DOI: https://doi.org/10.54361/LJMR.20.2.70

Libyan Journal of Medical Research

www.lmjr.ly/ eISSN: 2413-6096

Original Article

Estimation the Residual Pressure Component (RPC) Based on Transmembrane Pressure During Hemodialysis: A Retrospective Analysis of Clinical Dialysis Sessions

Aya Alhadi Armeelah[1], Safa Hasan Almousa[2]

[1] . Department of Physics, Faculty of Science, Sabratha University
[2]. Department of Nephrology, Qasr Akhyar General Hospital
Corresponding Author: Safa Hasan Almousa, safaalmosi@gmail.com

Abstract

Background: Transmembrane pressure (TMP) is a key indicator used to monitor ultrafiltration efficiency during hemodialysis sessions. However, traditional manual calculations of TMP rely solely on blood-side pressures, disregarding the dialysate pressure component—which is not directly measured by the machine—potentially leading to discrepancies between manual calculations. [1][2] **Objective:** This study aimed to evaluate the Residual Pressure Component (RPC) as a proxy for unmeasured dialysate pressure and to examine its contribution to explaining the differences between the transmembrane pressure value recorded by the machine ($TMP_{machine}$) and the manually reconstructed value (TMP_{manual}). calculated values and those recorded automatically. **Methodology:** A retrospective observational study was conducted involving 1,005 hemodialysis sessions using the Nipro Surdial X machine. Data on operating pressures, ultrafiltration rate, and blood flow rate were collected; the TMP_{manual} value was calculated using the formula ($TMP_{manual} = (AP + VP) / 2$),,[5][9][10] and the residual pressure component (RPC) was derived using the relationship ($RPC = TMP_{manual} - TMP_{machine}$). Statistical analyses included descriptive statistics, Pearson correlation analysis, and Bland–Altman agreement analysis, alongside an exploratory operational classification of RPC values based on the data distribution [8][7] **.Results:** The mean TMPmachine was approximately 44.9 ± 29.3 mmHg, while the mean TMPmanual was approximately 6.2 ± 4.9 mmHg, and the mean RPC was approximately -38.6 ± 30.5 mmHg. RPC showed a very strong inverse correlation with TMPmachine (r = -0.98). Bland–Altman analysis revealed a systematic bias and wide limits of agreement between the two methods. The RPC distribution also demonstrated three operational patterns: 62.2% of sessions fell within the operational range, 23.0% within the high negative pressure zone, and 14.8% within the positive pressure zone. **Conclusion:** The results indicate that the residual pressure component (RPC) is a promising operational indicator that could help explain transmembrane pressure dynamics and improve the understanding of the contribution of unmeasured dialysate pressure during hemodialysis. However, adopting this indicator in clinical practice requires validation through prospective, multicenter studies.

Keywords: TMP, Transmembrane Pressure, Nipro Surdial X, Hemodialysis, Dialysate Pressure, Residual Pressure Component, Bland-Altman Analysis, Operational Monitoring.

Introduction

Transmembrane Pressure (TMP) is a key parameter in hemodialysis sessions, representing the driving force that determines the ultrafiltration rate and, consequently, the efficiency of excess fluid removal from patients. In clinical practice[1][2], TMP is typically calculated based on pressure measurements on both sides of the membrane (venous and arterial pressures)[3] ; however, these methods overlook an additional pressure component arising from the dialysate side. This component can vary significantly during the session due to factors such as membrane resistance, blood viscosity, flow disturbances, and the system's compensatory mechanisms.[4]

Traditional manual calculations assume that dialysate pressure is zero or constant—an assumption that is inaccurate for modern systems featuring active pressure control. [5]

This simplification can introduce a systematic bias in the estimation of Transmembrane Pressure (TMP), potentially affecting the interpretation of the session's operational status and influencing clinical decisions, such as adjusting the ultrafiltration rate or detecting hazardous conditions

Received: *11-06-2026-****Accepted:*** *20-06-2026 -****Published:*** *05-08-2026*

DOI: https://doi.org/10.54361/LJMR.20.2.70

Libyan Journal of Medical Research

www.lmjr.ly/ eISSN: 2413-6096

like back-filtration or partial membrane occlusion. [6] [8][7]

Based on the identified research gap, this study posits that the Residual Pressure Component (RPC) serves as an analytical indicator reflecting the contribution of unmeasured pressures to the Transmembrane Pressure (TMP), and that there is a systematic discrepancy between the TMP value recorded by the machine ($TMP_{machine}$) and the manually calculated value (TMP_{manual}). The study further hypothesizes that analyzing RPC values helps explain this discrepancy and enhances the understanding of operational dynamics during hemodialysis sessions.

