement of mesothelial cell mass relative to traditional lactate-buffered acidic solutions. Nevertheless, neither trial showed statistically significant enhancements in technique survival or all-cause mortality, underscoring that improvements in surrogate endpoints may not correspond to definitive therapeutic benefits. Cost constitutes a substantial obstacle, as low-GDP treatments are priced 2 to 4 times higher than traditional fluids in numerous health systems, thus restricting access, especially in low- and middle-income nations. [22, 23, 26]

Icodextrin solutions offer advantages for fluid removal, especially in high transporters, but come with their own rare but significant risks. Amino acid solutions support nutrition yet pose metabolic challenges. Hybrid and sustainable approaches represent promising future directions to balance efficacy, patient safety, and environmental responsibility. Each type must be balanced for patient needs, risk profiles, and practical considerations. **Table 7** summarizes a comparison between dialysate fluid types, constituents, and complications.

The recyclable plastic waste figure (~103 kg/patient/year for standard CAPD) represents weighed dried fluid-contact materials only (approximately 21.4 kg PP + 81.4 kg PVC). Broader solid/medical waste, including outer packaging and disposables, is substantially higher. Ambulatory peritoneal dialysis generates a comparable or modestly higher recyclable plastic load depending on the cycler. [27]

COMPLICATIONS AND THEIR MANAGEMENT

Despite its efficacy as an RRT, PD is accompanied by a variety of complications that necessitate ongoing monitoring and management. Peritonitis is the most prevalent and significant complication, and it continues to be a primary cause of morbidity in patients with PD. Peritonitis is frequently associated with inadequate catheter exit site care, poor hand hygiene, or errors in technique and is characterized by fever, cloudy effluent, and abdominal pain. [28] Another contributing factor is the formation of biofilm on PD catheters, which enables microbial colonization and persistence. [28]

The incidence of peritonitis has markedly decreased over the years owing to advancements in catheter design, connecting methods (such as Y-set and twin-bag systems), biocompatible solutions, and preventive strategies. Data from the 1980s to 1990s indicate rates of 1.1 to 1.3 incidents per patient-year, highlighting initial difficulties in infection management. [29] In contrast, contemporary rates (2010s–2020s) have increased to 0.26 to 0.40 episodes per patient-year in nations such as the United States of America, Japan, and Canada, [30] with worldwide averages declining from 0.600 in 1992 to 0.303 in 2017. [31] Between 2009 and 2018, in the United States, the incidence rate among Medicare patients decreased from 0.581 to 0.307 incidents per patient-year. [32] Andalusia (Spain) had a reduction from 0.7 in 1999 to 0.33 in 2017. Recent quality improvement initiatives, including active retraining programs, exit-site prophylaxis (e.g., mupirocin/gentamicin), and adherence to ISPD 2022 targets (<0.40 episodes/patient-year), have further driven declines in many centers, with some reports achieving rates as low as 0.25 to 0.30 episodes/patient-year. [33–35]

Catheter-related infections, particularly those that occur at the exit site and conduit, are another common concern. Local redness, tenderness, and discharge at the catheter entry site are typically indicative of these infections. Suboptimal sanitation and inadequate catheter care protocols are among the risk factors that may facilitate the entry of pathogens into the peritoneal cavity and subcutaneous tissue. [36]

Prevention of peritonitis and catheter-related infections requires a multi-layered approach grounded in established guidelines. [35, 37] Daily topical application of mupirocin (for Staphylococcus aureus carriers and non-carriers) or gentamicin cream to the catheter exit site is recommended by ISPD 2022 and ISPD Catheter-Related Infection 2023 guidelines, as both have been shown to significantly reduce exit-site infections and PD-associated peritonitis rates. [35, 37] Furthermore, patients should be trained in strict hand hygiene (soap and water or alcohol-based sanitizer for ≥20 seconds before any catheter manipulation), mask use during exchanges, and dry catheter exit-site dressing with sterile gauze changed at least every 48 hours or when soiled. Y-set and twin-bag disconnect systems substantially reduce touch contamination compared to spike systems and are the standard of care in most contemporary PD programs. Moreover, patient training and retraining: Initial training should be comprehensive (minimum 5–7 days for CAPD; device-specific for APD), with mandatory retraining after

Table 7: Comparison of dialysate fluid types, constituents, and complications

Type of PD fluid	Constituents	Common complications	Advantages	Disadvantages
Glucose-based (standard)	Electrolytes, dextrose, lactate/bicarbonate buffer	Metabolic (hyperglycemia, weight gain), membrane injury	Cost, availability, efficacy	Risk of fibrosis, hyperglycemia, EPS, and high GDP exposure
Low-GDP/ biocompatible	Above but neutral pH, low GDP, bicarbonate/lactate	Higher cost	Membrane preservation, less inflammation	Expensive, uncertain long-term impact
Icodextrin-based	Icodextrin polymer, electrolytes, buffer	Rare allergies, acidosis	Effective ultrafiltration (esp. long dwells), less glucose	Cost, rare metabolic complications
Amino acid-based	Amino acids, electrolytes, buffer	Acidosis, high urea	Nutritional support	Cost, risk for metabolic complications
Hybrid/emerging (e.g., icodextrin + low-GDP)	Combinations of icodextrin/low-GDP glucose, tailored buffers	Limited data; potential rare reactions	Reduced glucose exposure, better metabolic/fluid control, membrane protection	Investigational/limited availability, higher cost, ongoing research needed
Sustainability considerations (all types)	Multi-layer PVC or polyolefin bags; energy- and water-intensive manufacturing and supply chains	High plastic burden with limited current recyclability	Lower per-session carbon footprint than in-center HD; potential for sorbent-based dialysate regeneration and regional manufacturing to reduce emissions	Substantial plastic waste (recyclable fraction ~103 kg/ patient/year for CAPD); environmental data largely absent from clinical trials

