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Review

The potential of forward osmosis in reducing water consumption in hemodialysis

El potencial de la ósmosis forzada para reducir el consumo de agua en la hemodiálisis

Faissal Tarrass *, Meryem Benjelloun

Center of Hemodialysis 2 Mars, Casablanca, Morocco

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ABSTRACT

Hemodialysis is a life-sustaining treatment for patients with end-stage renal disease, but it is notoriously resource-intensive, requiring vast quantities of high-purity water. This significant water footprint presents economic and environmental challenges, particularly in water-scarce regions. Forward osmosis (FO), an emerging membrane technology, offers a promising alternative to conventional reverse osmosis (RO) for dialysate preparation and regeneration by leveraging osmotic energy rather than hydraulic pressure. This literature review synthesizes current research on the application of FO in hemodialysis, focusing on its potential to reduce water usage, its operational principles, and the technical challenges hindering its widespread adoption. The analysis covers FO's roles in direct dialysate preparation from tap water and spent dialysate regeneration, its energy efficiency advantages, and critical hurdles such as membrane performance and draw solution recovery. The review concludes that while FO holds considerable promise for creating more sustainable and portable dialysis systems, targeted research into membrane optimization, biocompatible draw solutions, and hybrid systems is essential for its clinical translation.

Palabras clave:
Ósmosis forzada
Tecnología de membranas
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Regeneración de dializado
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RESUMEN

La hemodiálisis es un tratamiento vital para pacientes con enfermedad renal terminal, pero es notoriamente intensivo en recursos, ya que requiere vastas cantidades de agua de alta pureza. Esta significativa huella hídrica plantea importantes desafíos económicos y medioambientales, especialmente en regiones con escasez de agua. La ósmosis forzada (OF), una tecnología de membranas emergente, se presenta como una alternativa prometedora a la ósmosis inversa (OI) convencional para la preparación y regeneración del dializado, ya que aprovecha energía osmótica en lugar de presión hidráulica. Esta revisión bibliográfica sintetiza la investigación actual sobre la aplicación de la OF en hemodiálisis, centrándose en su potencial para reducir el consumo de agua, sus principios operativos y los desafíos técnicos que impiden su adopción generalizada. El análisis abarca el papel de la OF en la preparación directa de dializado a partir de agua de red y en la regeneración del dializado usado, sus ventajas en eficiencia energética, y obstáculos críticos como el rendimiento de las membranas y la recuperación de la solución de extracción. La revisión concluye que, si bien la OF es muy prometedora para crear sistemas de diálisis más sostenibles y portátiles, es esencial una investigación dirigida a la optimización de membranas, el desarrollo de soluciones de extracción biocompatibles y los sistemas híbridos para lograr su traducción clínica.

Introduction

Conventional hemodialysis relies on reverse osmosis (RO) systems to produce the large volumes, approximately 120–150 l per session, of ultra-pure water required for dialysate. This process is energy-intensive, operating at high pressures of 10–20 bar, and contributes significantly to the environmental footprint of dialysis care. Forward osmosis (FO) is an alternative membrane separation process that utilizes the natural osmotic pressure gradient between a feed solution and a highly concentrated “draw solution” to draw water through a semi-permeable membrane. This fundamental difference imbues FO

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* Corresponding author.
E-mail address: ftarrass@hotmail.com (F. Tarrass).

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with potential advantages for hemodialysis, including reduced energy consumption, lower membrane fouling propensity, and the ability to treat challenging feed waters. This review aims to explore the potential of FO technology to mitigate the high water usage associated with hemodialysis by examining its applications in dialysate preparation and regeneration, as analyzed in the current scientific literature.

Principles of forward osmosis

FO is an engineered separation process that harnesses a natural phenomenon. It utilizes the osmotic pressure gradient between two solutions separated by a semi-permeable membrane. In FO, water moves spontaneously from a feed solution (e.g., tap water or spent dialysate), which has a lower solute concentration, across the membrane to a draw solution, which has a significantly higher solute concentration and osmotic pressure.[1] This process is driven solely by the osmotic gradient, requiring minimal external energy input.

The core components of an FO system are the semi-permeable membrane and the draw solution. The performance of the membrane's selective layer is paramount, as it directly governs critical parameters for dialysis applications: water permeability, solute rejection, and fouling resistance.[2] The draw solution must possess a high osmotic potential and must be easily separable from the purified water in a subsequent recovery step, often achieved through low-energy methods like mild heating or a secondary low-pressure RO pass.[3]

The fundamental operational difference between FO and the RO process is summarized in Fig. 1. RO requires significant external hydraulic pressure to overcome the natural osmotic pressure and force water through the membrane. In contrast, FO utilizes the osmotic energy inherent in the draw solution to draw water passively from the feed solution, eliminating the need for high-pressure pumps.