This study aims to model the Residual Pressure Component (RPC) as an analytical tool to explore the impact of unmeasured pressure components on transmembrane pressure calculations and to determine its ability to explain systematic deviations in conventional TMP estimates.

Materials and Methods

Study Design

This study was designed as a single-center, retrospective observational study aimed at evaluating the Residual Pressure Component (RPC). It relied on the analysis of routine operational data recorded by hemodialysis machines, without any intervention in patient treatment protocols or the conduct of the treatment sessions.

The study included 1,005 hemodialysis sessions recorded by the Nipro Surdial X machine used at the study site—Qasr Al-Akhyar General Hospital. All data were extracted from the machine's electronic records after removing patient-identifying information, and the analysis was limited to the operational and physical variables necessary to achieve the study's objectives.

Dialysis Machine and Operational Parameters

All hemodialysis sessions were performed using the Nipro Surdial X, a hemodialysis machine equipped with an integrated electronic system for pressure monitoring and fluid removal management. The device utilizes a volumetric control system with balancing chambers to ensure precise fluid removal—achieving an accuracy of approximately ±30 g/h—and allows for the adjustment of the Ultrafiltration (UF) rate within a range of 100 to 4,000 mL/h. The device is equipped with sensors designed to measure arterial pressure, venous pressure, and dialysate pressure; it automatically calculates the transmembrane pressure (TMP) using an internal algorithm based on signals from these sensors. The TMP value recorded by the device was used as the reference value in this study.

The operational variables extracted from the device logs for each session included: Arterial Pressure (AP), Venous Pressure (VP), the TMP value measured by the device ($TMP_{machine}$), Blood Flow rate (BFR), Ultrafiltration Rate (UF Rate), Target Ultrafiltration volume (UF Goal), and Treatment Time. These variables were used to recalculate TMP_{manual} and derive RPC, as well as to examine the relationship between RPC and various operational conditions during hemodialysis sessions.

Data Collection

Following the receipt of ethical approvals from the center and the patients, data were collected retrospectively from the routine electronic logs of the Nipro Surdial X device during the hemodialysis sessions included in the study. The database comprised 1,005 hemodialysis sessions, and all variables were extracted directly from the device logs without altering the original values, except for the calculations required to reconstruct TMP_{manual} and derive the RPC.

The extracted data included the relevant operational and physical variables—as previously mentioned—wherever available in the device logs. The data were reviewed for completeness and consistency prior to statistical analysis, and any incomplete records were excluded.

Reconstruction of Manual TMP

To estimate pressure conditions across the dialysis membrane based solely on blood-side measurements, a manual TMP value (designated as TMPmanual) was reconstructed using blood-side pressure measurements available in the dialysis records. The TMPmanual value was calculated according to the following equation:

TMPmanual = (AP + VP) / 2 …… Eq (1)

- AP = Arterial pressure (mmHg).
- VP = Venous pressure (mmHg) [9] [10][5] .

This equation estimated relies on the assumption of a quasi-linear pressure gradient within the blood compartment of the dialyzer—a simplification consistent with the concept of TMP as the average transmembrane pressure in the absence of direct measurements of the dialysate-side pressure.

Estimation of Residual Pressure Component – RPC

To estimate the unmeasured pressure component on the dialysate side, the residual pressure component (denoted as RPC) was calculated by determining the discrepancy (difference) between the TMP value obtained from the machine (TMPmachine) and the manually reconstructed TMP value (TMPmanual). Given the lack of direct measurements for dialysate-side pressure, this indicator is interpreted as an indirect proxy for dialysate pressure rather

Received: 11-06-2026-Accepted: 20-06-2026 -Published: 05-08-2026

DOI: https://doi.org/10.54361/LJMR.20.2.70

Libyan Journal of Medical Research
www.lmjr.ly/ eISSN: 2413-6096

than an actual measurement of it. The RPC was calculated using the following equation:

RPC = TMPmanual - TMPmachine ……Eq (2)

where:

- TMPmachine = the TMP value reported by the hemodialysis machine.
- TMPmanual = the manually reconstructed TMP value [7][8].

