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A review of flow and volume sensors applications in hemodialysis

Stephanie Malavé Méndez*
https://orcid.org/0009-0002-4336-0172
malave_164010@students.pupr.edu
Universidad Politécnica de Puerto Rico
San Juan - Puerto Rico

Julio C. Martínez Ocasio
https://orcid.org/0009-0008-7667-7372
martinez_123888@students.pupr.edu
Universidad Politécnica de Puerto Rico
San Juan - Puerto Rico

*Correspondence author: malave_164010@students.pupr.edu

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Abstract. This article describes distinct types of flow and volume sensors, and their respective applications used during hemodialysis. Through a review of the literature, new opportunities in the field of non-invasive methods are explored to optimize and develop innovative technologies in the field of biomedical implants and accelerate the completion of kidney disease treatment. The findings reveal that the combination of these devices and noninvasive techniques contributes significantly to the treatment of kidney diseases. In addition, it helps in the development of biological models and the performance of operational/mechanical analyses to predict more effective and rapid implementation methods for patient recovery.

Keywords: biofluids, flow and volume sensors, hemodialysis.

Una revisión de las aplicaciones de sensores de flujo y volumen en hemodiálisis

Resumen. - Este artículo describe diferentes tipos de sensores de flujo y volumen, y sus respectivas aplicaciones durante la hemodiálisis. A través de una revisión bibliográfica se exploran nuevas oportunidades en el campo de los métodos no invasivos para optimizar y desarrollar tecnologías innovadoras en el campo de los implantes biomédicos y acelerar la finalización del tratamiento de enfermedades renales. Los hallazgos revelan que la combinación de estos dispositivos y técnicas no invasivas contribuye significativamente al tratamiento de enfermedades renales. Además, facilita el desarrollo de modelos biológicos y la realización de análisis operativos/mecánicos para predecir métodos de implementación más efectivos y rápidos para la recuperación del paciente.

Palabras clave: biofluidos, sensores de flujo y volumen, hemodiálisis.

I. INTRODUCTION

Hemodialysis (HD) is a life-saving treatment for chronic kidney failure, replacing key kidney functions by filtering blood through a dialyzer to remove waste, excess fluids, and toxins. Specifically, it serves patients with chronic kidney disease (CKD) and end-stage renal disease (ESRD), where maintaining a balance between fluid removal and replacement is essential. To achieve this, accurate control of blood and dialysate flow rates, as well as ultrafiltration volume [1], is ensured through integrated flow and volume sensors, which play a key role in treatment efficacy and patient safety. As dialysis therapies become more complex, the demand for reliable sensor technologies continues to grow. In addition, ESRD, one of the leading causes of reduced lifespan with a high mortality rate, requires long-term dialysis, and by 2030, an estimated 5.4 million patients will need this therapy. Effective dialysis depends on proper vascular access to ensure sufficient blood flow [2]. Thus, epidermal blood flow sensors have been introduced for real-time monitoring.

Furthermore, access points such as arteriovenous fistulas (AVF), arteriovenous grafts (AVG) and catheters [3] can fail due to stenosis or thrombosis, making wearable thermal anemometric flow sensors crucial for early detection. In addition, flow sensors measure the movement of liquids or gases through output signals [4] or pressure changes [5], enhancing the precision of treatment and patient outcomes. Similarly, volume sensors are integral to modern HD systems, providing real-time fluid balance monitoring. In general, this review highlights the role of bio-fluids in medical device design, emphasizing the importance of flow and volume sensors to align with biological properties for effective patient care. According to Yánez et al. [6], blood comprises 8% of an adult's body mass, while total water content ranges from 58% to 80%, distributed between organs such as brain (73%), heart (73%), skin (65%), lungs (84%), kidneys (79%), liver (71%) and pancreas (73%). Ultimately, as advancements in biomedical engineering continue, flow and volume sensors will play an increasingly vital role in enhancing treatment precision, improving patient outcomes, and shaping the future of dialysis technology.