EPS, encapsulating peritoneal sclerosis; GDP, glucose degradation product; HD, hemodialysis; PD, peritoneal dialysis; PP, polypropylene; PVC, polyvinyl chloride; CAPD, continuous ambulatory peritoneal dialysis.

each episode of peritonitis, after any technique break, and at regular intervals (e.g., annually). Facilities implementing systematic retraining programs have achieved up to 50% reductions in peritonitis rates. [37] In addition to these measures to reduce the risk of peritonitis in this population, prophylactic antibiotics (e.g., a single dose of first-generation cephalosporin or vancomycin) are recommended before catheter insertion and invasive abdominal procedures (e.g., colonoscopy, dental procedures) in PD patients. [32] Oral antifungal prophylaxis (e.g., nystatin or fluconazole) should be administered whenever systemic antibiotics are prescribed in PD patients to prevent fungal peritonitis, a serious and often catheter-loss-associated complication. [35] Finally, the role of catheter biofilm in the prevention of recurrent and refractory infections, emerging strategies include antimicrobial catheter coatings (silver-impregnated, antimicrobial-releasing) and novel locking solutions. The biofilm's antimicrobial effect remains under investigation but represents important future directions. [38, 39]

Mechanical complications are also noteworthy. Hernias are relatively prevalent among patients with PD, particularly when significant volumes of dialysate are administered. [36] This is predominantly due to chronically elevated intra-abdominal pressure. Patients with pre-existing abdominal wall impairment are at an even greater risk.

Dialysate leakage is frequently the result of compromised peritoneal membrane or adjacent tissue integrity, which frequently occurs during the initial period following catheter placement or as a result of inadequate placement techniques. Local swelling and discomfort may be indicative of leakage, necessitating a transient reduction or cessation of dialysate volume. [28]

Poor dialysate drainage can lead to a reduction in the efficacy of PD. This may be the result of catheter obstruction from fibrin, omental wrapping, constipation, or mechanical issues, such as malposition. Inadequate drainage not only restricts ultrafiltration but also elevates the risk of infection as a result of residual, inert dialysate. [36]

Peritoneal membrane fibrosis is another long-term complication that results from protracted exposure to bioincompatible dialysis solutions. This condition is characterized by progressive thickening and scarring of the peritoneal membrane. In its most severe form, it manifests as EPS: a fibrous sheath encasing the bowel that leads to obstruction, severe malnutrition, and elevated mortality. The EPS is reported in 0.5% to 3.3% in patients on PD for >5 years, per registry data. [40] The predominant risk factors for EPS are the prolonged duration of PD and recurrent peritonitis episodes. [28]

Metabolic complications are not uncommon. Careful monitoring and glycemic control strategies are necessary to prevent hyperglycemia, which can develop in both diabetic and non-diabetic patients as a result of glucose absorption from dialysate solutions. In contrast, hypokalemia is a condition in which potassium is progressively lost during dialysis exchanges, particularly in the presence of a low dietary intake. This can result in muscle weakness and potential cardiac arrhythmias if not promptly corrected. [41]

Weight gain, which may be a consequence of the glucose burden from dialysate, and back pain, which is frequently the result of elevated intra-abdominal pressure due to a high dialysate volume, are additional complications that can impact patient comfort and nutritional status. Constipation is

also prevalent and significant due to its potential to obstruct catheter flow and elevate the risk of infection. Low fiber intake and specific medications are predisposing factors for constipation. [38]

The long-term quality of life for PD patients is ultimately enhanced by the regular follow-up, patient education, and early intervention that are essential for managing and minimizing these complications. [38] **Table 8** summarizes the complications, their descriptions, and contributing factors.

EFFECTS OF INNOVATIONS ON RATES (PRE/POST DATA)

Biocompatible Fluids

Pre-innovation (standard lactate fluids): about 1 incident every 33 patient-months; post-innovation (bicarbonate/lactate): 1 per 52.5 patient-months, indicating a considerable decrease. [42]

Retraining Programs

Facilities that implement active retraining have significantly reduced rates, with a 50% decrease compared to those without retraining initiatives. [33] Antifungal Prophylaxis and Quality Initiatives: In pediatric populations, rates decreased fivefold via continual quality improvement. [34] Extensive programs (developing experience) attain reduced rates, for instance, the US average of 0.24 incidents per patient-year. [34] Device Connectivity and Moisture Contamination Procedures: There is no elevation in rates with device use, even among at-risk patients; moist contamination algorithms mitigate the risk of associated peritonitis. [35] Target Rates: ISPD 2022 revised to <0.40 episodes per patient-year (down from <0.50 in 2016); [35] pediatric benchmarks: 0.32 to 0.40 [34]. Culture-negative frequencies should be below 15%. [34] These enhancements are associated with fewer method failures (e.g., peritonitis constitutes 10%–20% of PD discontinuation) [43] and improved outcomes (e.g., 86%–88% functional recovery after an episode). [34]

ALGORITHM FOR THE MANAGEMENT OF PERITONITIS

According to the ISPD 2022 adult guidelines (with 2024 pediatric harmonization for wider applicability; principles overlap, although pediatric dosages and training differ). [34, 35] The following is a textual flowchart (**Figure 3**) representation of the empirical and organism-specific management algorithm.