This variable aims to characterize the portion of the transmembrane pressure that cannot be explained by blood-side pressures alone, thereby enabling the study of the impact of various operating conditions on hemodialysis system performance.

Exploratory Operational Classification of the Residual Pressure Component (RPC)

To facilitate the interpretation of RPC values and explore various operational patterns, the data were divided into three exploratory categories based on the statistical distribution of RPC values within the dataset. A threshold of -70 mmHg was established at the trough between the two components of the bimodal distribution, while a value of zero served as the natural dividing line between negative and positive pressure values. The categories were classified as follows:

- High negative pressure zone (RPC < -70 mmHg): Reflects sessions characterized by high negative pressure on the dialysate side, often intended to achieve a higher ultrafiltration rate.
- Stable operating range (-70 ≥ RPC ≤ 0 mmHg): Represents the majority of sessions operating under balanced pressure conditions.
- Positive pressure zone (RPC > 0 mmHg): Indicates conditions that may reflect increased fluid path resistance or a disruption in the pressure gradient.

This classification is exploratory in nature; it relies on statistical thresholds derived solely from the study's data and is not proposed as a substitute for established diagnostic or clinical standards, but rather as a descriptive tool for understanding the variation in operating patterns within the study sample.

Statistical Analysis

All statistical analyses were performed using Microsoft Excel 2021. Initially, descriptive statistics—including the mean, standard deviation, median, mode, and minimum and maximum values—were calculated for all study variables, alongside frequency histograms to explore distributional patterns. Pearson correlation analysis was conducted using Python, and scatter plots and the Bland–Altman method were employed to calculate the mean difference (bias) and limits of agreement (at a 95% confidence level) in order to assess the agreement between TMPmachine and TMPmanual and detect any systematic bias. In a subsequent analytical step, RPC values were classified into three exploratory operational categories (less than -70, between -70 and 0, and greater than 0) based on the statistical distribution; this classification served descriptive purposes aimed at analyzing the various operational patterns within the study cohort.

Results

Descriptive statistics

Descriptive statistics for the key variables are presented in Table 1. A vast difference is observed between the mean TMPmachine (44.9 ± 29.3 mmHg) and TMPmanual (6.2 ± 4.9 mmHg).

Table 1: Shows the Descriptive statistics for key hemodialysis indicators (N = 1005)

Variable	**Mean ± SD (mmHg or mL/hr)**	**Min (mmHg or mL/hr)**	**Max (mmHg or mL/hr)**
$TMP_{machine}$ (mmHg)	44.9 ± 29.3	20	88
TMP_{manual} (mmHg)	6.2 ± 4.9	-25	65
RPC (mmHg)	-38.6 ± 30.5	-93	59
UF Rate (mL/hr)	0.5 ± 0.2	0	5

Correlation Analysis

Pearson correlation analysis (Table 2) revealed a near-perfect inverse correlation between TMPmachine and RPC (r = -0.98), confirming that the variation in the machine reading is primarily attributable to the residual component (dialysate pressure).

Table 2 : Shows the Pearson correlation matrix for key indicators.

Received: 11-06-2026-Accepted: 20-06-2026 -Published: 05-08-2026

DOI: https://doi.org/10.54361/LJMR.20.2.70

Libyan Journal of Medical Research

www.lmjr.ly/ eISSN: 2413-6096

Variable	$TMP_{machine}$	TMP_{manual}	RPC	UF Rate (mL/hr)
$TMP_{machine}$ (mmHg)	1.00	-0.18	-0.98	0.10
TMP_{manual} (mmHg)	-0.18	1.00	0.33	-0.01
RPC (mmHg)	-0.98	0.33	1.00	-0.10
UF Rate (mL/hr)	0.10	-0.01	-0.10	1.00