II. FIELDS OF INTEREST TO THE SUBJECT

Flow and volume sensors are crucial in biomedical devices, ensuring precise fluid control in medication delivery and diagnostics. As medical technology continues to evolve, flow sensors have become essential for accurately monitoring and managing fluid movement in various applications. Their development, progressing from Microelectromechanical Systems (MEMS) to microfluidic devices on a single chip [7], has allowed for increasing efficiency and adaptability. Doppler ultrasound sensors enabled transcutaneous blood flow measurements [8], while wearable sensors expanded to track vital signs like heart rate and oxygen levels [9]. Meanwhile, Laser Doppler flowmetry provided a non-invasive way to assess circulatory function, including retinal blood flow in rabbits [10]. Alongside these advancements, volume sensors have been essential in medical applications, particularly in regulating physiological functions. Relative blood volume monitoring has been used to track hematocrit changes [11] and improve blood pressure regulation during hemodialysis [12]. As technology advanced, bioimpedance analysis emerged to estimate total body water [13], while ultrasound dilution sensors measured cardiac output in pediatrics [14]. Additionally, portable nuclear magnetic resonance improved disease diagnosis and tumor detection [15]. Eventually, biomarker sensors introduced biological markers like glucose detection [16], leading to portable glucose monitors for diabetes care. The miniaturization and non-invasive design of these sensors have ensured high sensitivity, precision, and low power consumption, enabling broad medical applications. This research highlights their growing role in modern healthcare, demonstrating how engineering advancements continue to shape the medical field.

A. A Brief Review: Flow Sensors

Flow sensors in hemodialysis (HD) are critical for monitoring the rate at which fluids, primarily blood and dialysate, circulate through the system. Among the various types, electromagnetic flow sensors offer high accuracy by detecting voltage changes induced by magnetic fields as blood flow through the sensor, although they tend to be costly and technically complex. Ultrasonic flow sensors, in contrast, are widely used due to their non-invasive nature; they measure fluid velocity using high-frequency sound waves. Optical flow sensors determine flow rate by analyzing changes in light transmission through the fluid, often leveraging suspended particles within the blood to enhance measurement precision. Together, these technologies provide essential data for optimizing hemodialysis treatment and ensuring patient safety.

B. Flow Sensor Types

Microelectromechanical Systems (MEMS) flow sensors have been developed for intravenous (IV) systems to measure small flow rates, such as those involved in drug delivery. One such sensor employs artificial hair cells (AHCs) on a silicon die, incorporating two differently sized AHCs designed to minimize flow disturbance [7]. The sensor is coated with a parylene film to ensure waterproofing and compatibility with various drugs. Doppler ultrasound flow sensors utilize diffraction grating transducers (DGTs) made of flexible biofilm to generate low-energy optical signals, making them well-suited for long-term implantation. These sensors enhance sensitivity by creating overlapping ultrasonic beams [8] that detect dispersed ultrasound signals from blood flow. Wearable flow sensors represent a noninvasive solution for real-time medical monitoring [9], integrating flexible, wireless, multipoint devices that measure pulse waves, skin color, and tissue temperature. The system includes sensors, cables, a data transmitter, and a tablet or smartphone for data display, with installation supported by medical film dressings and a polydimethylsiloxane sheet.

Laser Doppler flowmetry offers a noninvasive and wearable approach, using six wireless sensors to detect Doppler shifts from red blood cell movement, allowing simultaneous monitoring of blood perfusion at multiple sites [10]. Similarly, epidermal blood flow sensors provide noninvasive, wearable monitoring of skin blood flow, effectively adapting to sensor placement variability and tissue differences. These sensors capture weak temperature signals associated with high-volume blood flow [2], offering continuous surveillance valuable in managing end-stage renal disease (ESRD) patients. Lastly, anemometric flow sensors also present a wearable, noninvasive solution, designed to detect changes in blood flow through vascular access points such as arteriovenous fistulas (AVF) and arteriovenous grafts (AVG) [3]. These sensors deliver immediate physiological feedback with high sensitivity and have demonstrated accurate performance in vivo studies. Collectively, these technologies underscore the progress in flow sensing for hemodialysis and broader clinical applications, balancing precision, ease of use, and patient comfort.