Potential applications in hemodialysis

Dialysate preparation with reduced water volume

FO presents a promising alternative to RO for primary dialysate production. Zhao et al. demonstrated the feasibility of using FO for osmotic dilution to prepare dialysate directly from tap water.[4] Their research found that tailor-made hollow-fiber thin-film composite (TFC) membranes outperformed commercial cellulose triacetate (CTA) membranes, achieving higher water flux, lower reverse salt flux, which is a key metric where solutes from the draw solution diffuse back into the feed, and better overall ion rejection. Although minor draw solute loss occurred, compensation mechanisms ensured the final solution met dialysate suitability standards. However, practical studies using repurposed spiral-wound RO elements have shown that flow distribution and pressure limitations can constrain performance, indicating that modules must be specifically engineered for the low-pressure conditions of FO.[5] Further innovating on module design, the same group later developed a vacuum-assisted interfacial polymerization technique to fabricate high-performance FO membranes directly onto commercial dialyzer modules, demonstrating a direct pathway for integrating FO technology into existing dialysis hardware.[6] This highlights FO's potential for scalable and cost-effective dialysate production, though further membrane optimization is necessary to achieve the required real-time production rates for a full dialysis session, approximately 30–50 L/h.[4,6]

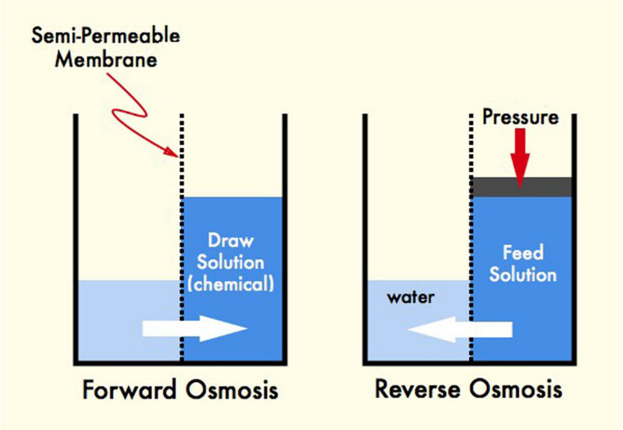

Fig. 1. Comparative schematic of forward osmosis and reverse osmosis processes.

Regeneration of spent dialysate

A highly impactful application of FO is in the regeneration of spent dialysate, which could drastically reduce the total pure water demand by recycling a portion of the water from the waste stream. Talaat proposed FO as a feasible option for ambulatory dialysis systems, suggesting that using a sodium chloride draw solution could recover up to 50% of water from spent dialysate.[7] A performance evaluation by Kim et al. confirmed the feasibility of using FO for spent dialysate reuse, but critically highlighted that organic fouling, from uremic toxins and proteins, and inorganic scaling pose significant challenges to maintaining stable water flux, underscoring the need for effective pre-treatment or advanced anti-fouling membranes.[8] The integration of advanced membranes, such as those enhanced with Aquaporin proteins, could further improve water permeability and solute rejection. However, a significant challenge identified by Dou et al. is the limited urea rejection of commercial FO membranes.[9] This reduced urea concentration gradient across the membrane could potentially diminish the efficiency of toxin removal, possibly necessitating an extension of dialysis treatment time to achieve adequate clearance, thereby presenting a critical clinical trade-off that requires further investigation.[9]

Advantages and technical challenges

Advantage: low energy consumption

A primary advantage of FO over RO is its significantly lower energy requirement. While RO for similar feedwater requires about 2.5 kWh/m^3 of water processed, the FO process itself consumes minimal energy. Zhao et al. estimated the electrical energy consumption for their FO process at atmospheric pressure to be approximately 0.05 kWh/m^3, which includes energy for membrane pumping (~0.03 kWh/m^3) and for pumping into the draw solution recovery column (~0.02 kWh/m^3).[3] The total energy cost is primarily associated with the subsequent recovery and reconcentration of the draw solution, which can often be achieved using low-grade or waste heat, further enhancing its energy efficiency profile in certain settings.