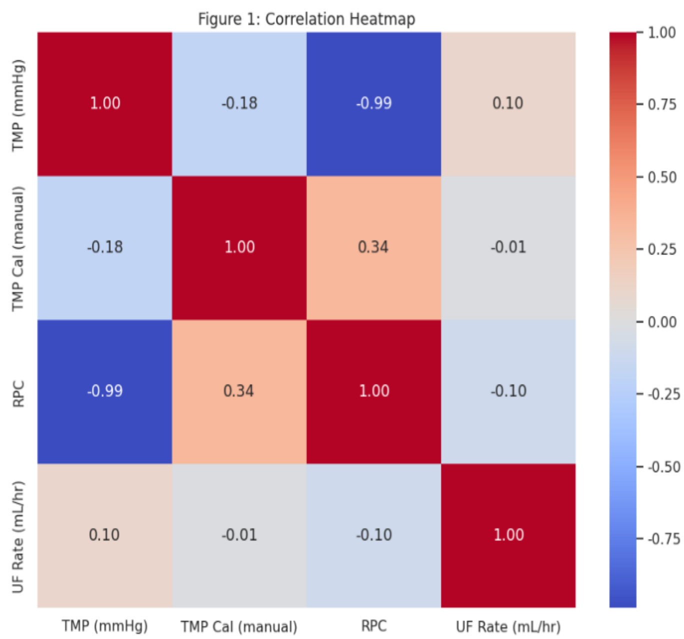

Figure1: Shows the Correlation Heatmap

This figure illustrates the strength and direction of the relationship between the key variables. A very strong, near-perfect inverse correlation (r = -0.99) is observed between the machine-recorded transmembrane pressure (TMPmachine) and the residual pressure component (RPC).

Analysis of multivariate and bivariate relationships

This plot displays the distribution of each individual variable (along the diagonal) and the scatter relationships between pairs of variables. We clearly observe that the distributions of RPC and $TMP_{machine}$ follow a bimodal pattern—meaning the frequency distribution exhibits two peaks.

Received: 11-06-2026-**Accepted:** 20-06-2026 -**Published:** 05-08-2026

DOI: https://doi.org/10.54361/LJMR.20.2.70

Libyan Journal of Medical Research

www.lmjr.ly/ eISSN: 2413-6096

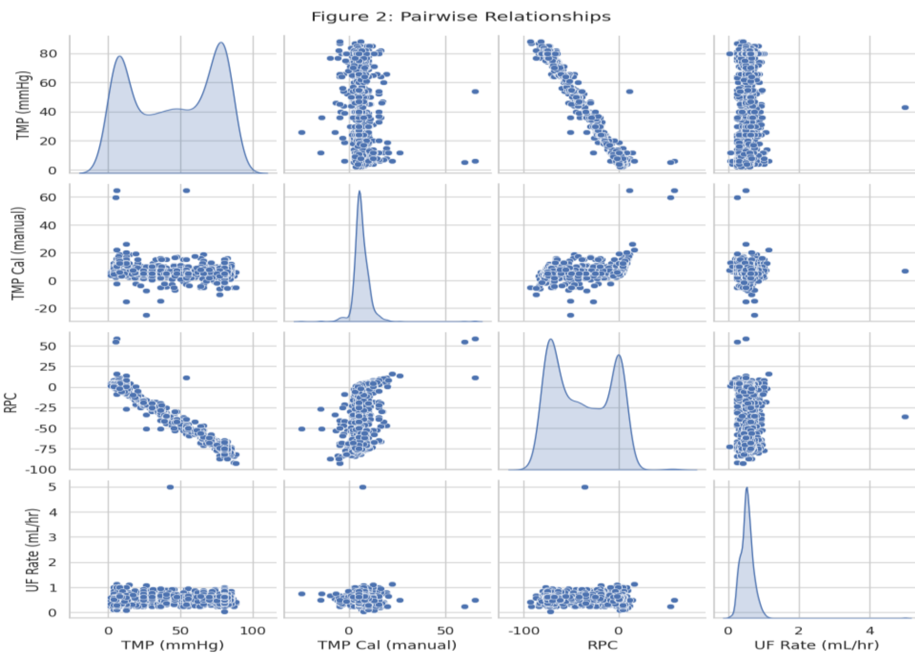

Figure 2 :Shows the Bivariate relationships and distributions of key hemodialysis indicators.

Bland-Altman Plot Analysis

This plot is used to assess the agreement between the manual and automated methods. The results showed a mean difference (bias) of -38.6 mmHg, with wide limits of agreement ranging from +21.2 to -98.5. as shown in figure 3.