C. A Brief Review: Volume Sensors

Volume sensor analysis in dialysis plays a crucial role in monitoring and managing fluid volumes within the dialysis system to ensure effective treatment and optimal patient care. By accurately measuring and tracking fluid movement across various components, such as dialysate delivery, blood flow, and ultrafiltration, these sensors help maintain proper fluid balance and prevent complications like fluid overload or dehydration. Techniques such as *relative blood volume monitoring (RBVM) and bioimpedance analysis (BIA)* are commonly used to assess patient hydration status and guide real-time adjustments to ultrafiltration rates during dialysis sessions. Two main types of volume sensors are employed: *cumulative volume sensors*, which continuously monitor the total volume of blood or dialysate processed, providing essential data on fluid removal or replacement; and *real-time volume sensors*, which offer instantaneous volume measurements to enable dynamic control and maintain equilibrium. Many of these devices also incorporate optical technologies to measure hematocrit levels, serving as indicators of hemoconcentration and aiding in the precise evaluation of blood volume changes. Together, these volume sensing approaches enhance dialysis safety, personalization, and clinical outcomes.

D. Volume Sensor Types

Volume sensors represent a fundamental category within monitoring and automation systems, allowing for the precise measurement of the quantity of liquid or gas contained in each space. Their applications span multiple sectors, from the medical and food industries to automotive engineering and smart manufacturing processes. The choice of the appropriate sensor type depends on factors such as the type of fluid, the required accuracy, the operating environment, and response speed. Below are the main types of volume sensors, their operating principles, and their advantages in different technological contexts.

Relative Blood Volume Monitoring (RBVM) is a key technique in dialysis that tracks changes in hematocrit [11], the ratio of red blood cells to plasma, as fluid is removed from the patient [12]. This allows for real-time adjustments of ultrafiltration targets, helping to prevent complications such as intradialytic hypotension by avoiding excessive fluid removal. *Bioimpedance Analysis (BIA)* complements RBVM by estimating body water compartments, including extracellular water (ECW), intracellular water (ICW), and total body water (TBW) [13], through the measurement of the body's electrical properties. BIA aids in determining a patient's dry weight and guides fluid removal strategies during dialysis. Various BIA methods exist, including single-frequency, multi-frequency, and bioimpedance spectroscopy (BIS), and can be applied using whole-body or segmental approaches. *Ultrasound dilution sensors* provide additional fluid status insights by measuring blood flow and cardiac output, detecting changes in ultrasound wave velocity [14] after injecting a known volume of fluid, such as saline, into the arterial line. *Portable nuclear magnetic resonance (NMR) sensors* utilize low magnetic fields [15] to quickly assess fluid status at the bedside, offering rapid differentiation between hypervolemic and euvolemic states, significantly faster than conventional MRI techniques. Lastly, *biomarker sensors* enable the detection and quantification of specific biological markers [16] using technologies such as paper-based platforms, vibrating resonators, and optical detection systems. These sensors support early disease detection, monitoring fluid overload, treatment tracking, and personalized therapy, contributing to improved outcomes in dialysis care. Collectively, these volume sensing technologies enhance the precision, safety, and personalization of fluid management in hemodialysis.

E. Integration of Flow and Volume Sensors in the Hemodialysis Process

Flow and volume sensors integrated into dialysis machines play a crucial role in delivering safe, efficient, and individualized treatment by providing real-time data to monitor and regulate both blood and dialysate flow. These sensors enable automatic system responses to abnormalities such as low blood flow or excessive fluid removal, thereby preventing complications like dehydration or intradialytic hypotension and enhancing overall patient safety. In clinical hemodialysis, flow and volume sensors serve several key functions. *Monitoring blood flow* is essential to maintain optimal perfusion through the vascular access and extracorporeal circuit [17], and flow sensors help detect access dysfunction early, ensuring treatment efficacy. *Dialysate flow regulation* is another critical application, as dialysate flow rate directly impacts solute clearance; accurate monitoring via flow sensors improves dialysis efficiency and clinical outcomes [18]. *Ultrafiltration management* relies on volume sensors to precisely control the amount of fluid removed during treatment, aiding in the achievement of patient-specific dry weight targets and avoiding the risks of fluid overload or hypotension. Additionally, while non-flow sensors per se, *leak and air detection* systems use differential flow measurements between blood inflow and outflow to identify anomalies such as tubing leaks or air ingress, prompting immediate corrective action. Together, these sensor technologies enhance the safety, accuracy, and personalization of dialysis therapy.