This algorithm emphasizes prompt empiric treatment, adjustment based on cultures (within 72 hours), and catheter removal for refractory cases (e.g., >5 days of unclear effluent). For pediatric-specific: Shorter training (<20 hours) increases rates; early onset is <5% with proper dressing protocols. [34]

Peritonitis

Peritonitis is a common and severe complication of PD, often caused by *Staphylococcus aureus or coagulase-negative Staphylococci*. [35] Management involves (A) Empirical antibiotic therapy: Intraperitoneal antibiotics covering Gram-positive and Gram-negative organisms, usually a combination of vancomycin or cefazolin with ceftazidime or an aminoglycoside. [35] Dialysis catheter removal: If presenting features do not improve within 48 to 72 hours, catheter removal should be conducted. [43] More important is prevention by proper catheter care and use of mupirocin or gentamicin at the exit site, diminishing the risk of peritonitis. [37] However, after starting these empirical therapies, antibiotics should be tailored according to the peritoneal fluid culture and sensitivity results.

Table 8: Complications, their descriptions, and contributing factors for PD.

Complication	Description	Contributing factors
Peritonitis	Abdominal pain, fever, and cloudy dialysate	Poor hand hygiene, inadequate exit-site care, and biofilm on the catheter
Catheter exit site infection	Redness, tenderness, and discharge at the catheter site	Inadequate hygiene and catheter maintenance
Hernias	Abdominal or groin protrusion (e.g., umbilical, inguinal, incisional)	Increased intra-abdominal pressure from high dialysate volumes
Dialysate leakage	Swelling/discomfort from fluid escape	Improper catheter placement, increased intra-abdominal pressure
Poor dialysate drainage	Incomplete drainage of dialysate increases infection risk	Catheter blockage, constipation, malposition
Peritoneal membrane fibrosis	Thickening/scarring of the peritoneal membrane	Long-term use of bioincompatible solutions
EPS	Severe fibrosis leading to bowel obstruction	Prolonged PD duration
Hyperglycemia	Elevated blood glucose	Glucose absorption from dialysate, especially in diabetes
Hypokalemia	Low potassium, muscle weakness, arrhythmia	Potassium loss during dialysis, low intake
Weight gain	Increase in body weight	Glucose-based dialysate caloric load
Back pain	Lower back discomfort	Increased intra-abdominal pressure
Constipation	Difficult/infrequent bowel movements affect dialysis	Low fiber intake, certain medications

PD, peritoneal dialysis; EPS, encapsulating peritoneal sclerosis.