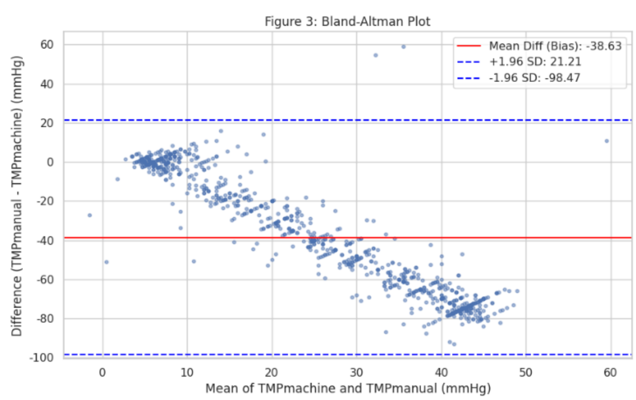

Figure 3: Shows the Bland-Altman plot comparing TMPmachine and TMPmanual.

Boxplot Analysis

This Plot illustrates the distribution of RPC values at various blood flow rates (from 200 to 400 mL/min). It can be observed that the median (the line within the box) remains relatively stable, whereas the dispersion (indicated by the box length and outliers) increases significantly as blood flow rises.

Received: 11-06-2026-Accepted: 20-06-2026 -Published: 05-08-2026

DOI: https://doi.org/10.54361/LJMR.20.2.70

Libyan Journal of Medical Research

www.lmjr.ly/ eISSN: 2413-6096

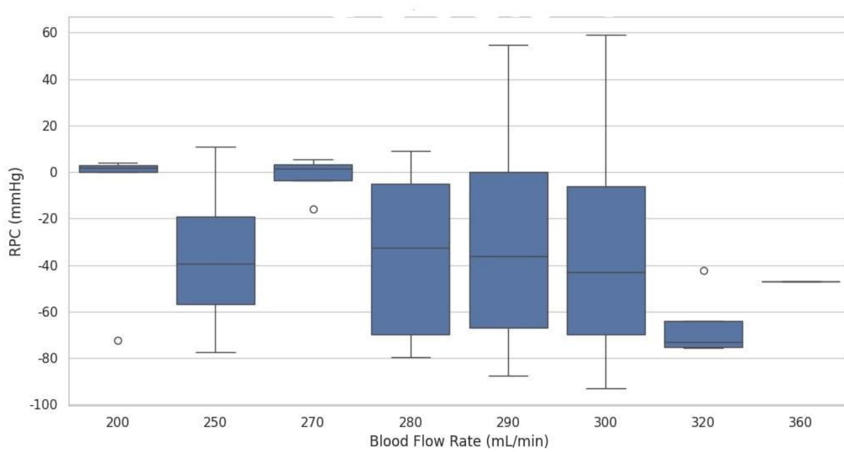

Figure 4 :Shows the Distribution of the RPC across different Blood Flow Rates.

Clinical classification and distribution of the RPC.

This curve highlights the frequency of RPC values while identifying danger zones: the high negative pressure zone (below -70) and the positive pressure zone (above 0).

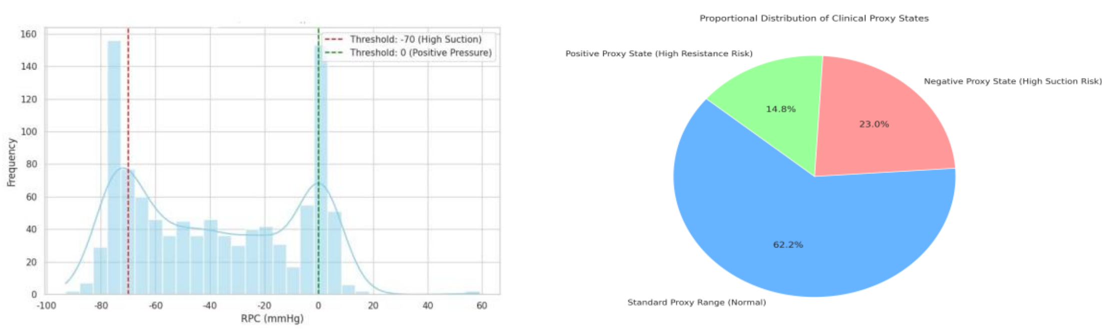

Figure 5: Shows the Distribution of the RPC, showing clinical thresholds and proportions of clinical indicator cases.