F. Dialysis Machines

Dialysis machines [19] are critical medical devices used to perform renal replacement therapy in patients with end-stage renal disease (ESRD) or acute kidney injury. These machines mimic the filtration function of healthy kidneys by removing waste products, excess fluids, and toxins from the bloodstream through a semi-permeable membrane. Hemodialysis, the most generic form, circulates blood through an external dialyzer, while peritoneal dialysis uses the patient's peritoneal membrane as the filtration surface. Dialysis machines tightly regulate parameters such as blood flow rate, dialysate composition, temperature, and ultrafiltration volume to ensure safe and effective treatment. Modern systems, such as the Fresenius 5008 CorDiax and Baxter's AK 200 ULTRA S, are equipped with real-time monitoring, integrated sensors, and customizable treatment protocols to improve patient outcomes. Integrated flow and volume sensors within these machines enhance safety by implementing air detectors, pressure monitors, and blood leak detectors to minimize risks of detecting air bubbles, pressure anomalies, and blood leaks, allowing for automatic system adjustments. Peritoneal dialysis machines, such as the Baxter Amia, use the peritoneal membrane for filtration and are designed for home use, offering patients greater flexibility and autonomy. Dialysis machines also store historical treatment data, aiding clinicians in personalizing therapy and tracking patient progress over time. The primary goal of these machines is to maintain fluid and electrolyte balance, reduce uremic symptoms, and improve survival and quality of life in patients with compromised renal function. Continued technological advancements aim to increase efficiency, portability, and patient comfort, making dialysis therapy more accessible and effective.

G. Method Calculations

Since this review serves as a collection of relevant research, it focuses on providing information that supports and sustains the discussion. Among the key topics, flow rate is widely assessed due to its versatility and extensive applications in flow and volume sensors. Understanding this concept is essential, as equation (1) defines the relationship between fluid velocity, cross-sectional area, and the volume of fluid passing through a point over time [20]:

$$Q = \frac{V}{S} \tag{1}$$

where Q represents the flow rate (e.g., blood flow), V denotes the average velocity, and S corresponds to the cross-sectional area of the fluid (e.g., blood).

Equation (2) expands upon flow rate by incorporating volume flow rate (Q_0), which can be modified depending on the specific application. For instance, when analyzing laminar blood flow in a rectangular channel, the volume flow rate is expressed as:

$$Q_0 = \frac{4ba^3}{3\mu}\left(-\frac{d\hat{p}}{dx}\right)\left[1 - \frac{192a}{\pi^5 b}\sum_{i=1,3,5,\ldots}^{\infty}\frac{\tan h\left(\frac{inb}{2a}\right)}{i^5}\right] \tag{2}$$

where b represents the width, a is the half-height of the channel, and μ signifies the fluid viscosity. The term $-\frac{d\hat{p}}{dx}$ refers to the pressure gradient within the channel, while $\sum_{i=1,3,5,\ldots}^{\infty}$ the summation term accounts for the influence of odd integers on the flow behavior. Additionally, $\tan h\left(\frac{inb}{2a}\right)$ represents the geometric characteristics of the channel.

Another essential equation used in flow and volume sensors is the Doppler equation (3), primarily utilized to measure the velocity of blood flow:

$$f_d = \left(\frac{V}{\lambda}\right)\left(\frac{4}{d}\right) = \frac{V}{d} \tag{3}$$

where f_d is denotes the Doppler frequency shift, V represents the velocity of blood flow, λ is the wavelength of the transmitted wave, and d is the distance.