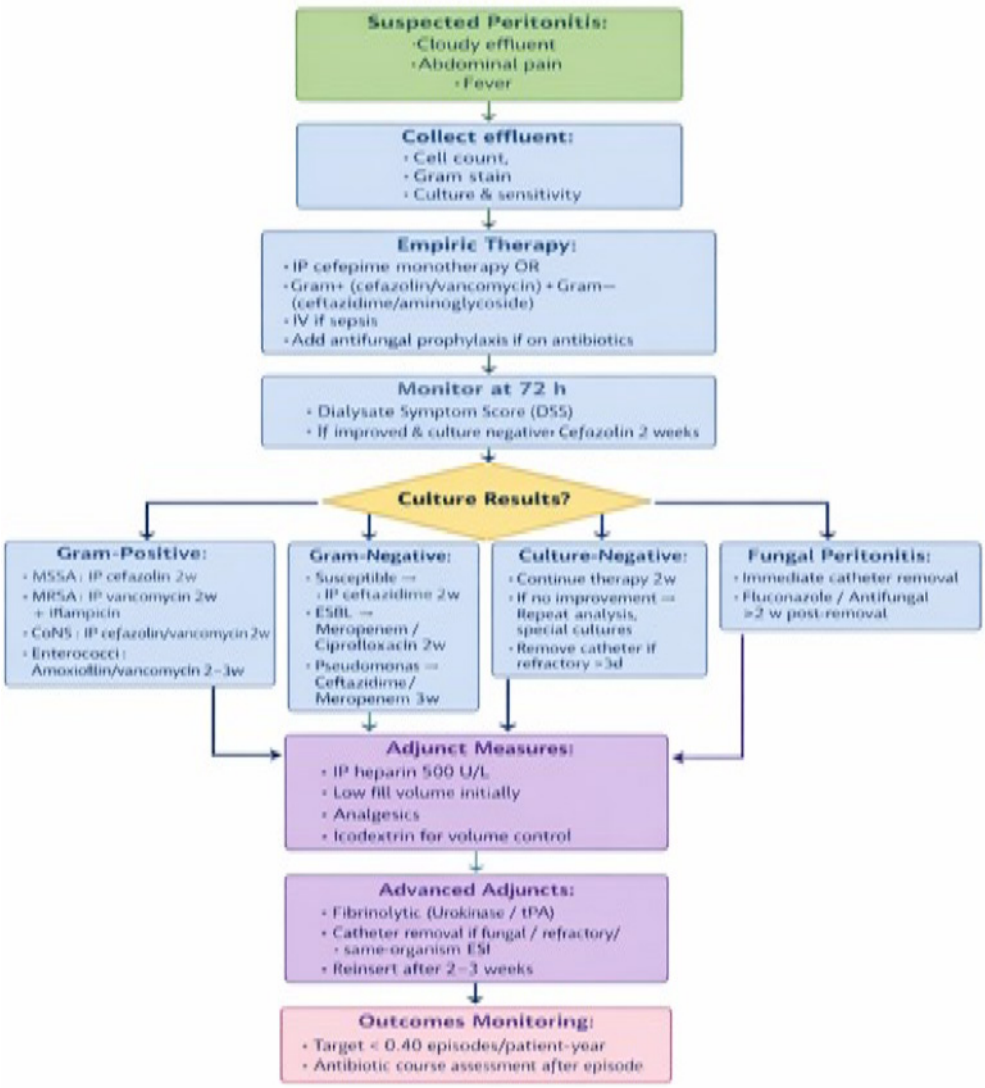

Figure 3: Algorithm for peritonitis management.

Exit-Site and Tunnel Infections

The most common organisms on this site are infections caused by *S. aureus and Pseudomonas aeruginosa*. Empirical oral and topical agents, such as fluoroquinolones for Pseudomonas infections 17 usually manage these site infections. Simultaneously, catheter removal and replacement have been proven effective for refractory infections. However, using another tunnel is advisable, particularly when tunnel abscesses occur. [44] PD complications require prompt recognition and targeted management to improve patient outcomes. Adherence to preventive measures, early intervention, and individualized treatment strategies is crucial in reducing morbidity associated with PD. [45]

Catheter Malfunction and Flow Obstruction

Catheter obstruction can be due to fibrin clots, constipation, or omental wrapping. The usual management strategies include fibrinolysis by Alteplase. [46] Laxatives and regular stool evacuation prevent catheter displacement. [16] In the failure of these conservative interventions, laparoscopic surgical repositioning may be required. [47]

Dialysate Leaks

Dialysate leaks can occur at the catheter exit site or between the pleura membranes, leading to hydrothorax. Management of the dialysate leak includes temporary PD cessation and switching to HD for 2 to 4 weeks to allow healing and leakage stoppage. [48] Surgical repair is required for a persistent dialysate leak, except when the conservative management mentioned above failed. [49]

Hyperglycemia and Dyslipidemia

PD solutions contain glucose, leading to insulin resistance, dyslipidemia, and hyperglycemia. [50, 51] Management of these abnormalities includes adjusting the glucose load in the dialysate. Using icodextrin-based solutions instead of dextrose-based ones positively impacts blood sugar dysregulation control. [35] Dietary and pharmacological management using statins and fibrates for lipid control and

insulin for glycemic management improves lipid and sugar control, respectively. [52]

Fluid Overload

Fluid overload results from insufficient ultrafiltration, which lowers the permeability of the peritoneal membrane due to fibrosis or recurrent infection. Treating and preventing the incapability of the peritoneal membrane can be helped by using diuretics in individuals with RRF and good urine output. [49] Extending the dwell time and adjusting the dialysate dilution strength are crucial treatment strategies for both preventing and managing fluid overload. [53]

GAPS IN PD: CHALLENGES AND FUTURE DIRECTIONS

Although PD is an effective treatment for ESKD, significant gaps remain in patient selection, technique longevity, infection management, technological advancement, and psychosocial support, which hinder its wider application and optimal results. Persistent challenges, particularly infections, are well-documented. Recent guidelines continue to emphasize ISPD-aligned practices for better outcomes, [54, 55] while studies on contamination algorithms show a reduced risk. [35] Future efforts should integrate AI for predicting [34] and expand biocompatible fluids, as per a review on innovations. [56]

Patient Selection and Utilization

PD is markedly undervalued relative to HD, despite data indicating equivalent or even higher outcomes for some ESKD individuals. [57] Several factors influence this underutilization, including physician prejudice, insufficient patient education, and restricted access to organized PD training programs. Numerous nephrologists misconstrue the contraindications for PD and exhibit hesitance in recommending it, whereas non-nephrologists frequently lack assurance in the management of PD-dependent ESKD individuals. The lack of established patient selection criteria and variability intensifies this problem, especially in old and frail groups. [57, 58]

In resource-constrained environments, the cost-effectiveness of PD is recognized; however, access is impeded by the elevated costs of PD fluids and consumables, a scarcity of trained personnel, and insufficient infrastructure, making PD unaffordable or inaccessible for many ESKD patients lacking governmental or insurance assistance. [58] Moreover, diminished dexterity, cognitive deterioration, and frailty lead to increased failure rates, underscoring the necessity for validated, objective screening instruments to standardize patient selection. [57, 58]

Peritoneum Membrane Failure and Dialysate Types

Long-term PD therapy is impeded by the deterioration of the peritoneal membrane, primarily due to chronic exposure to glucose-based dialysates, which provoke inflammation, fibrosis, and a decline in ultrafiltration capacity, ultimately leading to membrane failure. [59] Despite the development of low-GDP biocompatible fluids—which, as detailed in the "PD Fluid Types, Advantages, and Disadvantages" section, attenuate GDP-mediated EMT and reduce peritoneal inflammation—their implementation stays constrained by economic and logistical factors (discussed in the "PD Fluid Types, Advantages, and Disadvantages" section and **Table 9**).

