

Dialysis: historical development, modalities and contemporary practice

Abstract

Dialysis is a life-sustaining renal replacement therapy used in acute kidney injury and chronic kidney disease. It enables the removal of uremic toxins, correction of electrolyte imbalances, and maintenance of fluid balance. Since its conceptual origins in the 19th century, dialysis has evolved from experimental diffusion studies into a cornerstone of modern medicine. Key historical milestones include Thomas Graham's description of diffusion (1854), early extracorporeal experiments by John Abel (1913), and Willem Kolff's first practical hemodialysis machine (1943). The introduction of the arteriovenous shunt by Belding Scribner in 1960 enabled long-term dialysis, while subsequent decades saw expansion through public funding and technological innovation. Modern dialysis emphasizes patient-centered care, home-based therapies, and advanced technologies. Dialysis operates through diffusion, ultrafiltration, and convection across semipermeable membranes. Major modalities include hemodialysis, peritoneal dialysis, hemodiafiltration, and continuous renal replacement therapy. Peritoneal dialysis offers advantages such as preservation of residual renal function and greater patient independence, while home-based therapies are increasingly utilized. Dialysis is indicated in end-stage renal disease, acute kidney injury, severe electrolyte disturbances, metabolic acidosis, fluid overload, and certain toxic ingestions. Complications vary by modality and include hypotension, infections, and membrane dysfunction. Recent advances include high-flux membranes, online hemodiafiltration, and expansion of home dialysis technologies. Updated international guidelines emphasize individualized care, infection prevention, and structured patient training. Peritoneal dialysis is increasingly used in resource-limited settings and in acute kidney injury. Future directions include wearable devices, artificial kidneys, telemedicine, and personalized treatment strategies.

Keywords: dialysis, peritoneal dialysis, Hemodialysis, renal replacement therapy, acute kidney injury, chronic kidney disease, home dialysis, technological advances

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Introduction

Dialysis is a renal replacement therapy that substitutes essential kidney functions in patients with acute kidney injury and chronic kidney disease. It facilitates removal of uremic toxins, correction of electrolyte imbalance, and maintenance of fluid homeostasis.¹ Since its conceptual origin in the 19th century, dialysis has evolved into a cornerstone of modern medicine, transforming kidney failure from a fatal condition into a chronic manageable disease.²

Historical evolution of dialysis: foundational discoveries (1850s): the concept of dialysis originated from the work of Thomas Graham, who described diffusion across semipermeable membranes in 1854 and coined the term "dialysis". His work demonstrated selective permeability, forming the scientific basis for extracorporeal therapy.³

Experimental applications (1910s-1930s): in 1913, John Jacob Abel and colleagues performed the first extracorporeal dialysis experiments in animals using collodion membranes. These studies demonstrated feasibility but were limited by clotting and membrane fragility.⁴

Clinical breakthrough (1940s): Willem Kolff developed the first practical hemodialysis machine in 1943, using a rotating drum dialyzer. This device enabled removal of uremic toxins and led to the first successful treatment of acute renal failure in 1945.⁵ Chronic dialysis development (1960s): the introduction of the arteriovenous shunt by Belding Scribner in 1960 enabled repeated vascular access and long-term dialysis treatment. This marked the beginning of maintenance dialysis programs.⁶

Expansion Era (1970s-1990s): the expansion of dialysis was facilitated by public funding programs, particularly the U.S. Medicare End-Stage Renal Disease Program in 1972. During this period, technological advances such as hollow-fiber dialyzers and ultrafiltration systems improved efficiency and safety.² Peritoneal dialysis emerged as an alternative modality during this era.⁷ Modern Era (2000s-present): modern dialysis emphasizes patient-centered care, home-based therapies, and technological innovation, including high-flux membranes and portable devices.⁸

Principles of dialysis: dialysis relies on three fundamental mechanisms. Diffusion refers to the movement of solutes down their concentration gradients, allowing substances to pass from an area of higher concentration to one of lower concentration. Ultrafiltration involves the removal of fluid driven by pressure gradients across the membrane, enabling excess water to be extracted from the bloodstream.¹ Convection, in turn, describes the transport of solutes along with the flow of fluid, facilitating the clearance of larger molecules.⁹ These processes occur across semipermeable membranes, either synthetic (hemodialysis) or biological (peritoneum).¹