Discussion

The study results revealed a fundamental systematic discrepancy between the automatically measured transmembrane pressure (TMPmachine) and the manually reconstructed values (TMPmanual), with the latter showing a marked decrease (6.2 ± 4.9 vs. 44.9 ± 29.3 mmHg). This positive bias (Bias = -38.63) aligns with the findings of Ficheux et al. (2020)[11] , who demonstrated that conventional calculations relying solely on blood-side pressures fail to capture the dynamic component of dialysate pressure, rendering them inaccurate for modern systems و with the findings of Eloot et al. (2002)[12]

The near-perfect inverse correlation (r = -0.98) between TMPmachine and the RPC index serves as strong evidence that TMP variations are primarily driven by negative pressure on the dialysate side. This finding aligns with the study by Sakam (2025)[13], which noted that modern dialysis machines employ complex algorithms integrating dialysate-side pressures to ensure filtration accuracy—a factor that explains the discrepancy between manual and automated measurements. Furthermore, the bimodal distribution pattern of the RPC supports Schneditz's (2017)[14] hypothesis regarding the existence of two operational states: a steady state and a state of active pressure compensation to counteract membrane resistance. Regarding the effect of blood flow rate (BFR), the results showed increased dispersion of RPC values as flow increased; this aligns with the mathematical models of

Received: 11-06-2026-Accepted: 20-06-2026 -Published: 05-08-2026

DOI: https://doi.org/10.54361/LJMR.20.2.70

Libyan Journal of Medical Research

www.lmjr.ly/ eISSN: 2413-6096

Abaci & Altinkaya (2010)[15] and Cancilla et al. (2025)[16], who confirmed that higher velocities heighten hydraulic turbulence and the complexity of the pressure gradient within dialyzer fibers. These observations also intersect with the findings of Eloot et al. (2018)[17], who emphasized that membrane permeability is instantaneously affected by flow variations, thereby influencing RPC fluctuations.

Compared to the study by Pallone et al. (1989)[18] on the mathematical modeling of filtration, RPC offers a practical, data-driven solution that bypasses the computational complexity of traditional models. Furthermore, studies by Maduar et al. (2025)[19] and Sakam (2025)[20] support the concept that digital monitoring of TMP is key to developing "digital twins" for dialysis systems—an approach advanced by our research through the use of RPC as a sensitive operational indicator. Finally, our findings align with the Guidelines for Automated Infusion (2013)[21] and Deranged Physiology (2018)[22] in establishing that a precise understanding of TMP is the only safeguard against the risks of back-filtration or filter clotting, particularly under high-flow conditions.

Conclusion

This study concludes that transmembrane pressure during hemodialysis sessions is a multidimensional variable, and that representing it solely through blood-side measurements is an oversimplification that fails to reflect operational reality. The RPC index demonstrates a strong ability to bridge the analytical gap between manual and automated measurements, providing quantitative insight into the contribution of dialysate pressure, which is not directly measured.

Limitations of the study include its design as a single-center, retrospective observational study utilizing a specific type of device (Nipro Surdial X), which may restrict the generalizability of the findings to other dialysis systems employing different calculation algorithms. Furthermore, the study did not correlate RPC values with long-term clinical outcomes for patients. We recommend incorporating the RPC index as an additional parameter into the digital monitoring systems of hemodialysis machines to enhance early detection of hydraulic deviations. Furthermore, future multicenter studies are needed to evaluate how RPC is influenced by different membrane types (high-flux vs. low-flux) and to investigate the relationship between RPC fluctuations and arteriovenous fistula (AVF) longevity, thereby assessing its utility as a predictive indicator for flow-related issues.