The preservation of RRF is a vital determinant of patient survival; nonetheless, existing strategies to sustain RRF—such as the avoidance of nephrotoxic drugs, optimization of volume status, and the use of pharmacological agents like angiotensin-converting enzyme inhibitors (ACEis) and angiotensin receptor blockers (ARBs)—are applied inconsistently and frequently inadequate. [60] Novel treatment strategies aimed at mitigating peritoneal inflammation and fibrosis exhibit potential but necessitate additional clinical validation. [59, 60]

Infection Control and Catheter-Related Complications

Infections, especially peritonitis and exit-site infections, remain the predominant cause of PD method failure globally. [35] Nevertheless, despite the widespread use of mupirocin and gentamicin for exit-site prophylaxis (as discussed in the "Complications and Their Management" section), persistent infections continue—chiefly due to biofilm formation on catheter surfaces, which renders embedded organisms impervious to systemic and topical antibiotics, rather than due to deficiencies in prophylactic coverage itself. Current infection prevention techniques are typically uniform, overlooking patient-specific risk factors such as diabetes, obesity, or immunosuppression. [61] Innovative methods, such as probiotic therapy and immunological modulation, have been investigated but remain unincorporated into standard clinical practice. [61] Innovative antimicrobial catheter coatings, such as silver-impregnated and antimicrobial-releasing devices, exhibit potential to diminish infection rates; nonetheless, their elevated cost and restricted availability hinder extensive adoption. [37]

Technological Advancements and Innovation

The use of technology in PD care is lagging behind the improvements available. APD with remote patient monitoring has shown potential to decrease complications; nevertheless, its adoption is not widespread due to elevated costs and a lack of technical proficiency. AI-driven predictive analytics have the capacity to enhance dialysis prescriptions and tailor patient treatment; nonetheless, these technologies have not yet been fully integrated into clinical practice. [62] A personalized PD prescription may be guided by peritoneal membrane transport characteristics (classified as low, low-average, high-average, or high transporter by the peritoneal equilibration test), RRF trajectory (measured by 24-hour urine collections at regular intervals), and patient-specific metabolic profiles (e.g., glucose intolerance guiding icodextrin use and nutritional status guiding amino acid solution frequency). Integrating longitudinal clinical data with machine learning (ML) models—incorporating membrane transport, RRF, comorbidities, and prior complication history—represents the most clinically actionable near-term application of AI for PD prescription optimization. [62, 63]

The advancement of WAKs offers the potential for continuous low-volume dialysis while improving patient mobility. The fundamental technological basis for most WAK designs for PD, including the AWAK-PD system, which has received FDA Breakthrough Device Designation, is sorbent-based dialysate regeneration. This method involves retaining wasted peritoneal dialysate after each dwell, which is then processed via a compact sorbent cartridge including activated carbon, urease, zirconium phosphate, and ion-exchange resins. These layers systematically eliminate urea (transformed

into ammonia by urease and subsequently captured), creatinine, phosphate, and other uremic solutes, thereby rejuvenating the dialysate for reutilization in succeeding exchanges. This closed-loop regeneration significantly diminishes the quantity of fresh dialysate needed—from the 8 to 10 L used in traditional daily CAPD to around 1 to 2 L—facilitating the downsizing essential for a wearable device. Preclinical and early clinical trials (including human safety data from previous trials, the continuous advancement of sorbent-based regeneration, and new FDA breakthrough designations for AWAK-PD and associated AI technologies) show promise for enhanced ultrafiltration and portability, but significant obstacles, including fluid regeneration processes, biocompatibility, power supply, and infection risks, persist and require resolution, [64] with pivotal trials and further human studies actively progressing, though full regulatory approval and widespread clinical adoption remain years away.

From a regulatory standpoint, the AWAK-PD system has received FDA Breakthrough Device Designation, which expedites review but does not constitute approval. Full regulatory clearance and commercial availability are expected to be years away, pending completion of pivotal clinical trials. Clinicians and patients should interpret early feasibility data cautiously, as device iteration, manufacturing scale-up, and post-market surveillance infrastructure are prerequisites for broad clinical adoption. [54, 64]

Psychosocial and Patient-Centered Care

Quality of life and adherence to PD protocol are frequently adversely affected by the substantial psychosocial burdens that long-term PD-dependent individuals experience, such as anxiety, depression, and caregiver fatigue. [64] Globally, there is a notable lack of standardized, customized PD training programs, resulting in a wide range of outcomes and technique survival. Psychosocial interventions and telehealth-based training programs have the potential to improve the PD-dependent individuals' confidence, self-care skills, and technique adherence; however, they will require additional development and evaluation in well-structured prospective studies. [64]

In summary, PD encounters multifaceted challenges, including underutilization associated with insufficient patient selection and training, procedural failures primarily due to peritoneal membrane damage and infections, sluggish adoption of emerging technologies, and psychosocial factors that hinder long-term efficacy. Addressing these deficiencies requires the following actions. (A) Formulation and execution of standardized, evidence-informed patient selection and educational processes. [57, 58] (B) Biocompatible dialysis solutions and established procedures for preserving RRF have been widely used. (C) Tailored infection prevention strategies, encompassing the availability of antibiotic and probiotic treatments. [35, 37, 61] (D) Investment in technology-based solutions includes AI, wearable dialysis equipment, and remote patient monitoring, in conjunction with initiatives to address economic and technical obstacles. [26, 62, 64] (E) The implementation of tailored psychosocial support and telehealth educational initiatives seeks to improve patient compliance and elevate their quality of life. [64]