Challenge: membrane performance

The feasibility of FO in hemodialysis is contingent on membrane performance. As illustrated in Fig. 2, membrane-related issues like concentration polarization and fouling are central problems. Current-generation FO membranes, such as CTA, typically achieve water fluxes of 10–20 L/m^2/h, which may be sufficient for small-scale or regenerative applications but fall short of the high fluxes needed for real-time, high-volume dialysate production.[4] Thin-film composite membranes show promise with fluxes approaching 40 L/m^2/h, but they remain susceptible to fouling by uremic toxins, proteins, and salts present in spent dialysate.[8] A pilot-scale study on hollow fiber FO modules identified that the selected draw solute and its concentration

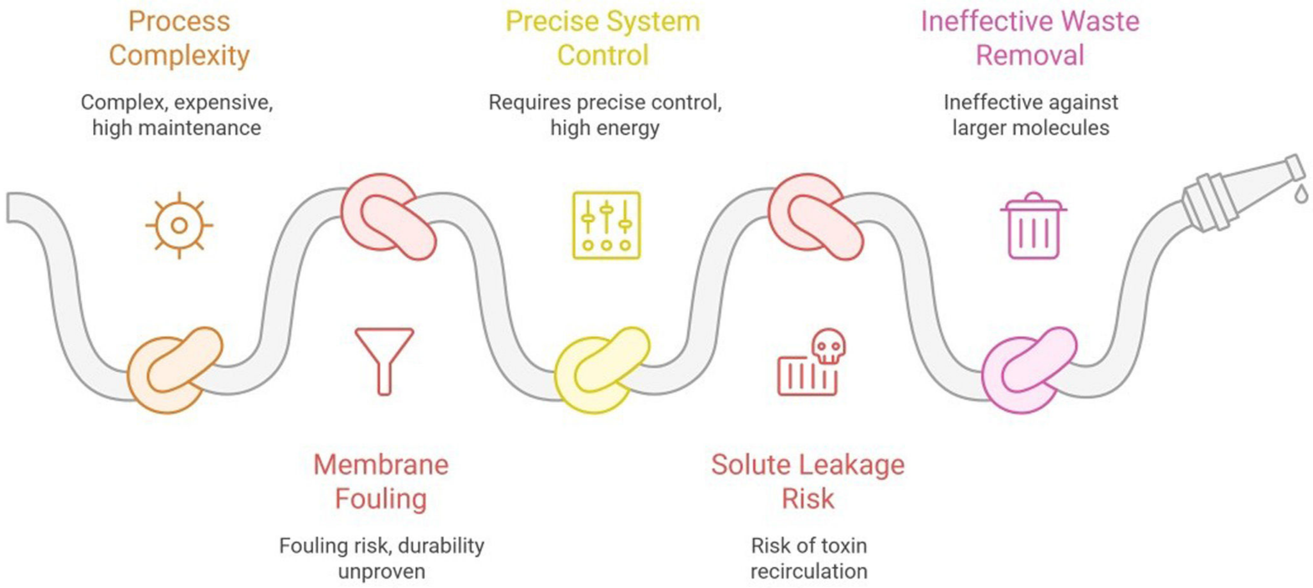

Fig. 2. Key challenges and influencing factors in forward osmosis process performance.

have the biggest impact on membrane performance due to internal concentration polarization, a finding that underscores the challenge of achieving high, stable flux in real-world systems.[10] The design of the selective layer is therefore a critical research frontier, as its properties, including thickness, hydrophilicity, and charge, dictate the fundamental trade-off between water flux and solute rejection that is so crucial for dialysis efficacy.[2]

A highly promising avenue to overcome this trade-off is the development of biomimetic membranes. This approach draws inspiration from nature, incorporating biological components to create advanced membrane systems.[11] The most significant advancement in this area involves the integration of aquaporins (AQPs), which are transmembrane proteins that act as highly selective and ultra-efficient water channels in all living organisms.[12,13] First discovered by Peter Agre,[14] AQPs are known as water channels as they do not function as ion/molecule carriers but facilitate water transport at an estimated rate of 700 l per second per gram of protein, offering the potential for simultaneously high water flux and near-perfect solute rejection.[14,15] The primary challenge lies in stabilizing these proteins within a synthetic membrane matrix. A successful strategy has been to encapsulate AQPs within robust synthetic vesicles known as polymersomes, which mimic the natural lipid bilayer and overcome the degradability of natural liposomes.[16,17] These AQP-embedded polymersomes are then incorporated as additives during the interfacial polymerization process used to fabricate the selective polyamide layer of thin-film composite (TFC) membranes, significantly enhancing their permeability and selectivity.[18,19] As an alternative to biological proteins, research is also advancing in the design of synthetic polymeric water channels that aim to mimic the exceptional performance of AQPs.[20,21]

Future development must focus on optimizing these next-generation membranes for dialysis-specific conditions. This includes further refinement of biomimetic additives, the application of anti-fouling coatings, improved pre-filtration, or novel materials that offer simultaneously high water flux and superior solute rejection, particularly for key uremic toxins like urea.