References

1. Tattersall, J., Martin-Malo, A., Pedrini, L., et al. (2007). *EBPG guideline on dialysis strategies. Nephrology Dialysis Transplantation, 22*(Suppl 2).
2. Pedrini, L. A. (2011). Transmembrane pressure, ultrafiltration coefficient and the optimal infusion rate in haemodiafiltration. Nephrology Dialysis Transplantation.
3. Prasad, B., Hemmett, J., & Suri, R. (2022). Five things to know about intradialytic hypertension. Clinical Kidney Journal, 15(10), 2054–2060. https://doi.org/10.1177/20543581221106657
4. Bratsiakou, A., Iatridi, F., Papasotiriou, M., et al. (2024). The effect of different dialysate sodium concentrations on ambulatory blood pressure in hemodialysis patients. Clinical Kidney Journal, 17(8), sfae041. https://doi.org/10.1093/ckj/sfae041
5. Ronco, C., Garzotto, F., Neri, M., & Villa, G. (2019). Measuring intradialyser transmembrane and hydrostatic pressures: Pitfalls and relevance in haemodialysis and haemodiafiltration. Clinical Kidney Journal, 12(6), 882–888.
6. Solomon, D., Arumugam, V., Sakthirajan, R., et al. (2024). A pilot study on the safety and adequacy of a novel ecofriendly hemodialysis prescription. Kidney International Reports, 9(5), 1496–1503. https://doi.org/10.1016/j.ekir.2024.02.014
7. Iatridi, F., Ekart, R., Karkamani, E., et al. (2024). Dialysate sodium and blood pressure variability in hemodialysis patients. Journal of Human Hypertension, 38(8), 750–757. https://doi.org/10.1038/s41371-024-00947-w
8. Daugirdas, J. T., Blake, P. G., & Ing, T. S. (2015). Handbook of Dialysis (5th ed.). Wolters Kluwer.
9. Abaci, H. E., & Altinkaya, S. A. (2010). Modeling of hemodialysis operation. Annals of Biomedical Engineering, 38(11), 3324-3341.
10. Daugirdas JT, Blake PG, Ing TS. Handbook of Dialysis. 5th ed. Philadelphia: Wolters Kluwer; 2015.
11. Ficheux, A., Gayrard, N., Szwarc, I., Duranton, F., Vetromile, F., Brunet, P., Servel, M. F., Jankowski, J., & Argilés, À. (2020). Measuring intradialyser transmembrane and hydrostatic pressures: Pitfalls and relevance in haemodialysis and haemodiafiltration. Clinical Kidney Journal.
12. Eloot, S., De Wachter, D., & Verdonck, P. (2002). Fluid dynamics and pressure drop profiles in hollow fiber dialyzers: Local vs. global assessment. Journal of Membrane Science, 204(1–2), 321–333.

Received: 11-06-2026-**Accepted:** 20-06-2026 -**Published:** 05-08-2026

DOI: https://doi.org/10.54361/LJMR.20.2.70

Libyan Journal of Medical Research

www.lmjr.ly/ eISSN: 2413-6096

13. Dinu, A., Frunzete, M., & Mihailovschi, D. (2026). Data-Driven Operational Bounds of Transmembrane Pressure for Modelling and Digital Twin Development in Haemodialysis and Haemodiafiltration. Bioengineering.
14. Sakam, S. (2025). Understanding TMP in Dialysis – Made Simple. LinkedIn Professional Series.
15. Schneditz, D. (2017). Hydraulics and hemodynamics in the dialysis circuit. In: Principles of Hemodialysis.
16. Abaci, H. E., & Altinkaya, S. A. (2010). Modeling of hemodialysis operation. Annals of Biomedical Engineering, 38(11), 3324–3341.
17. Cancilla, N., Gurreri, L., Ciofalo, M., et al. (2025). Mathematical modelling of hollow-fiber haemodialysis modules. Physical Sciences Reviews.
18. Eloot, S., et al. (2018). The role of membrane permeability and flow dynamics in transmembrane pressure monitoring. Nephrology Dialysis Transplantation.
19. Pallone, T. L., Hyver, S., & Petersen, J. (1989). The simulation of continuous arteriovenous hemodialysis with a mathematical model. Kidney International, 35(1), 125–133.
20. Maduar, et al. (2025). Data-driven operational bounds of transmembrane pressure for dialysis system modelling. Bioengineering.
21. Deranged Physiology. (2018). Troubleshooting the dialysis circuit. Retrieved from derangedphysiology.com.
22. Guidelines for automated manual infusion. (2013). A practical way of prescribing postdilution on-line haemodiafiltration. Revista Nefrología..

Received: 11-06-2026-**Accepted:** 20-06-2026 -**Published:** 05-08-2026