The "Conclusions" elaborate on future research goals, including cost-effective biocompatible fluid creation, scalable remote monitoring, portable dialysis technology, and AI integration, as well as the trial infrastructure required for their validation. Moreover, enhancing PD accessibility in marginalized and resource-limited areas through policy reforms and infrastructure enhancements will be essential to improving worldwide outcomes in ESKD management. **Table 9** summarizes the key gaps, implications, strategies, and future direction. challenges, gaps, implications, and strategies**.**

ADVANCES IN PD DIALYSATE

The standard biocompatible dialysate in PD predominantly depends on glucose-based solutions. Their prolonged usage, while successful, is linked to peritoneal membrane damage, angiogenesis, and fibrosis. The GDP-mediated EMT and downstream fibrotic pathways are detailed in the "PD Fluid Types, Advantages, and Disadvantages" section (see also the mechanistic summary in Figure 1 and the discussion of "Biocompatible Fluids"). This presents a paradox: although glucose-based fluids facilitate osmotic ultrafiltration, they concurrently induce peritoneal membrane cellular damage and fibrosis, potentially hastening method failure. This presents a paradox: although glucose-based fluids facilitate osmotic ultrafiltration, they concurrently induce peritoneal membrane cellular damage and fibrosis, potentially hastening method failure.

Innovative treatments, including low-GDP fluids, have demonstrated potential in mitigating inflammation and fibrosis, consequently extending the integrity of the peritoneal membrane and the longevity of the PD procedure. [65] Amino acid–based solutions and icodextrin serve as alternatives by diminishing the total glucose load, potentially enhancing metabolic profiles and patient outcomes. [66]

Nonetheless, debates persist. The clinical benefits of low-GDP fluids for hard outcomes (technique survival, mortality) remain uncertain, as detailed in the "PD Fluid Types, Advantages, and Disadvantages" section and **Table 9**. Moreover, icodextrin, although efficacious for ultrafiltration in high transporters, has been associated with infrequent yet serious metabolic consequences, including hypersensitivity reactions and metabolic acidosis in susceptible patients.

Personalized therapy is gaining attention, with electrolyte-adjusted, pH-optimized, and patient-tailored buffer formulations being explored. [66] Nevertheless, some critics caution that such customization might complicate logistics and increase healthcare costs without clear evidence of improved long-term technique survival.

The integration of AI and predictive analytics for dialysis fluid prescription, particularly in diabetic ESKD, has generated optimism. [63] Still, skepticism persists regarding the actual readiness of AI systems, as most algorithms remain in prototype stages and lack large-scale validation. Rigorous multicenter trials are needed to confirm their clinical utility. [67]

Strengthen head-to-head trials between conventional versus novel PD fluids to clarify clinical benefit beyond surrogate outcomes. Foster cost-benefit analyses in real-world settings

Table 9: Outlines the key challenges, gaps, implications, and strategies for addressing peritoneal dialysis and future perspectives.

Category	Key challenges/gaps	Implications	Strategies/future directions
Patient selection and utilization	Underutilization due to physician bias, limited patient education, insufficient training, lack of standard criteria, high costs, and limited access	Poor uptake despite favorable outcomes; high failure rates in frail, elderly patients	Develop standardized selection guidelines, increase training and education, and improve access in resource-limited settings.
Membrane failure and dialysate types	Glucose-based dialysis causes inflammation and fibrosis, limited implementation of low-glucose degradation product fluids, and inconsistent residual renal function preservation strategies.	Progressive loss of ultrafiltration; increased technique failure	Promote biocompatible fluids and validated preservation protocols, including drug avoidance and pharmacologic agents.
Infection control and catheter complications	Persistent infections despite prophylaxis, biofilm-mediated antibiotic resistance, and lack of personalized strategies	Infection remains the main cause of technique loss.	Develop risk-stratified protocols based on patient microbiome and immune status.
Technological advancement	Slow adoption of automated peritoneal dialysis and AI; high cost; lack of expertise; challenges in wearable artificial kidney technology	Missed opportunities to improve technique survival and patient quality of life	Invest in technology development, address cost and regulatory barriers, and expand remote patient monitoring and artificial intelligence use.
Psychosocial and patient-centered care	High psychosocial burden; lack of tailored education programs; variable technique adherence	Reduced quality of life and adherence	Implement tailored psychosocial interventions and telehealth educational programs.

to determine the feasibility of personalized PD solutions. Establish regulatory frameworks to safely and transparently integrate AI into PD decision-making.

In summary, the primary unsolved inquiry about new PD fluids is whether enhancements in surrogates—diminished GDP exposure, maintained mesothelial shape, and prolonged RRF—result in significant variations in overall survival, cardiovascular outcomes, and death rates. Addressing this necessitates the robust trial infrastructure outlined in the "Conclusions".

INNOVATIONS IN PD TECHNIQUES AND TECHNOLOGY

WAKs are being developed to offer continuous, low-volume dialysis, thereby enhancing patient autonomy and quality of life. [54] Preclinical trials indicate enhanced mobility; nonetheless, issues regarding patient safety, such as the risk of infection from wearing catheters and potential device malfunctions, remain unsolved. Certain skeptics contend that the technology remains several years away from practical clinical implementation.