Classification of dialysis modalities: hemodialysis: conventional in-center hemodialysis is typically performed three times weekly using an extracorporeal circuit.¹ Home hemodialysis has gained renewed interest due to improved outcomes and flexibility.⁸ Nocturnal hemodialysis, introduced in the 1990s, provides prolonged treatment and improved toxin clearance. Short daily hemodialysis improves metabolic stability and reduces cardiovascular stress.¹⁰

Peritoneal dialysis: continuous ambulatory peritoneal dialysis, introduced in the late 1970s, allows manual exchanges throughout the day. Automated peritoneal dialysis uses a machine to perform exchanges overnight.⁷ Peritoneal dialysis preserves residual renal function and offers greater independence.¹¹ Hemodiafiltration: combines diffusion and convection to improve clearance of middle-molecular-weight toxins and reduce mortality risk.⁹

Continuous renal replacement therapy: is used in critically ill patients with acute kidney injury and provides slow, continuous solute removal. It includes modalities such as continuous venovenous hemofiltration, continuous venovenous hemodialysis, and continuous venovenous hemodiafiltration.¹² Sustained low-efficiency dialysis: combines advantages of intermittent hemodialysis and continuous renal replacement therapy, providing improved hemodynamic stability.¹²

Indications for dialysis: dialysis is indicated in end-stage renal disease, acute kidney injury, hyperkalemia and severe electrolyte imbalance, metabolic acidosis, fluid overload refractory to therapy and toxic ingestions (e.g., lithium, ethylene glycol).^{1,12} Complications: hemodialysis complications include hypotension, vascular access infection, and cardiovascular instability.^{1,13} Peritoneal dialysis complications include peritonitis, catheter infections, and membrane failure.⁷

Technological advances: recent advances include high-flux membranes and online hemodiafiltration, improving toxin clearance and survival outcomes.⁹ Home dialysis technologies have expanded significantly, enhancing patient autonomy and quality of life.⁸ Peritoneal dialysis remains a cost-effective and efficient modality, particularly in low-resource settings.¹⁴ Incremental peritoneal dialysis strategies improve adherence while maintaining adequacy.¹⁵ Infection prevention strategies have been refined in recent international guidelines.¹⁶

Contemporary guidelines: updated guidelines from international nephrology organizations emphasize individualized care and infection prevention.¹⁶ Structured training programs for patients and caregivers improve outcomes in home dialysis.¹⁷ Peritoneal dialysis is increasingly used in acute kidney injury, particularly where resources are limited.¹⁸ Outcomes and global trends: dialysis remains essential worldwide, though transplantation offers superior long-term outcomes. Global trends include increased chronic kidney disease prevalence, expansion of home therapies, and adoption of peritoneal dialysis-first strategies.^{19–21}

Future directions: future developments include wearable dialysis devices, implantable artificial kidneys, and regenerative therapies. Advances in telemedicine and personalized dialysis prescriptions are expected to further improve patient outcomes.²²

Conclusion

Future directions in the bioartificial kidney: the bioartificial kidney is evolving toward a fully implantable, cell-based renal replacement system that restores not only filtration but also tubular transport, endocrine, and metabolic functions.²³ Cell sources and engineering: transition to induced pluripotent stem cell (iPSC)-derived renal epithelial cells with gene editing (e.g., CRISPR) to enhance transport, durability, and immune compatibility.^{24–26}

Advanced biomaterials: development of hemocompatible, low-fouling membranes and nanoporous silicon filters enabling selective clearance without systemic anticoagulation.^{23,27} Microfluidics & organ-

on-chip: integration of kidney-on-a-chip systems for physiologic flow, real-time monitoring, and optimization of solute handling.²⁸

Implantable devices: progress from wearable systems to implantable hemofilter–bioreactor units powered by blood pressure, targeting continuous, autonomous therapy.²⁷ Immunomodulation: engineering of renal cells and surfaces to reduce inflammation and complement activation, potentially improving cardiovascular outcomes.²⁷

Regenerative convergence: synergy with organoids and tissue engineering aiming toward partial or complete bioengineered kidney replacement.^{25,28}

Digital integration: use of biosensors and artificial intelligence-driven closed-loop control for individualized fluid and electrolyte management.²⁸ Remaining challenges: scalable good manufacturing practice (GMP)-grade cell production, long-term safety and durability, immune protection without systemic immunosuppression and regulatory and cost-effectiveness barriers.²⁷

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None.

Conflicts of interest

None.

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