In contrast to the Doppler equation, the wavelet spectrum equation (4) is applied to evaluate signals from flow and volume sensors:

$$W(s,\tau) = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} x(t)\psi^* \left(\frac{t-\tau}{s}\right) \tag{4}$$

where $W(s,\tau)$ represents the wavelet transform of the signal, s is the scale parameter, $x(t)$ is the evaluated signal, τ corresponds to the time parameter, and ψ^* is the complex conjugate of the wavelet function.

Additionally, the non-dimensional temperature equation (5) is implemented in flow and volume sensors to adjust temperature measurements for improved accuracy:

$$T_{nondim} = \frac{T - T_{standard}}{\Delta T_{standard}} \tag{5}$$

where T_{nondim} represents the non-dimensional temperature, T is the measured temperature, $T_{standard}$ signifies the reference temperature, and $\Delta T_{standard}$ is the difference between two reference temperatures.

Finally, the flow sensitivity equation (6) is incorporated into flow and volume sensors to assess their responsiveness to variations in flow rate:

$$Sensitivity(\%) = \frac{\Delta T_{100mL/min} - \Delta T_{800mL/min}}{\Delta T_{800mL/min}} \times 100 \tag{6}$$

where $\Delta T_{100mL/min}$ represents the time change at a lower flow rate of 100mL/min, and $\Delta T_{800mL/min}$ corresponds to the time change at a higher flow rate of 800mL/min.

H. Outcomes of flow sensors

Experiments on flow sensors provided significant insights across various applications. For instance, MEMS flow sensors demonstrated a dynamic range of 2–200 ml/h, but showed output saturation near 200 ml/h, while IV system testing at 0.05 ml/min confirmed adaptability. Additionally, Doppler ultrasound flow sensors measured velocities between 110–122 cm/s with minimal variation, though estimates deviated by 5.9% across flow rates of 60–500 mL/min. Meanwhile, wearable flow sensors in clinical trials achieved physician agreement rates of 96%–99.2%, with 90% of patients recommending future use. In addition, laser Doppler flowmetry studies showed perfusion decreased when transitioning upright, but increased in a head-down position, with forehead measurements exhibiting minimal microcirculation changes. Notably, blood pressure and heart rate were consistently higher in vertical positions. Furthermore, epidermal blood flow sensors provided precise vascular access monitoring, showing a 12.2% deviation from Doppler ultrasound across flow rates of 100–600 ml/min, with a compact design suitable for hemodialysis. Lastly, anemometric flow sensors accurately monitored blood flow in CKD patients, adapting to AVF development, vascular stenosis, thrombosis, and access failure, while maintaining reliable performance despite minor setup imbalances. Ultimately, in vivo studies validated their precision across different flow conditions, with benchtop models confirming the impact of vessel structure on sensor sensitivity. These findings highlight the essential role of flow sensors in advancing patient monitoring and medical technology.

I. Technological Advancements and Innovations in Sensors

Recent advancements in dialysis technology have significantly improved the performance and integration of flow and volume sensors. *Miniaturization* has led to the development of smaller, more compact sensors that can be seamlessly embedded within dialysis machines, reducing the overall system size and enhancing portability. *Smart sensors*, powered by AI-based algorithms, now offer predictive analytics capabilities that anticipate potential complications and automatically adjust treatment parameters to enhance patient safety and optimize outcomes. Additionally, *wireless monitoring* has transformed clinical practice by enabling real-time, remote access to sensor data, allowing healthcare providers to oversee a patient's dialysis session without being physically present. These innovations are complemented by improved accuracy, achieved using advanced materials and technologies such as high-precision electromagnetic and miniaturized ultrasonic sensors, which ensure greater measurement reliability and clinical effectiveness.

J. Challenges and Limitations

Flow and volume sensors in dialysis systems, while essential for ensuring accurate and safe treatment, are subject to several limitations. *Sensor drift* is a common issue, where prolonged use leads to gradual loss of accuracy, necessitating routine recalibration to maintain performance. Additionally, *external interference*, including fluctuations in temperature, pressure, and changes in the chemical composition of blood or dialysate, can compromise the reliability of sensor readings. *Mechanical failures* also pose a significant risk; malfunctions can result in erroneous data that may threaten patient safety if not promptly detected. Furthermore, these sensors demand consistent *maintenance and cleaning* to prevent blockages or clogs, ensuring continuous, unobstructed operation and accurate monitoring throughout the dialysis process.