Remote monitoring and telemedicine systems included in APD improve compliance, facilitate early identification of problems, and enhance communication between patients and providers. [55] Patient data security and equitable access remain controversial, particularly in low-resource environments with inadequately established telehealth infrastructure.

Hybrid and incremental PD strategies, where PD is integrated with either home hemodialysis (HHD) or commenced at reduced intensity, have been documented to enhance flexibility, maintain RRF, and improve patient adaptability. [68] However, the evidence is inconclusive about whether incremental PD results in enhanced long-term patient survival compared to routine PD beginning. [68] However, the evidence is inconclusive about whether incremental PD results in enhanced long-term patient survival compared to routine PD beginning. [68] Given the growing evidence base and the International Society for Peritoneal Dialysis (ISPD)'s increasing attention to incremental starts, a more substantive treatment is warranted. Incremental PD (typically defined as <7 exchanges per week or <4–5 nights of APD per week, with stepup as residual kidney function declines) has been associated with preserved RRF, lower peritoneal glucose exposure, and reduced patient burden in observational studies. [69] These challenges can be mitigated by supporting international registries that oversee WAK pilot trials to guarantee transparency and patient safety, promoting telehealth equity initiatives to ensure that rural and low-income areas receive equal access to digital PD monitoring, and conducting randomized studies to validate incremental PD strategies for long-term outcomes.

STRATEGIES FOR INFECTION PREVENTION AND PERITONEAL MEMBRANE PROTECTION

Infection prevention remains a cornerstone of PD success. Antimicrobial catheter coatings, including silver-impregnated and antimicrobial-releasing catheters, have demonstrated reduced bacterial colonization and infection rates. [39] Nevertheless, concerns remain about the potential development of resistant microbial strains and cost implications.

Alternative strategies, such as gut microbiota modulation with probiotics and immunomodulators, are being investigated for enhancing host immunity and reducing infectious complications. [61] However, findings are inconsistent, and some studies argue that potential dysbiosis and unintended systemic effects must be carefully monitored.

Emerging anti-fibrotic agents targeting TGF-β and inflammatory cascades show potential in slowing peritoneal membrane deterioration. [70] Similarly, mesenchymal stem cell (MSC) therapies have demonstrated experimental success in regenerating damaged mesothelium and limiting fibrosis. [71] However, significant skepticism exists regarding their translation into routine clinical practice, given cost, scalability, ethical considerations, and the possibility of uncontrolled cellular activity. [72]

To reduce the risk of infection and even prevent it, the implementation of post-marketing surveillance for antimicrobial catheter technology is necessary to monitor resistance patterns. Moreover, standardized criteria for probiotic interventions in PD should be implemented to avoid unregulated supplement use.

ARTIFICIAL INTELLIGENCE IN PD

AI is progressively revolutionizing PD through improved predictive accuracy, enabling healthcare professionals to foresee and manage complications, including technique failure, infections, and mortality. AI and ML models demonstrate enhanced efficacy compared to traditional methods in forecasting significant outcomes, such as fluid overload, cardiovascular events, and patient classification based on peritoneal membrane transport. For example, random forest algorithms have been applied to predict technique failure in PD-associated peritonitis, outperforming conventional statistical approaches, [73] while explainable ML models have demonstrated predictive accuracy for cardiovascular events in PD patients [74] collectively illustrating the expanding scope of AI-driven risk stratification in this population.

Artificial neural networks (ANNs) and deep learning models are capable of processing extensive clinical datasets to predict risks and tailor PD regimens more efficiently than conventional statistical methods. [62, 75] AI-driven management systems, typically incorporated into telehealth platforms or mobile applications, facilitate real-time monitoring, enhance patient adherence to treatment, and improve quality of life. Recent studies demonstrate that these systems can improve blood pressure regulation, anemia management, nutritional status, and patient engagement by providing timely feedback and intervention, particularly in home-based PD. [76] Additionally, chatbots and decision-support systems enhance self-care and education, thereby decreasing the likelihood of complications by assisting patients in daily management and early complication detection. [56]

However, results are promising; challenges remain, such as the necessity for larger, multicenter studies and external validation to establish the reliability and generalizability of AI models. Ongoing research and technological integration are anticipated to reinforce AI's role in personalized PD, with the ultimate goal of enhancing clinical outcomes and patient safety. [56, 62, 75] In summary, while promising, the integration of AI into routine PD care requires overcoming hurdles related to data privacy, model interpretability, and demonstrating improved hard clinical outcomes in large-scale trials.

Patient data privacy is a particular concern in AI-driven PD management, as algorithms depend on continuous transmission of sensitive health data from home monitoring devices to cloud platforms. Regulatory frameworks such as GDPR (Europe) and HIPAA (USA) provide baseline protections, but their implementation in real-world PD telehealth systems is inconsistent. Equity of access is a further issue: AI-enabled monitoring platforms require reliable internet connectivity, digital literacy, and compatible devices, placing rural, elderly, and low-income patients at risk of exclusion from these advances. Responsible implementation requires prospective equity assessments alongside efficacy trials. [67]