Challenge: draw solution recovery and biocompatibility

The draw solution is central to the FO process, and its efficient recovery is crucial for the system's overall efficiency and economic viability. Thermal methods, such as heating an ammonium bicarbonate solution to around 60 °C to decompose it into gaseous CO_2 and NH_3 for separation, add an energy cost of 0.5–1 kWh/m^3 that partially offsets FO's inherent energy advantage.[22] Alternative methods like low-pressure RO reduce energy use but add system complexity. Furthermore, for dialysis applications, any potential leakage of draw solutes into the dialysate stream must be absolutely safe for patients. Therefore, the development of novel, biocompatible draw solutions, for example, non-toxic osmotic agents like glucose-based solutions where trace remnants would be harmless, is a critical area for future research.[7,23]

Future directions

The integration of FO into hemodialysis represents a paradigm shift toward more sustainable and potentially portable renal replacement therapy. To translate this potential into clinical reality, future research must address key barriers through targeted solutions:

Overcoming membrane efficiency limitations

- Barrier: Current FO membrane fluxes, ranging from 10 to 40 $L/m^2/h$, fall short of the real-time dialysate production requirement of 30–50 L per hour for a full system. Furthermore, fouling by uremic solutes rapidly diminishes this performance.[8]
- Solution: Research must prioritize engineering next-generation membranes with dialysis-specific fluxes targeting 50–100 $L/m^2/h$. This could involve novel materials like graphene or advanced thin-film composites integrated with anti-fouling coatings, for example, hydrogel layers. A targeted approach to optimizing the selective layer's architecture and chemistry is essential to break the perennial flux-rejection trade-off.[2] The efficacy of these membranes must be rigorously validated in trials using spent dialysate to simulate real-world conditions.

Optimizing draw solution recovery and biocompatibility

- Barrier: The energy cost of thermal draw solution recovery partially negates FO's core energy advantage. Furthermore, the library of draw solutions proven to be safe and biocompatible for dialysis applications is severely underdeveloped.

- Solution: Innovation is needed in low-energy recovery processes, such as osmotic backwashing or advanced membrane distillation, aiming to reduce energy demand to 0.1–0.3 kWh/m^3. Concurrently, a major initiative must focus on developing and testing dialysis-safe draw solutions, for example, glucose or specific electrolytes, to ensure any trace reverse solute flux meets strict AAMI water quality standards. Industry partnerships with dialysis equipment and consumable manufacturers are crucial to drive this development.

Demonstrating clinical scalability

- Barrier: A significant hurdle is the absence of commercially available, integrated FO systems designed for dialysis, which delays clinical adoption and widespread use.
- Solution: The most viable path to scalability is through the development and deployment of pilot-scale hybrid systems, for example, FO-RO for pre-concentration or FO-sorbent for regeneration, in partner dialysis centers. Innovative module designs, such as those fabricated directly onto dialyzers,[6] represent a critical step toward this integration. A strategy of incremental deployment, supported by techno-economic analyses and cost-sharing models with manufacturers, can de-risk the investment and build the necessary evidence for full-scale implementation.

Finally, comprehensive life cycle assessments are needed to quantify the environmental gains in water and energy savings, and clinical trials are essential to validate final water quality and patient outcomes. Initial costs for FO membranes and draw solution recovery may exceed RO setups, though long-term water and energy savings could offset this. Pilot studies are needed to assess this economic feasibility.

Conclusion

FO holds significant potential for dramatically reducing the water footprint of hemodialysis through more efficient primary production and direct regeneration of spent dialysate. Its low-energy operational paradigm, with a core process consumption as low as 0.05 kWh/m^3 compared to ~2.5 kWh/m^3 for RO, offers a compelling advantage.[3] However, the technology's transition from the laboratory to the clinic is dependent on overcoming key technical hurdles related to membrane flux and selectivity, draw solution management, and overall system integration. By focusing on the targeted solutions of developing high-flux membranes, low-energy recovery processes, biocompatible draw solutions, and hybrid pilot systems, researchers and industry partners can work toward realizing the goal of efficient, sustainable, and patient-centered dialysis systems. This review underscores the novelty of this application and outlines a clear roadmap for its development.

Conflict of interest

The authors declare that they have no conflicts of interest.

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