III. METHODOLOGY

This review focused on the assessment of mechanical and operational properties for flow and volume sensors using a diverse range of scientific literature and academic contributions. The primary sources included peer-reviewed journal articles, doctoral and master's theses, and conference presentations, all provided by researchers, and recognized scientific organizations. The objective was to gather comprehensive, high-quality information that reflects the current state of knowledge in the field. To ensure a comprehensive and inclusive literature review, an exhaustive search was conducted across American and European academic databases, emphasizing repositories affiliated with institutions specializing in biomedical engineering. The primary search focused on publications from 2021 to 2025 to capture the most recent advancements, utilizing databases such as PubMed, Scopus, IEEE Xplore, EBSCOhost, Google Scholar, and ScienceDirect. These platforms were selected for their broad coverage of biomedical and interdisciplinary research, allowing the identification of high-quality peer-reviewed articles, conference proceedings, and technical reports. Supplementary information from secondary sources, including engineering textbooks, technical manuals, handbooks, internet-based resources, and review articles, further enriched the contextual and technical depth of the review. To determine the most appropriate flow or volume sensor for a given clinical setting, several critical criteria must be considered according to the researched data evaluated from collected references. These include performance characteristics such as accuracy and reliability, and material properties like durability, biocompatibility, and ease of sterilization. Cost factors compassing initial investment, maintenance, and operational expenses, are also evaluated. Additionally, the simplicity of use, including training requirements and the ease of integration into existing dialysis systems, plays an important role in sensor selection. Real-time monitoring capabilities are essential for continuous assessment during the dialysis process. A comparative analysis of these criteria for each sensor type is presented in Table 1, with each criterion rated on a scale of Low, Medium, or High.

Tabla 1. Inclusion and Rejection Criteria.

<table>
<tr><th>Criteria</th><th>Key Questions</th><th>Rating (Low/ Medium/High)</th></tr>
<tr><td>Accuracy</td><td>How accurate is the sensor?
What is the reliability of the sensor?</td><td rowspan="7">Refer to Tables 2 and 3 for a complete evaluation of flow and volume sensor criteria.</td></tr>
<tr><td>Material of Construction</td><td>What is the durability of the sensor?
Is it biocompatible with other equipment?
Is it easy to sterilize the sensor?</td></tr>
<tr><td>Cost</td><td>What is the initial investment cost?
What is the cost of maintenance?
What is the cost for operation?</td></tr>
<tr><td>Simplicity</td><td>How easy is it to use?
What training does it require?
How hard is it to integrate with the system?</td></tr>
<tr><td>Invasiveness</td><td>Does it require direct access to blood or a vascular access point?</td></tr>
<tr><td>Real-Time Monitoring</td><td>Does it provide real-time monitoring during the dialysis process?</td></tr>
<tr><td>Clinical Maturity</td><td>Is it used in clinical dialysis centers or mostly in research settings?</td></tr>
</table>

IV. RESULTS

Table 2 presents the flow sensor types analyzed and their distinctive characteristics, as well as their applications in health situations based on the information collected from the references obtained during this document's preparation.

Table 3 presents the volume sensor types analyzed and their distinctive characteristics, as well as their applications in health situations based on the information collected from the references obtained during this document's preparation.

According to the obtained results presented on Table 2, the best flow sensor option for hemodialysis mentioned on this paper should be Doppler Ultrasound flow sensor based on its high accuracy, real-time performance, non-invasive characteristics and clinically validated use. These characteristics prove the effectiveness in dialysis clinics for vascular access flow surveillance and early detection of complications like thrombosis and stenosis. For the other hand, MEMS flow sensors and wearable devices could enhance monitoring, especially for continuous, home-based settings, but they need more

Tabla 2. Flow Sensors Results.