LIMITATIONS

This review offers a comprehensive synthesis of current knowledge and advancements in PD; however, we must address several limitations. Although we have tried our best to cite the most newly published data and articles, bias in selection can be and must be addressed in this type of article. The evaluation predominantly depends on previously published material, which may not encompass the latest advancements in technology and biocompatible dialysis treatments. Moreover, the emphasis on literature from 2010 to 2025, although suitable for clinical and epidemiological data, may inadequately represent essential mechanistic studies concerning peritoneal membrane biology, mesothelial cell physiology, and the biochemistry of GDPs predominantly conducted between the 1980s and early 2000s. Numerous mechanistic assertions in this review—especially those concerning EMT, GDP-mediated injury, and the justification for biocompatible fluids—are based on prior experimental literature. Future comprehensive reviews should explicitly incorporate foundational pre-2010 studies with current clinical evidence. The extensive range from foundational physiology to novel therapeutics means that certain topics have not received deep coverage. Due to the scarcity of data from some nations, the analysis inadequately examines regional inequalities in healthcare infrastructure, patient selection criteria, or practice patterns, hence constraining the generalizability of many suggestions, especially for underprivileged groups. The lack of original patient-level data and thorough meta-analyses renders the conclusions reliant on secondary sources, which may be susceptible to publication bias. Future research should prioritize diverse, multicenter trials, particularly in low-resource and underrepresented settings, to address regional disparities, improve generalizability, and validate emerging interventions in varied populations. Ultimately, while we mention potential developments, many require additional clinical confirmation before we can firmly endorse their routine clinical implementation. Several referenced works include anticipatory or 2025 publications that correspond to the review's preparation timeline (noting that the current date is early 2026 and data sources encompass 2025 publications); emerging domains such as AI readiness, incremental professional development strategies, and wearable technologies are accurately characterized as

promising yet necessitating further validation. A heightened focus on the necessity for extensive, multicenter randomized controlled trials (RCTs) in varied populations, encompassing underrepresented and resource-constrained environments, would bolster future recommendations and improve the generalizability of suggested advances.

CONCLUSIONS

PD remains a vital and evolving RRT, offering significant benefits such as patient autonomy, preservation of RRF, and suitability for home-based care. However, its full potential is hampered by persistent challenges, including infectious complications, peritoneal membrane degradation, and technique failure.

Recent innovations in biocompatible dialysis solutions, antimicrobial catheter technology, and artificial intelligence hold promises for improving clinical outcomes and patient experience. Furthermore, pioneering developments like WAKs and personalized dialysis prescriptions signal a transformative future for PD care. To fully realize these advancements, a concerted effort is required to bridge existing gaps. The path forward must prioritize three key actions: standardizing patient selection, investing in biocompatible solutions and technology, and providing robust psychosocial support.

Ultimately, by integrating these strategies with rigorous clinical research and policies that enhance global accessibility, we can significantly improve technique survival, patient quality of life, and long-term outcomes for individuals with ESKD worldwide.

RECOMMENDATION FOR CLINICIANS, POLICYMAKERS, AND RESEARCHERS

Based on this review, the following actionable recommendations are proposed and summarized in **Table 10**.

AUTHORS' CONTRIBUTION

All authors have significantly contributed to the work, whether by conducting literature searches, drafting, revising, or critically reviewing the article. They have given their final approval of the version to be published, have agreed with the journal to which the article has been submitted, and agree to be accountable for all aspects of the work.

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CONFLICT OF INTEREST

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Table 10: Actionable recommendations for clinicians, researchers, and policymakers to improve PD access and outcomes.

For clinicians	For researchers	For policymakers
1. Apply standardized patient selection criteria incorporating peritoneal membrane transport assessment, functional status, social support evaluation, and comorbidity profiling to guide modality selection.	1. Prioritize multicenter randomized controlled trials comparing conventional and biocompatible PD solutions, using hard clinical outcomes (technique survival, cardiovascular events, mortality) as primary endpoints.	1. Design reimbursement structures that incentivize home-based therapies, including PD and home hemodialysis, to reduce financial barriers to uptake.
2. Adopt evidence-based infection prevention protocols, including exit-site prophylaxis (mupirocin or gentamicin cream), systematic patient retraining, and antifungal prophylaxis during antibiotic courses.	2. Develop and externally validate AI-based predictive models for peritonitis risk, technique failure, and fluid overload across ethnically and geographically diverse cohorts.	2. Fund assisted PD programs and community-based PD training infrastructure in underserved and low-resource settings.
3. Prioritize low-GDP biocompatible fluids in patients with early peritoneal membrane changes, high GDP exposure risk, or early signs of technique failure, when cost and access permit. However, surrogate benefit justifies use in high-risk patients pending definitive trials.	3. Establish international registries to track pilot trials of wearable artificial kidneys, ensuring transparency, safety monitoring, and generalizability.	3. Develop national PD training competency standards and mandate periodic retraining benchmarks for PD programs.
4. Monitor residual renal function at regular intervals and consistently employ nephroprotective strategies (ACEi/ARB use, avoidance of nephrotoxins, volume optimization).	4. Investigate scalable, cost-effective anti-fibrotic strategies targeting the TGF-β/EMT pathway to preserve the peritoneal membrane.	4. Integrate environmental sustainability metrics—including plastic waste generation and supply chain carbon footprint—into procurement and regulatory frameworks for dialysate products.

PD, peritoneal dialysis; GDP, glucose degradation product; AI, artificial intelligence; ACEi, angiotensin-converting enzyme inhibitor; ARB, angiotensin receptor blocker; TGF-β, transforming growth factor-beta; EMT, epithelial-mesenchymal transition.

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