Sensor Type	Accuracy	Durability	Cost	Ease	Invasive	Real-Time	Maturity	Clinical Application
MEMS	H	M	H	L	L	M	L	Experimental implantable blood flow monitors
Doppler Ultrasound	H	H	M	M	L	H	H	Vascular access blood flow measurement, stenosis detection
Wearable	M	M	M–H	H	L	L	L	Home/outpatient vascular monitoring
Laser Doppler Flowmetry	L	H	H	M	L	M	L	Monitoring superficial skin blood flow; not suitable for hemodialysis circuits
Epidermal	L–M	H	H	L	L	H	L	Skin perfusion monitoring, future vascular access checks
Anemometric	M	M	L–M	H	L	H	M	Prototypical dialysis blood flow monitoring

Legend: H = High, M = Medium, L = Low

Tabla 3. Volume Sensors Results

Sensor Type	Accuracy	Material Durability	Cost (USD)	Ease to Use	Invasiveness	Real-Time Monitoring	Clinical Maturity	Clinical Application
RVBM	M–H	H	L–M	H	L	H	H	Intradialytic blood volume tracking to prevent hypotension
BIA	M	H	L	H	L	L	H	Assessment of fluid overload pre-/post-dialysis
Ultrasound dilution	H	H	M–H	M	L	M	M–H	Blood volume and cardiac output monitoring during dialysis
NMR	H	H	H	L	L	L	L	Detailed body composition and hydration state
Biomarker	M	M	M–H	M	L	M	L	Monitoring biochemical markers related to hydration (natriuretic peptides)

Legend: H = High, M = Medium and L= Low

validation and ruggedization. Corresponding to obtained results presented on Table 3, the best volume sensor option for hemodialysis mentioned on this paper should RBVM (Relative Blood Volume Monitoring) volume sensor based on its real-time performance, non-invasive characteristics, cost-effective and clinically validated use. These characteristics prove the effectiveness for blood volume management during hemodialysis. For the other hand, Biomarker sensors and advanced NMR techniques could enhance fluid management in the future but are not yet practical for routine use. Along the course of the review, it was found that sensor accuracy is directly linked with sensitivity. This means that at a higher sensitivity, it can increase the performance of the sensor. In hemodialysis the incorporation of these sensors is crucial, because it can guarantee the well-being of the patient and at the same time ensure treatment effectiveness.

CONCLUSIONS

The review covered a comprehensive range of topics centered on flow and volume sensors and their applications in hemodialysis treatment. Each sensor type demonstrated specific strengths and limitations under various clinical conditions, yet all effectively fulfilled their intended roles in accurately monitoring blood flow and fluid dynamics. Flow and Volume sensors play a vital role in enhancing the precision of fluid management, thereby contributing to improved patient outcomes. The selection of an appropriate sensor depends on a combination of clinical requirements, resource availability, and cost considerations. Continued advancements in sensor technologies, especially regarding integration with dialysis systems and real-time monitoring capabilities, offer promising prospects for further improving the safety, efficiency, and overall effectiveness of hemodialysis therapy.

Moreover, interdisciplinary research efforts and collaborations between medical device manufacturers and healthcare providers are essential to accelerate innovation in this field. Future developments should focus on miniaturization, increased sensor sensitivity, and seamless integration with automated control systems to facilitate personalized treatment protocols. Such advancements will not only optimize hemodialysis procedures but also enhance patient comfort and reduce long-term healthcare costs.

Additionally, emerging trends emphasize the incorporation of artificial intelligence and machine learning algorithms into sensor technologies, enabling predictive analytics for early detection of complications such as clot formation, vascular access dysfunction, and fluid overload. These intelligent systems, already under exploration in advanced healthcare centers worldwide, have the potential to revolutionize hemodialysis management by providing data-driven insights for personalized treatment adjustments in real time. As seen in recent studies from leading institutions in the United States, Germany, and Japan, this technological convergence is paving the way for more adaptive and resilient dialysis systems, ultimately aiming to improve survival rates and quality of life for patients undergoing long-term treatment.

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